

Development of a Molten-Salt Thermocline Thermal Storage System for Parabolic Trough Plants

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Thermal storage improves the dispatchability and marketability of parabolic trough power plants allowing them to produce electricity on demand independent of solar collection. One such thermal storage system, a thermocline, uses a single tank containing a fluid with a thermal gradient running vertically through the tank, where hotter fluid (lower density) is at the top of the tank and colder fluid is at the base of the tank. The thermal gradient separates the two temperature potentials. A low-cost filler material provides the bulk of the thermal capacitance of the thermal storage, prevents convective mixing, and reduces the amount of fluid required. In this paper, development of a thermocline system that uses molten-nitrate salt as the heat transfer fluid is described and compared to a two-tank molten salt system. Results of isothermal and thermal cycling tests on candidate materials and salt safety tests are presented as well as results from a small pilot-scale (2.3 MWh) thermocline. [DOI: 10.1115/1.1464123]

Introduction

Thermal storage for parabolic-trough power plants offers the potential to dispatch electricity without fossil fuel backup. The value of the electricity is often higher during peak periods. A plant that can meet the peak demand independent of the solar resource has the potential to generate more revenue.

The Solar Electric Generating Station (SEGS) I plant had a two-tank thermal storage system that used Caloria[®] heat transfer fluid. This fluid was pumped through the collector field. The storage tanks were conventional atmospheric tanks. Caloria[®] is a liquid at atmospheric pressures when its temperature is below about 315°C. The SEGS I thermal storage system operated at temperatures between about 175°C and 295°C. The hot Caloria[®] oil was pumped through a steam generator to make saturated steam. Fossil fuel was used to superheat the steam to generate electricity.

The Solar One central receiver pilot plant also used Caloria[®], but in a thermocline tank. A thermocline tank is one that uses a single tank to store thermal energy. A thermal gradient separates the hot from the cold fluid. A low-cost filler material is used to displace the higher-cost liquid. The filler material as well as buoyant forces help to maintain the thermal gradient. When the system is charged, cold fluid is drawn from the bottom, heated as it passes through a heat exchanger (heated with the receiver heat transfer fluid) and returns to the top of the tank. When the tank is discharged, hot fluid is drawn from the top, cooled as it passes through a heat exchanger (to transfer heat for steam generation), and returns to the bottom of the tank. In the Solar One thermocline storage system, steam from the receiver passed through a heat exchanger, which heated the Caloria[®] oil drawn from the bottom of the tank. The heated Caloria[®] returned to the top of the tank where it transferred heat to the rock and sand (the filler material). During a discharge cycle, hot Caloria[®] was pumped from the top of the tank, through a steam generator that made

low-pressure steam, and returned to the bottom of the tank. The low-pressure steam was fed to the turbine to make electricity or was used as an auxiliary steam supply. Since the thermal storage system used Caloria[®], its operating temperature was between 218°C and 302°C. The tank was designed for a thermal capacity of 182 MWh. It used 6170 tonnes (1 tonne = 1000 kg) of rock and sand and 906 m³ of Caloria[®]. Physically, the storage tank stood 13.3-m tall and 18.2-m diameter [1]. Because of the limited upper temperature capability of the thermal storage system, the Rankine-cycle conversion efficiency was only about 21% [2]. Despite the limitations of Caloria[®], the thermocline storage concept worked well. It was able to establish a thermal gradient and maintain the gradient until it was used. Heat loss through the tank walls was acceptable. Because of its upper temperature limitations, Caloria[®] is not practical for the current technology troughs.

The current baseline design for a SEGS plant uses Therminol VP-1[®] heat transfer fluid in the collector field. Therminol VP-1[®] has been used successfully for 10 years in the SEGS II to IX plants located in the Mojave Desert of California. Therminol VP-1[®] has a low freezing point (12°C) and is stable up to 400°C [3]. The higher temperature capability of Therminol VP-1[®] (relative to Caloria[®]) allows these plants to use higher pressure, higher temperature, and more efficient Rankine turbines. It is difficult to use Therminol VP-1[®] as a thermal storage media because its vapor pressure is too high (> 1 MPa at 400°C) to practically store it in any significant quantity at its upper temperature. Multiple thick-walled pressure-vessels would have to be used to store the hot oil, which would be too costly to be practical. Dispatching power in these plants is done with natural gas-fired boilers.

Nexant—a subsidiary of Bechtel—and Pilkington performed analyses of potential near-term thermal storage options for parabolic troughs [4,5]. For a near-term solution of thermal storage for parabolic troughs, Nexant wanted to find a storage system that could work with the current state-of-technology trough. Several indirect thermal storage options were considered where heat from the collector field was transferred from the Therminol[®] oil to another thermal storage media, such as molten salt, which could be stored at atmospheric pressure.

Because of the favorable experience of the two-tank molten-salt

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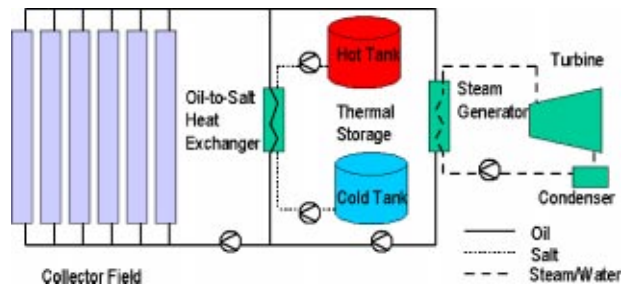


Fig. 1 Schematic of a two-tank thermal storage system integrated into a trough plant

thermal storage system used at the Solar Two demonstration plant [6], its low risk, and cost-effectiveness, Nexant selected this design as a baseline. In this design to charge the storage system, hot Therminol[®] oil coming from the collector field would transfer heat through an oil-to-salt heat exchanger, and then it would return to the collector field to be heated again. Salt pumped from the cold tank would be heated as it passed through the oil-to-salt heat exchanger and would flow into the hot tank. To discharge the storage system, hot salt would be pumped from the hot tank and would transfer its heat through the same oil-to-salt heat exchanger and return to the cold tank. Therminol[®] oil would be heated by the heat exchanger, then pass through a steam generator to make steam. A schematic of the two-tank molten-salt system integrated into a trough plant is shown in Fig. 1. Nexant estimated the capital cost of a 688 MWh_t two-tank molten-salt system used with the current state-of-technology troughs to be about \$31/kWh_t, including the nitrate salt inventory, the installed tanks, and the oil-to-salt heat exchangers.

In a recent roadmap of trough technology [7], the long-term goal for the capital cost of a thermal storage system is \$10/kWh_t. In order to realize this cost reduction, innovative development is needed.

The goal of this project was to improve on the economics of an indirect thermal storage system by assessing the feasibility of using molten salt in a thermocline. We chose to study a thermocline system because it has the potential to reduce the cost of the thermal storage system and it can dispatch thermal energy at nearly a constant temperature over most of its discharge cycle. Both laboratory and engineering-scale experiments were conducted. To come up with a feasible molten salt thermocline system, we broke the development activity into three major areas:

1. Modeling—where we simulated the performance and estimated the economics of a thermocline system,
2. Filler Evaluation: Isothermal Testing—where we screened potential candidate filler materials in isothermal baths of molten salt—and Thermal Cycling Testing—where we took the most promising fillers and subjected them to repeated thermal cycling, and
3. Thermocline Test—where we built a small (2.3 MWh) thermocline system to validate performance and evaluate practical operational issues of a thermocline system.

Also as part of this effort, we evaluated potential low melting-point salts and evaluated salt-safety issues related to using an organic heat-transfer fluid alongside oxidizing nitrate salts.

Modeling

To understand the parameters that affect the performance and economics of a thermal storage system, a model was developed. The thermal behavior of the tank is simulated by the Schumann equations, which describe the heat transfer between the fluid and a packed bed [Eqs. (1) and (2)]

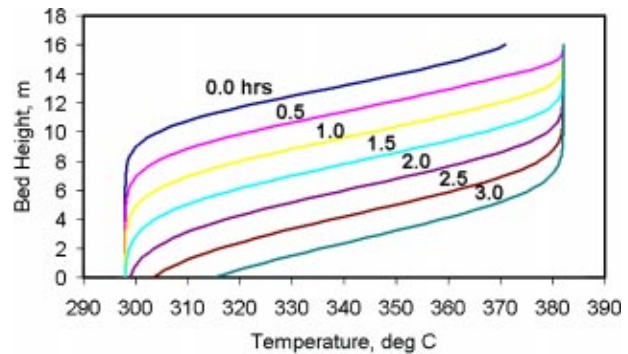


Fig. 2 Temperature gradient every 0.5 h during a charging cycle of a 688 MWh_t thermocline tank 16 m tall and 34.3 m diameter filled with quartzite and sand

$$(\rho C_p)_f \varepsilon \frac{\partial T_f}{\partial \tau} = - \frac{(m C_p)_f}{A} \frac{\partial T_f}{\partial y} + h_v (T_b - T_f) \quad (1)$$

$$(\rho C_p)_b (1 - \varepsilon) \frac{\partial T_b}{\partial \tau} = h_v (T_f - T_b) \quad (2)$$

where f subscripted variables denotes fluid properties and b denotes bed properties. The model consisted of a one-dimensional, finite difference representation of the above equations. The tank was divided into equal horizontal slices, typically 0.2 m thick. An initial vertical temperature distribution was specified. The model then calculated the local heat transfer coefficients, then calculated the local temperatures of the fluid and the bed using the partial differential equations. It used the modified Euler's method to correct the predicted fluid and bed temperatures. The model would repeat the above process at fixed time intervals, typically every 4 seconds.

All the code was written in Visual Basic using Microsoft Excel and ran as a macro. The following parameters could be specified: bed material, fluid, void fraction, tank height, tank diameter, filler material and diameter, surface area shape factor, time step, differential height thickness, initial temperature profile, time dependent inlet fluid temperature, and flow rate.

Figure 2 shows a plot of the thermal gradient during a charging cycle for a 688 MWh_t thermocline tank. Figures 3 and 4 show the inlet and outlet temperatures of the nitrate salt (going into or coming out of the tank) during charging and discharging cycles. As can be seen from Fig. 2, the gradient requires a certain amount of vertical space. Because of the height required for the gradient, taller tanks with smaller diameters are favored over shorter tanks with larger diameters. The tallest tanks that can practically be fabricated have a bed height of 16 m. Note that during the charge-

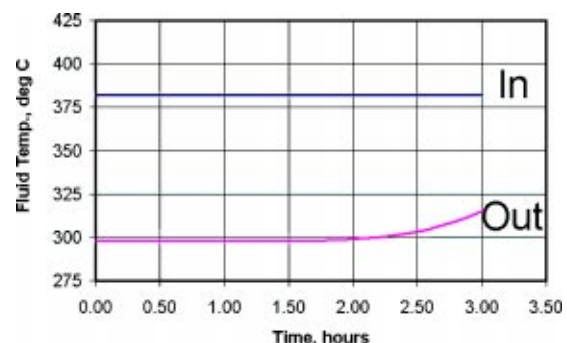


Fig. 3 Salt temperature going into (upper line) and coming out (lower line) of a 688 MWh_t thermocline tank during a charge cycle (same tank as in Fig. 2)

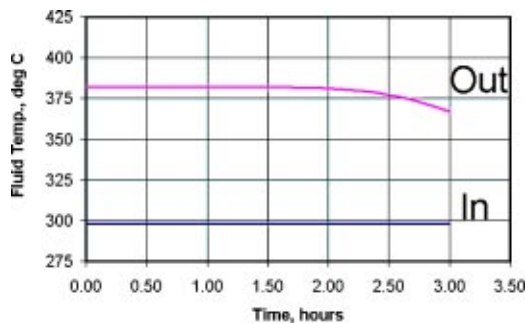


Fig. 4 Salt temperature coming out of (upper curve) and going into (lower curve) a 688 MWh_t thermocline tank during a discharge cycle (same tank as in Fig. 2)

ing cycle, the temperature of the cold salt entering the heat exchanger is constant until the gradient reaches the bottom of the tank. At that point the temperature coming out of the bottom of the tank starts to rise. Similarly during a discharge cycle, the hot salt coming off the top of the tank is nearly constant until the gradient enters the top. At that point the hot salt temperature starts to decay.

One way to quantify the practical storage capacity of a thermal storage system is to compare it to the amount of energy the storage media could hold if the entire inventory were at its upper temperature and discharged completely to its lower temperature. This has been named the *percent theoretical capacity*. In a two-tank molten salt system, the percent theoretical capacity is typically about 85% because each tank has a heel of salt (about 1 m deep) which cannot be used for its storage capacity. In a thermocline storage system, the percent theoretical capacity is a function of the tank height and is typically about 69% because of the space required by the thermal gradient.

Screening of Potential Filler Materials and Nitrate Salts.

To develop a list of potential filler materials, we consulted with a geologist and a nitrate salt expert who recommended several commonly mined minerals and crushed rock. We believed that relatively pure materials could be found and delivered at a low cost. The ideal filler material would be inexpensive and widely available, have a high heat capacitance, a low void fraction (to reduce the amount of liquid required), be compatible with the nitrate salts, and be non-hazardous. Seventeen minerals were selected for testing. These included anhydrite, barite, bauxite, carborundum, cassiterite, corundum, fluorapatite, hydroxyapatite, illmenite, limestone (from Kansas - KS), limestone (from New Mexico - NM), magnesite, marble, quartzite, scheelite, taconite, and witherite.

1 Compatibility of Common Minerals with Nitrate Salts

A study had been performed on the compatibility of granite rock and iron ore pellets (taconite) in nitrate salts. It showed that taconite should maintain its integrity for years at 550°C. Granite rock, however, underwent significant erosion/dissolution, which could in time clog the system [8].

To evaluate our 17 candidate minerals, samples were weighed, photographed, and immersed in known masses of Hitec XL[®] nitrate salt—a commercially available salt containing calcium nitrate, potassium nitrate and sodium nitrate (circa. 42 wt% Ca(NO₃)₂/15% NaNO₃/43% KNO₃)—then removed at specific intervals: 10, 100, and 1000 hours of exposure. A few candidates (limestone, marble, quartzite, and taconite) were also tested in solar salt (a mixture of 60 wt% NaNO₃ and 40 wt% KNO₃) and removed after 400 hours. The samples were washed, weighed, and photographed again following removal. Samples of the salts were also taken for analysis of contaminants.

The witherite and barite samples reacted with the Ca(NO₃)₂ during their initial 10 hour exposure to Hitec XL[®]. Bauxite, illmenite, and KS limestone samples crumbled after exposure to the nitrate salt. Anhydrite experienced significant weight loss. Carborundum and taconite gained weight, most likely due to their porous structure and the difficulty in removing trace amounts of salt. The most successful candidates were quartzite, taconite, marble, NM limestone, apatite, corundum, scheelite, and cassiterite. Because taconite, marble, NM limestone, and quartzite are available in bulk quantities for a reasonable price, we focused our attention on these materials to conduct thermal cycling tests, which are discussed later in this paper.

2 Nitrate Salt Mixtures.

In addition to screening filler materials, we evaluated mixtures of nitrate salts. Studies had shown that the freezing point and upper temperature limit of nitrate salts are functions of the amount of each constituent [9]. Mixtures of sodium nitrate and potassium nitrate, as well as mixtures of sodium nitrate, potassium nitrate, and calcium nitrate were evaluated.

In the Solar Two project, solar salt was used because of its stability at temperatures up to 600°C, its low cost, its compatibility with common piping and valve materials, and its favorable performance in tests conducted at Sandia National Laboratories.

Hitec XL[®] is shipped premixed dissolved in water. To remove the water, the solution must be heated to drive off the water. After the water is driven off, it has a freezing point of about 120°C and is stable to temperatures around 500°C.

3 Safety Issues Related to Using Nitrate Salt and Therminol[®].

To store energy for dispatch, heat from the oil exiting the collector field would be transferred to the salt through an oil-to-salt heat exchanger. Because the nitrate salt is classified as an oxidizer and the Therminol[®] oil is a fuel, there was concern that having these two fluids in close proximity posed an unacceptable hazard in the event that a component failed, leaking oil into the salt or vice versa. Earlier studies were conducted with Hitec[®] (a mixture of sodium nitrate, potassium nitrate, and sodium nitrite) and organic liquids. Motor gasoline, cracked gasoline, gas oil, and crude oil were separately mixed with sulfur and released below the surface of an open container of Hitec[®] at 593°C. In each case, the hydrocarbon burned. The principal reactions were between the vaporized hydrocarbons and the air above the salt bath and not with the salt itself. Experimental data indicate that Hitec[®] is not explosive. Draw salt or any other mixtures of sodium nitrate and potassium nitrate were expected to act similarly to Hitec[®] [10].

To verify that Hitec XL[®] behaved similarly to Hitec[®], Therminol[®] was introduced into a beaker of Hitec XL[®] at approximately 400°C three different ways: on the surface, below the surface, and trapped below the surface in a vial. In each case, the Therminol[®] rapidly volatilized when it came in contact with the hot nitrate salt. The oil did not burn under or on the surface of the salt. We repeated these tests with Caloria[®] oil. The first two tests behaved similarly to the Therminol[®] tests. However, in the third test after covering the beaker with insulation, trapped Caloria[®] oil vapor caught fire and burned for approximately two minutes. The presence of a fuel, oxygen, and a heat source resulted in the small fire. The fire was not a result of a chemical reaction with the nitrate salts that were used. In fact, any heat source would have yielded the same result. As a follow up test, we added an ignition source (spark plug) to simulate an external source of ignition such as a motor in a power plant to verify a fire would occur under the right conditions. We were able to ignite the Therminol[®] vapors above the salt after energizing the spark plug.

The safety concerns in a plant that uses Therminol[®] and nitrate salt in a heat exchanger are not anymore dangerous than using Therminol[®] around other high-temperature heat sources. Accidentally mixing the two components should not create combustion, but combining hot Therminol[®] vapors with oxygen from the air is

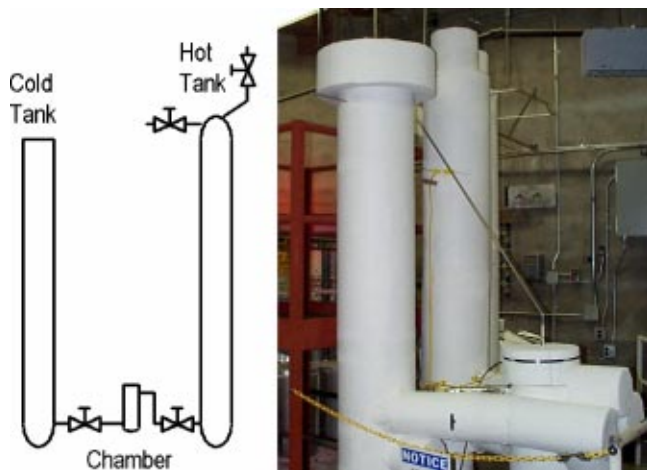


Fig. 5 Schematic and photograph of thermal cycling system to test selected candidate materials

dangerous. The design of the thermal storage system should address the unlikely event of having hot oil vapors released into the ullage space of a nitrate salt tank where oxygen could be present.

Thermal Cycling Tests

The purpose of these tests was to evaluate how well the materials selected in the isothermal tests held up to thermal cycling conditions typical of a thermocline system. We focused on taconite, NM limestone, marble, and quartzite for the thermal cycling experiments. We added filter sand to the test matrix because this material is similar to quartzite and drastically reduces the void fraction in a thermocline tank.

A small 10 cm diameter chamber 30 cm tall containing the filler material was placed between two vessels, each 15 cm in diameter by about 2 m tall as shown in Fig. 5. One vessel contained hot salt at 400°C and the other cold salt at 290°C. Hitec XL[®] salt was used in these tests. To cycle the temperature of the filler material, the vessel containing hot salt was pressurized with air to about 27 kPa, forcing the hot salt through the rock bed, which heated it up and increased the salt level in the cold vessel. After about a one half-hour soak, the pressure was bled off the hot vessel, which allowed cold salt to flow back through the filler material, cooling it off. The cold salt was allowed to soak for approximately $\frac{1}{2}$ hour as well. This process continued 24 hours a day. Typically 15 to 19 cycles were actually completed per day. After a specified number of cycles (typically 350) the experiment was stopped and the samples were inspected.

The NM limestone, a sedimentary rock consisting of hydrated calcium carbonate, should be insoluble to nitrate salt. It fell apart after 365 cycles, becoming soft and looking like mud. This material fared the worst and is unacceptable as a filler material.

Marble is a metamorphic rock, which is calcium carbonate that has been exposed to tremendous heat and pressures. The marble held together after cycling, but softened. The individual grains in the samples appeared to grow in size and prominence during the test. At these temperatures, it is possible that the grains were recrystallizing into larger crystals. Another explanation is that the surface was being preferentially eroded by an unknown process during the test, making the surface features higher in contrast. The marble also became discolored, most likely due to oxidation of entrapped iron. This material fared poorly and is unacceptable as a filler material.

The taconite pellets held together fairly well. Because the pellets are porous, salt wicked into the pellets, but this did not seem to affect them. There were some fines (small particles of material)

produced, but not so much to be concerned with clogging the system. Some of these may have been present in the initial material. Taconite is acceptable for use in molten salt.

The quartzite rock held up remarkably well after 553 cycles. The edges of individual rocks appeared sharp and unaffected. Some pieces of quartzite went from a bluish to slightly reddish color. The change in color was likely due to oxidation of iron that is present in the quartzite. White pieces of quartzite did not change color or appear affected at all. The silica filter sand behaved similarly to the quartzite. Some grains appear slightly reddish in color after exposure, but overall held up well.

Because of the successful experience of the quartzite in the isothermal tests and quartzite and silica filter sand in the thermal cycling tests, we chose these materials for the small thermocline test. Also, quartzite and silica filter sand are widely available, more so than taconite—the second choice.

Thermocline Test

To evaluate the molten-salt thermocline concept on a larger scale, a small, 2.3 MWh, thermocline system was designed and built. The goal of this test was to verify the operation and performance of a molten-salt thermocline system on a larger-than-laboratory scale. A mixture of quartzite and silica filter sand was chosen as the filler media because of the positive results from the previous tests. Since the economics of a thermocline system are a strong function of the void fraction, tests were done to determine the highest packing density of quartzite and silica filter sand. We were able to achieve void fractions of 0.25 in half drum quantities by using a 2:1 ratio of quartzite to sand. The final void fraction measurement of the rock/sand mixture in the tank based on actual quantities of salt used was 0.22.

1 Description of the Thermocline Tank. A carbon steel tank, 6.1 m tall by 3.0 m diameter, was fabricated to American Petroleum Institute (API) Code 650 Appendix J—Shop Assembled Storage Tank. A thermocouple tree was placed in the middle of the tank with thermocouples every 15 cm, vertically. In addition, thermocouples were placed on three radial arms each at 0.36 m, 3.05 m, and 4.88 m from the bottom. The tank had a radial flow distribution manifold at 10 cm from the bottom, which was connected to a standpipe, housing the cold pump. The hot pump was supported from below to pump salt from the top of the tank. Seven electric mineral-insulated heat-trace cables, each rated at 4.8 kWe, were wrapped on the exterior surface of the tank to provide heat input during the initial heating process and make up for heat loss. The tank was insulated with 23 cm of fiberglass insulation on the sides and with 20 cm of calcium silicate ridged block insulation on the top of the tank.

The tank was filled with a mixture of quartzite and silica filter sand. First, a 3-cm layer of sand was laid on the bottom of the tank, followed by a 20-cm layer of quartzite rock. A fine mesh stainless-steel screen was laid down to prevent the sand from working down to the manifold. Next, 5-cm layers of a 2:1 mixture of quartzite rock and sand was added and compacted in place with pneumatic tampers until the filler level reached 5.2 m. In total, we used 49.9 tonnes of quartzite and 21.9 tonnes of silica filter sand. All manifolds had a stainless steel screen installed on them to prevent filler material from entering the piping system.

The tank and inventory of rock and sand were initially heated by energizing the exterior heat trace and forcing hot air from a small propane heater using a venturi into the lower manifold at the bottom of the tank. Once the entire volume was above about 260°C, the salt melting process began. Because of time constraints related to receiving technical grade calcium nitrate, we chose to use a nearly eutectic mixture of sodium nitrate and potassium nitrate without any calcium nitrate. Equal numbers of 23-kg bags of sodium nitrate and potassium nitrate were loaded into a propane-fired salt melter, placed on the top of the tank. The salt was melted and heated to about 290°C, and then a valve was opened to dump the salt into the tank. Once enough salt was

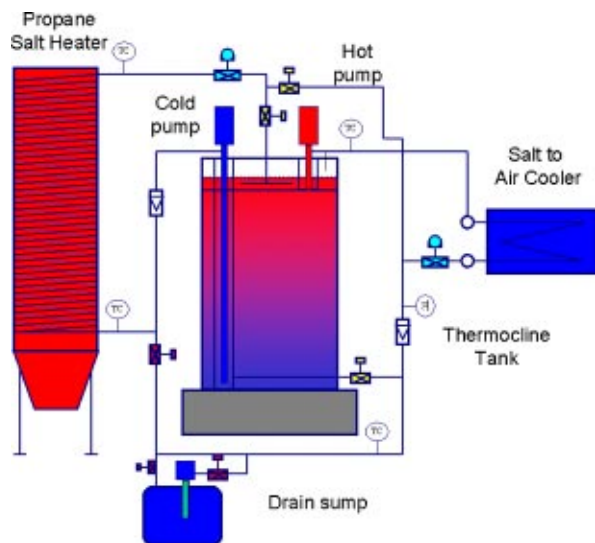


Fig. 6 Schematic of the 2.3 MWh thermocline flow loop

melted so the cold pump could be started, the propane heater was brought online and solid salt was added directly to the top of the tank to be melted by the hot salt returning from the heater.

2 Description of the Flow Loop. A schematic of the flow system is shown in Fig. 6. The system incorporated a propane heater to simulate the heat input from the oil-to-salt heat exchanger. To charge the system, cold salt was drawn off the bottom of the tank through a manifold using a multistage turbine pump. The cold salt was heated with a propane heater and returned to the top of the tank. Both the flow rate of the salt and the heat input from the propane heater could be controlled. In general, the flow rate was fixed, then the propane flow valve was adjusted to get the desired salt-outlet temperature. As the hot salt made its way through the sand and rock, it heated the filler materials and established a thermal gradient.

To discharge the system, hot salt was drawn off the top of the tank through a manifold and pumped through a forced-air salt cooler to reject the heat from the salt. The cold salt exiting the cooler returned to the bottom of the tank. At the end of a test, both the heater and cooler were drained into a sump. The sump's inventory could then be pumped back into the tank.

3 Test Plan. The main purposes of this test were to: 1) verify the heat capacity of a thermocline system, 2) evaluate the size and shape of the thermal gradient, 3) evaluate the change in shape of the thermal gradient over time, and 4) evaluate the heat loss of the thermocline.

The following tests were planned to gather the data necessary to meet the objectives above: 1) initial charging test, 2) full discharge test, 3) full charge test, 4) partial charging test, 5) partial discharging test, and 6) heat loss test.

4 Test Results. Figure 7 shows the temperatures of the cold salt pumped from the bottom of the tank and of the hot salt returning to the top of the tank after being heated by the propane heater. The propane heater slightly overshoot the set point during start up. Also, towards the end of the charging cycle, the salt temperature pumped from the bottom of the tank started to climb as the gradient reached the bottom of the tank. During this charging cycle, the amount of energy added to the salt was approximately 2.6 MWh_t. This is slightly higher than the system rating of 2.3 MWh_t, because the salt in the space above the rocks and sand was at a temperature of about 330°C instead of 390°C as assumed in the model.

During the discharge cycle, the temperature of the salt coming

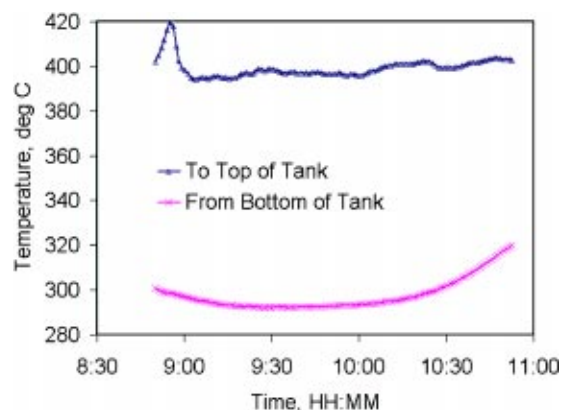


Fig. 7 Measured temperatures of salt pumped from the bottom and returned to the top of the thermocline tank during a charging cycle

off the top of the tank had a slight downward trend that became more pronounced when the gradient reached the top of the tank. Figure 8 shows the temperature gradient through the bed at $\frac{1}{2}$ -hour increments while discharging. During this discharge cycle, the energy extracted was approximately 2.44 MWh_t, which is about equal to the amount of energy added to the salt during the charging cycle, within experimental error. The final hot salt temperature exiting the thermocline was 361°C.

Over a 41-hour period, average heat loss was measured to be approximately 20 kW, which is much higher than the predicted value of 12 kW. It should be noted that there is a large uncertainty associated with heat loss measurement because it is based on the change in internal energy of the tank, which cannot be measured very accurately with the instrumentation installed. Also, in this small tank there are heat sinks such as pump penetrations, which were not accounted for in the heat loss model. The penetrations in a larger system will have less affect on the overall heat loss.

The shape of the thermocline profile is illustrated over this 41-hour period in Fig. 9. Since no heat was added during this test, the thermocline profile went from a fairly flat profile (0.0 hours in Fig. 9) to a more tapered profile after 41 hours. Because this tank had a high volume-to-surface-area ratio, edge effects are more pronounced than would be the case in larger tanks. Despite this fact, after nearly two days, the thermocline profile was still well pronounced and could yield useful energy extracted at a reasonable temperature potential.

5 Economic Analysis of a Thermocline System. Since the goal of this development effort was to reduce the costs of an indirect thermal storage system, we wanted to compare the costs

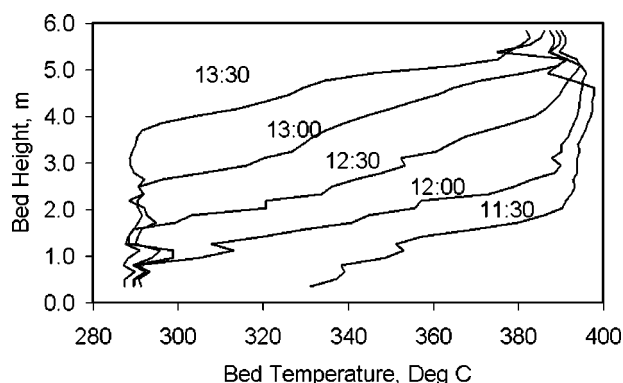


Fig. 8 Measured temperatures of the thermocline profiles during a discharge cycle

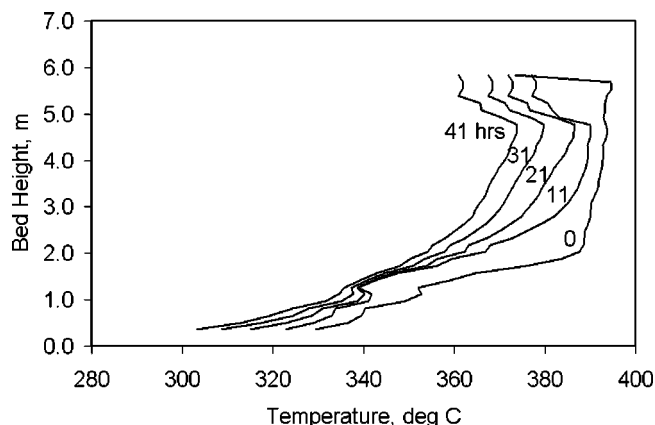


Fig. 9 Degradation of the thermocline profile over a period of 41 hours without supplementary heat

of a two-tank molten-salt system with a thermocline molten-salt system. We did a survey of actual costs of delivered crushed rock and nitrate salt components in early 2000. Table 1 summarizes the costs of several candidate crushed-rock, sand, and taconite. As can be seen from the table, a significant amount of the cost is for transportation, when the product is not locally produced. We also found that sometimes the cost of crushed rock can be reduced significantly, if purchased directly from the quarry.

Table 2 shows the cost of nitrate salt components and mixtures, not including transportation. The calcium nitrate, is the tetrahydrate form, $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$. As it is heated, the molecule sequentially dehydrates with increasing temperature. The water molecules comprise 30.5% of the mass of the tetrahydrate salt. The cost of the calcium nitrate without the water is \$2.06/kg.

The Hitec XL[®] we employed was shipped as a water solution. The inventory we received contained 59% water by mass, which had to be evaporated. The cost of dewatered Hitec XL[®] is actually

Table 1 Cost of crushed rock, sand, and taconite delivered to Albuquerque, NM

Rock	Cost Material, \$/tonne	Transport -ation, \$/tonne	Supplier
Limestone, ¾ inch crushed	41	7	Rocky Mountain Stone, Albuquerque, NM
Limestone, 1 inch crushed	15	6	LaFarge, Albuquerque, NM
Limestone, ½ inch crushed	17	6	LaFarge, Albuquerque, NM
Marble, ¾ inch crushed	120	7	Rocky Mountain Stone, Albuquerque, NM
Taconite, 1.2 cm pellets	66	44	Dale Paulson Geneva Steel, Provo, Utah
Quartzite, ¾ inch crushed	43	7	Rocky Mountain Stone, Albuquerque, NM
Silica Sand, 8 mesh	14	3	J.P.R Decorative Gravel, Albuquerque, NM
Filter Sand, 8x12	89	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x9	168	34	Colorado Silica Sand, Colorado Springs, CO
Filter Sand, 6x12	153	34	Colorado Silica Sand, Colorado Springs, CO

Table 2 Cost of nitrate salts, Hitec[®] XL, and Hitec[®], not including transportation

Salt	Cost of Material, \$/kg	Supplier
NaNO_3 – Technical Grade	0.41	Chilean Nitrate, Memphis, TN
KNO_3 – Technical Grade	0.62	Chilean Nitrate, Stockton, CA
$\text{Ca}(\text{NO}_3)_2$ – Technical Grade (tetrahydrate)	1.43	Coastal Chemical
Hitec [®] XL (in 59% water)	1.43	Coastal Chemical
Hitec [®] (dry)	0.93	Coastal Chemical
60:40 Na:K Nitrate Salts (Solar Salt)	0.49	Mixed
42:15:43 Ca:Na:K Nitrate Salts (dewatered)	1.19	Mixed

\$3.49/kg. In large quantities (e.g., Megaton), sodium nitrate and potassium nitrate can be purchased at reduced rates of approximately 10%.

Table 3 shows the cost breakdown of a 688 MWh_t two-tank molten salt system and a 688 MWh_t thermocline thermal storage system. The thermocline system assumes that the filler material is a mixture of ¾ inch crushed quartzite and silica filter sand (8 × 12) and has a void fraction of 0.24. The most costly component in a two-tank molten salt system is the nitrate salt inventory. The thermocline system is about 66% of the cost of a two-tank molten salt system.

Conclusions

A thermocline indirect storage system has been developed that is about 2/3 the cost of a two-tank molten salt system for parabolic trough power plants. Screening studies on candidate filler materials showed that silica filter sand, quartzite rock, and taconite were compatible with nitrate salts, both in isothermal and cyclic conditions. We chose quartzite and silica sand as the most practical filler materials for a small, pilot-scale test because of their availability and cost. Results from the pilot-scale test confirmed the thermal capacity of the thermocline was near the calculated value. The height of the thermal gradient corresponded to that predicted by the model. Heat losses were higher than predicted primarily due to the heat losses through pump penetrations on the top of the tank, though in a large thermal storage system (100s MWh_t) that effect will have a smaller (near negligible) impact. The results of this work show that a molten-salt thermocline system is a feasible option for thermal storage in a parabolic trough plant.

Table 3 Cost of two-tank and thermocline molten-salt thermal storage systems each 688 MWh. Assumptions: Tank $\Delta T = 84^\circ\text{C}$, Mixed filler cost=\$72/tonne, Salt cost=\$0.45/kg, Tank cost=\$155/m³, Thermocline practical capacity=69%.

Component	Two-Tank Molten Salt	Thermocline with Quartzite
Nitrate Solar Salt, \$k	11800	3800
Filler Material, \$k	0	2200
Tank(s), \$k	3800	2400
Salt-to-oil Heat Exchanger, \$k	5500	5500
Total, \$k	21100	13900
Specific Cost, \$/kWh	31	20

Nomenclature

- A = cross sectional area of bed, m^2
 C_p = specific heat of fluid (f) or bed (b), J/kg K
 D = particle diameter, m
 h = heat transfer coefficient between bed and fluid, $\text{W/m}^2\text{K}$
 h_v = $6h(1 - \varepsilon)\alpha/D$ = volumetric heat transfer coefficient, $\text{W/m}^3\text{K}$
 T = temperature of fluid (f) or bed (b), $^\circ\text{C}$
 y = vertical dimension, m
 α = surface area shape factor
 ε = void fraction of bed
 ρ = density of fluid (f) or bed (b), kg/m^3
 τ = time, s

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