ASSESSMENT OF A MOLTEN SALT HEAT TRANSFER FLUID IN A PARABOLIC TROUGH SOLAR FIELD

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ABSTRACT

An evaluation was carried out to investigate the feasibility of utilizing a molten salt as the heat transfer fluid (HTF) and for thermal storage in a parabolic trough solar field to improve system performance and to reduce the levelized electricity cost. The operating SEGS[1] plants currently use a high temperature synthetic oil consisting of a eutectic mixture of biphenyl/diphenyl oxide. The scope of this investigation included examination of known critical issues, postulating solutions or possible approaches where potential problems existed, and the quantification of performance and electricity cost using preliminary cost inputs. The two leading candidates were the so-called solar salt (a binary salt consisting of 60% NaNO3 and 40% KNO3) and a salt sold commercially as HitecXL (a ternary salt consisting of 48% Ca(NO3)2, 7% NaNO3, and 45% KNO3). Assuming a 2-tank storage system and a maximum operation temperature of 450°C, the evaluation showed that the levelized electricity cost can be reduced by 14.2% compared to a state-of-the-art parabolic trough plant, such as the SEGS plants in California. If higher temperatures are possible, the improvement may be as high as 17.6%. Thermocline salt storage systems offer even greater benefits.

[1] Solar Electric Generating Systems located in Mojave Desert, California.

INTRODUCTION

The use of molten salt HTF in a trough plant has several obvious advantages. With salt, it may be possible to raise the solar field output temperature to 450-500°C, thereby increasing the Rankine cycle efficiency of the power block steam turbine to the 40% range, compared to 393°C with the current high-temperature oil and a cycle efficiency of 37.6%. The HTF temperature rise in the collector field can increase up to a factor of 2.5, reducing the physical size of the thermal storage system for a given capacity. Moreover, molten salt is cheaper and more environmentally benign than the present HTF. In this evaluation, the Solar Two experience [1] with salts was both pertinent and valuable, especially concerning issues related to piping, vessels, valves, and pumps.

The major challenge of the molten salt is its high freezing point, leading to complications related to freeze protection in the solar field. The synthetic oil currently used freezes at about 15°C, whereas the ternary and binary molten salts freeze at about 120°C and 220°C, respectively. This demands innovative freeze protection methods and increased operation and maintenance (O&M) requirements. There are also other important considerations related to the use of molten salts. For example, header piping materials and fittings on the hot side of a collector loop will be more expensive, and the desired high-side temperature limit may be restricted by the durability and performance of the selective surface of the receivers. On the other hand, thermal-and fluid characteristics of the collector field are improved.

Therefore, this evaluation tackled several basic questions, such as: What is the practical upper temperature limit? Is the O&M with salt feasible in a trough field, particularly freeze protection? Do materials, O&M, performance, heat tracing and other factors push the solar system capital cost too high, or in fact will the cost be reduced? Will electricity costs for trough systems be reduced with this approach? Does the integration of thermal storage change the economic results and comparisons?

This evaluation addressed all these questions. The result is a comprehensive comparison, on the basis of levelized electricity costs, of a wide range of trough system options using a molten salt HTF, plus an identification of crucial engineering issues. Selected findings in the evaluation have been discussed in recent papers [2,3].

METHODOLOGY

The benefits of a molten salt HTF were compared on a basis of Levelized Electricity Cost (LEC) to a reference configuration solar power plant using a synthetic oil HTF. After selection of the power plant parameters and candidate salts, comprehensive parametric calculations were carried out on performance and cost of various power systems, leading to the LEC results. It was determined early in the study that a salt HTF was only attractive for a configuration that includes thermal storage. Along the way, a number of conceptual design analyses were developed to address potential engineering barriers and to arrive at reasonable cost estimates. Table 1shows the final parametric conditions discussed in this paper.

Table 1 Parametric operating conditions for analyses

Power block type:	Steam Rankine cycle	
Power block capacity:	55 MWe gross	
Steam turbine inlet conditions:		
Pressure Temperature	66 bar, 100 bar nominally 400-500C	
Steam turbine cycle efficiency: determined by GateCycle calculation, nominally 38.5-41.1% for these conditions.		
Solar field outlet salt temperature:	Nominal Maximum	450°C ~500°C
Optical:	Overall optical efficiency	0.75
Performance runs:	Thermal storage capacity	6h
	Annual Insolation	Barstow
Collector type	Generic SEGS type with advanced features	
Receiver	Current Solel Receiver	ε=0.1@ 400C
Operating scenario	Solar only	

CANDIDATE SALTS

Nitrate salts were selected for Solar Two use because of their favorable properties compared with other candidates. In particular, these nitrate salts have low corrosion rates with common piping materials, are thermally stable in the upper temperature range required by steam Rankine cycles, have very low vapor pressures, are widely available, and are relatively inexpensive. Solar Salt was selected as the most practical salt for molten-salt power tower applications because the upper operating temperature limit (600°C) allows the technology to be used with the most advanced Rankine cycle turbines. In addition, it is one of the lowest cost nitrate salts. However, a major disadvantage with Solar Salt is its relatively high freezing point of 220°C. Hitec salt offers a lower freezing point of about 140°C at a higher cost.

The freezing point is of major importance in a trough solar field because of the likely difficulties and cost associated with freeze protection due to the need for extensive heat tracing equipment on piping and collector receivers. Primarily for this reason, a calcium nitrate salt mixture (basis of the commercial product HitecXL), with a lower freezing point of about 120°C, is favored here. Other characteristics, like cost, are important, but in the final analysis were deemed secondary to the risks associated with freezing.

The density, viscosity and heat capacity properties are generally similar for the nitrate salts, as shown in Table 2. Calcium nitrate salt has an upper operating temperature limit of about 500°C, but it is expected that the chemical stability of the receiver selective surface, not the salt, will be the limiting operational factor on the maximum operating temperature level. The vapor pressures at these temperatures are very low, typically a fraction of a Pascal. Chemical reactivity and environmental issues are similar for the nitrate salts and are acceptable for this application.

Table 2 Characteristics of the Nitrate Salts and Therminol VP-1

Property	Solar Salt	Hitec	Hitec XL (Calcium Nitrate Salt)	$LiNO_3$ mixture	Therminol VP-1
Composition, %					Diphenyl biphenyl oxide
$NaNO_3$	60	7	7		
KNO_3	40	53	45		
$NaNO_2$		40			
$Ca(NO_3)_2$			48		
Freezing Point, C	220	142	120	120	13
Upper Temperature, C	600	535	500	550	400
Density @ 300C, kg/m^3	1899	1640	1992		815
Viscosity @ 300C, cp	3.26	3.16	6.37		0.2
Heat capacity @ 300C, J/kg-K	1495	1560	1447		2319

Because thermal storage is an important issue for a trough system, the cost effectiveness of nitrate salts in a trough solar field was initially evaluated in terms of cost per unit thermal energy stored. That is, the costs were analyzed taking into account not only the raw costs of the salt constituents, but also the effective heat capacities of the salt solutions. Raw costs were based on dry industrial grade costs of the appropriate constituents or costs of commercial pre-mixed products. The temperature rise in the solar field was varied from 100°C to 200°C. The cost of the SEGS HTF (Therminol VP-1) was used for comparison at the 100°C point. The comparison is shown in Table 3, with the freezing points indicated in the square brackets. Thermal storage equipment is not included in this comparison.

Table 3 Effective Storage Fluid Cost

Salt	Temperature Rise	Cost per Kg	Storage Cost
	°C	$/kg	$/kWh$_t$
Hitec (a) [142°C]	200	0.93	10.7
Solar Salt (b) [220°C]	200	0.49	5.8
Calcium Nitrate [HitecXL] (c) [120°C]	200 150 100	1.19 1.19 1.19	15.2 20.1 30.0
Therminol VP-1 (d)	100	2.2	57.5

a) 7:53 Na:K Nitrate, 40 Na Nitrite c) 42:15:43 Ca:Na:K Nitrate
b) 60:40 Na:K Nitrate d) Diphenyl/biphenyl oxide

The calcium nitrate salt (HitecXL composition) is significantly less expensive in terms of energy capacity than Therminol VP-1 at the same solar field temperature rise, and over 70% lower if used at a 200°C rise. Although solar salt shows an even further cost reduction, the high freezing point poses severe problems. Hitec has a lower cost and higher freezing point than the calcium nitrate salt, and remains an option. However, it does require an N_2 cover gas in the thermal storage tanks at atmospheric pressure to prevent the nitrite from converting to nitrate, thus raising its freezing point.

ENGINEERING ISSUES

Preliminary conceptual design work defined the system requirements and estimated costs of changes in the solar steam system design and equipment necessary for operation with a molten salt HTF. The following list highlights the main issues taken into account:

- Operation and durability of the heat collection element, particularly the selective surface, at higher operating, temperatures; this includes increased radiation heat losses at higher fluid temperatures and the potential exacerbation of the asymmetric temperature distribution around the circumference due to a lower salt flow rate,

- Solar field HTF flow rate, piping layout and parasitic pumping power, which are affected by salt properties and fluid temperature rise across the solar field, and the selection of more expensive steels for the headers operating at higher temperatures,
- Freeze protection of the solar field piping and heat collection elements, including the ball joints used between collectors,
- Detailed thermal storage system analysis using either two-tank or thermocline systems, with use of the same or different fluids in the solar field and the storage system. For example, a VP-1 solar field is configured to use molten salt for thermal storage by installing an oil-to-salt heat exchanger between the two systems. These choices have large effects on power cycle operation and costs.
- Enhanced operation of the power block at higher steam temperatures, taking into account the detailed effects of the storage system, and
- Selection of valves, fittings and pumps for molten salt application.

Many detailed design and cost evaluations were carried out on the areas outlined above in order to develop reasonable information for the performance and cost analyses. Particular attention was placed on the design of the thermal storage systems, major heat exchangers, and power cycle performance [4,5].

Furthermore, issues associated with freeze protection methods, costing, and operation were identified, evaluated; and resolved, at least at a preliminary stage. These included freeze protection operating scenarios for nighttime (low-flow circulation of hot salt from thermal storage tanks throughout the solar field); routine loop maintenance that requires HTF removal; freeze protection methods for piping, fittings, HCEs, and ball joints; and recovery from freeze incidents. For example, an innovative approach using impedance heating for freeze protection of the HCE, in contrast to an external heating coil, was deemed to be feasible. Ball joint freeze protection, on the other hand, was left unresolved and requires further investigation.

Since the engineering issues regarding operation of a trough solar plant using molten salt in the solar field pose worthy challenges, we turn our attention here to some of the more important considerations.

Routine Freeze Protection Operation

Since the freezing point of the considered salt is considerably higher than the freezing point of VP-1, special attention has to be dedicated to freeze protection operation. In principle, the same strategy as in the SEGS plants can be applied for freeze protection overnight:

1) The HTF is circulated through the solar field during the whole night. By this means the piping will be kept warm, thus avoiding critical thermal gradients during start up.
2) If the HTF temperature falls below a certain value, an auxiliary heater is used to maintain a minimum temperature of 150°C.

According to the results of annual performance calculation the annual fuel consumption for freeze protection will be about 2 million m^3 of Natural Gas for a 55 MW plant with molten salt as HTF. Assuming a gas price of $0.081/$m^3$, freeze protection will cost $162,000 per year. This is small compared to the normal total O&M cost.

This procedure can be modified and improved slightly for systems with thermal storage. Assuming a cold storage temperature of about 300°C and a total salt mass of 2,000,000 kg (6h storage) the thermal capacity of the storage related to its freezing temperature is still more than 1200 MWht. Instead of using fossil energy to heat up the salt, salt from the cold tank can be taken to keep the solar field and the whole system warm. Assuming heat losses of approximately 25 W/m^2 during night the total heat loss of the solar field will be 10.7 MWt. Hence, the storage capacity of the cold tank is enough for 112 hours or 4.6 days of freeze protection operation. Of course, the cold tank has then to be heated up again at beginning of operation, which consumes solar thermal energy. On the other hand, fossil fuel can be saved. According to annual performance calculation a storage capacity of 1h is enough for freeze protection operation during the night. This is depicted in Figure 1. In this figure cooling curves for the solar field are shown for configurations with and without thermal storage. In the case without thermal storage the solar field reaches the critical temperature after 6h. Then a fossil heater has to maintain the temperature at 150°C. In the case of thermal storage, the energy of the cold tank is used for freeze protection. For a normal winter day the minimum temperature of the storage at start-up in the morning will be 250°C for a 1h storage and 280°C for 6 h storage. The inlet temperature in the solar field is the same as the cold storage tank temperature. Hence, routine freeze protection operation can be done by the thermal storage. However, an auxiliary heater still must be installed in configurations with thermal storage in case of emergency.

Solar Field Preheat Methods

The heat collection elements and piping within a solar collector assembly require an electric heating system to perform the following functions: preheating prior to filling with salt to minimize transient thermal stresses; and thawing frozen salt following a failure in the salt circulation equipment.

Heat Collection Elements

Two methods have been proposed for the heat collection elements. The first is an impedance system, which passes an electric current directly through the heat collection element. Transmitting a current through an electrical conductor incurs a loss in power due to the resistance of the circuit. For a direct current, the impedance losses are given by the familiar expression $P = I^2 R$, where I is the current and R is the resistance. The losses are manifested by a temperature rise in the conductor. Impedance heating has been used in thousands of reliable pipe heating systems over the past 30 years. In addition, a 5.4 kWe impedance heating system on a 16 m section of nitrate salt piping was successfully tested at Sandia National Laboratories in 1996 [6].

The second method is a resistance heating system, which uses a resistance heating cable placed inside the heat collection element. The cable consists of an Inconel tube 9.5 mm in diameter, two Nichrome heating wires inside the tube, and mineral insulation separating the wires from the tube. The cables are available for a number of commercial applications, and were used successfully on the 10 MWe Solar Two central receiver project near Barstow, California.

The beneficial features of the impedance concept include the following:

- Heating occurs uniformly around the circumference of the pipe. In contrast, the resistance systems depend on conduction and radiation to distribute the thermal energy around the pipe.
- Power densities up to 250 Watts per meter are possible due to the distribution of the current across the full cross section of the pipe. In comparison, the power density of mineral insulated cables is limited to about 165 W/m to prevent corrosion of the Inconel tube in contact with the cable. The principal benefit of a high power density is a shorter preheat time.
- No heating elements are placed inside the heat collection element. Thus, the flow characteristics and pressure losses in the solar collector assembly remain unaffected. Also, there are no penetrations through the wall of the

heat collection element or connecting piping to act as potential leak sites.

The principal liability of the impedance systems is the size of the electric equipment. The stainless steel in the heat collection elements has a low electric resistance; therefore, to achieve a reasonable preheat period, high electric currents are required. The high currents, in turn, require large transformers, cables, and switchgear.

Example of an Impedance Heating System for Heat Collection Elements

The electric power required to preheat a heat collection element is given by the following:

$m\ c_p\ \Delta T\ /\ \tau = I^2\ \rho\ L\ /\ A$, where m is the mass of the heat collection element (kg), c_p is the specific heat of Type 347 stainless steel (J/kg-C), ΔT is the preheat change in temperature (°C), τ is the preheat time (seconds), I is the impedance current (Amps), ρ is the resistivity of Type 347 stainless steel (Ohm-m), L is the length of the heat collection element (m), and A is the metal cross section of the heat collection element (m^2).

Assuming a preheat change in temperature of 180°C, a preheat time of 30 minutes, and a steady state thermal loss of 323 Watts, the electric power required for each heat collection element is 939 Watts. The electric resistance of a heat collection element is 0.0076 ohms, which, in turn, leads to a preheat current of 352 Amps and a voltage drop of 2.67 Volts. The IEEE standard for impedance heating lists a maximum allowable system operating voltage of 80 Volts. As a result, up to 30 heat collection elements could be placed in series. The optimum collector field arrangement for a 55 MWe plant, identified by Flabeg in an earlier project phase, consists of 10 solar collector assemblies in a loop. Each solar collector assembly has 24 heat collection elements; thus, a candidate wiring arrangement would supply the preheat current of 352 Amps to each of the 10 solar collector assemblies at a voltage of 64 Volts. The remaining potential of 16 Volts is then available for losses in the distribution wiring.

To reduce the potential for stray voltages and currents, the electric circuits can be arranged in two parallel and identical legs; current is introduced at the juncture of the legs, and then collected at the end of each leg. The required voltage distribution leads to a wiring arrangement of 5 parallel circuits, each with two solar collector assemblies in parallel. The current is introduced between the two solar collector assemblies, and collected at the end of each assembly.

Collector Field Piping

The wall thickness of the collector field piping is much greater than the wall thickness of the heat collection elements. Thus, the mass per meter of the field piping is much higher, and the electric resistivity is much lower, which makes an impedance heating system impractical. As a result, the field piping uses conventional resistance heating equipment to trace heat the piping. Since the heating cables are notoriously brittle, the heat trace zones are arranged to begin and end at the piping ball joints.

Collector Loop Maintenance with an Impedance Heating System

The field wiring for the impedance system power distribution and the resistance heat tracing would be a permanent installation, while the step-down transformer for the impedance heating system would be carried on a loop maintenance truck. The entire field, baring unforeseen problems, would need to be filled perhaps 15 times during the life of the project. As a result, the capital investment in a permanent transformer and associated supply wiring for each loop probably cannot be justified, and portable engine-generators and transformers are used.

A collector loop would be filled, as follows:

- The maintenance truck would park at the end of a loop, and the electric connections to the permanent wiring buses would be made.
- The permanent electric heat tracing on the fixed piping would be activated.
- A 300 kW engine-generator on the maintenance truck would be started, supplying electric power to the transformer. After about 30 minutes, the temperatures of the fixed piping and the heat collection elements would reach 200°C. The isolation valves at the inlet to, and the outlet from, the loop would be opened, and a flow of salt established in the loop.
- The set point for the electric heat tracing on the fixed piping would be reduced to 150°C for emergency freeze protection.
- The engine-generator would be stopped, the electric connections to the wiring buses would be removed, and the truck would move to the next collector assembly loop.

A 55 MWe plant with 6 hours of thermal storage requires a field with 78 solar collector assembly loops. If one hour is required to preheat and fill a loop, an operating staff of 8, with 4 maintenance trucks, could preheat and fill the entire field in about two working days.

A collector loop would be drained, as follows:

- The maintenance truck would park at the end of a loop, and the electric connections to the permanent wiring buses would be made. The engine-generator would be started, and electric power delivered to the heat collection elements to maintain a minimum temperature of 200°C.
- The permanent electric heat tracing on the fixed piping would be activated.
- The isolation valves at the inlet to, and the outlet from, the loop would be closed. A temporary line would be installed between the loop drain valve and a vacuum tank on the maintenance truck, and a vacuum would be established in the tank. A vent valve, on the opposite end of the loop from the drain valve, would be opened, and the flow of air through the loop would push the salt into the vacuum tank.

All of the salt will probably not drain from the loop; however, this is an acceptable condition for maintenance of, and restarting, the loop. As long as void spaces are established everywhere in the loop, there is little danger of plastically deforming the heat collection elements or the piping when the electric preheating system is activated and the salt is thawed in preparation for refilling the loop.

Materials Considerations

The proposed nitrate salt heat transport fluid is relatively benign in terms of corrosion potential. Nonetheless, the industrial grade of the salt does contain impurities, of which the most chemically active are the chlorides and perchlorates. The upper limit on the total chloride content in industrial grades is typically 0.6 percent, in which case the commercial materials shown in Table 3 should be suitable:

The most problematic materials issue for nitrate salt systems is the packing material for valve stems. Sandia National Laboratories has tested numerous packing materials, and found the following combination to be generally acceptable: alternating layers of 1) wire-reinforced graphite braid packing over a fiberglass core, and 2) Teflon® washers filled with fiberglass. Nonetheless, the nitrate salt slowly oxidizes the graphite in the braid, and the packing must be replaced periodically. In addition, the Teflon® has an upper temperature limit of 315°C, and valves with extended bonnets must be use on the hot side of the equipment loops. To avoid some of these problems, Sandia is currently testing two alternate valve designs. The first replaces the graphite braid and Teflon® washers with metal o-rings; the second uses a linear electric actuator, immersed in the salt, to avoid the need for external seals.

Table 4 Commercial Materials[a] for Salt HTF Operation

Peak temp-erature	Basic material	Pipe	Fittings	Valves	Tubes [b]	Plate [c]
325°C	Carbon steel	A 106, Grade B	A 234, Grade WPA	A 216, Grade WCB	A 192	A 516, Grade 70
450°C	Ferritic steel	A 335, Grade P22	A 234, Grade WP22	A 217, Grade WP22	A 213, Grade T22	A 387, Grade 22
500°C	Ferritic steel	A 335, Grade P91	A 234, Grade WP91	A 217, Grade WP91	A 213, Grade T91	A 387, Grade 91

Notes: a) American Society for Testing and Materials designations; b)For steam generator heat exchangers; c) For thermal storage tanks and heat exchanger shells

LEC COST COMPARISON

The purpose of this step was to evaluate the economics of the proposed salt HTF concept and compare it with the state-of-the-art parabolic trough power plant. The evaluation is based on a LEC calculation. The following tasks need to be carried out to estimate the LEC of a power plant:

- Plant design,
- Annual performance calculation,
- Estimation of O&M cost,
- Estimation of investment cost, and
- Determination of economic boundary conditions and LEC calculation.

The best concept design can only be determined by comparing performance and cost of different approaches. Both performance and cost are reflected in the LEC. An optimization of the concept requires several iterative steps and re-definition of input parameters and assumptions within the evaluation process. Investment costs and O&M costs were estimated based on past work [7] and the conceptual design work carried out for this study.

Cost Sensitivity

Sensitivity analyses determined the required accuracy for cost estimates for this comparative evaluation. LEC runs were carried out to evaluate the sensitivity of the LEC to 10% variations in several key factors (investment cost, O&M cost, and system performance) in a molten salt HTF system. The results showed that a 10% variation in each of these factors had the following impacts on LEC:

- Investment cost 8%

- O&M cost 2%
- Performance 10-12%.

This leads to the issue of the magnitude of additional costs resulting from the use of a molten salt HTF compared to the total investment costs. It was found that for a 20% uncertainty in most cost adders (e.g., trace heating system, more expensive materials, higher cost of valves) the effect on LEC would be less than 0.5%. For the salt inventory cost, a 20% uncertainty can have an effect on LEC on the order of 1-1.5%. Based on this analysis, it was concluded that the cost bases for the present cost evaluation are adequate for making comparisons.

Nevertheless, for some factors such as salt inventory cost and selective surface emissivity, specific sensitivity runs were carried out to quantify the effect of uncertainties on LEC. The sensitivity of the results to the emissivity coefficient was examined by calculating the LEC for several cases at a value of 0.15 (at 350°C) in contrast to the reference emissivity of 0.1. This 50% increase in the emissivity coefficient lowered the solar field efficiency and resulted in an LEC increase of 0.6 cents/kWh for the salt cases, which corresponds to an increase of about 5%. By no means insignificant, this points to the importance of improvements in the selective surface. However, even with the increased emittance the analysis favors a salt HTF system over the VP-1 system with storage.

Performance Model

A comprehensive parabolic trough model developed at FLABEG was used for performance and economic analyses. This computer code simulates the performance of entire solar power plants. Such a tool is indispensable when the daily, monthly, and annual output of a certain solar power plant configuration is to be estimated, the output of an existing plant is to be recalculated, or the potential of improvements is to be assessed. The model accommodates normal quasi-steady state conditions, daily start-up and shutdown, or changing weather conditions during operation.

The model was developed based on experience gained from similar programs such as SOLERGY and the LUZ model for plants of the SEGS type. It has been significantly extended to include power plant configurations with combined cycles, thermal energy storage and dry cooling. The computer model output has been validated with measured data from actual performance reports of SEGS plants [8].

From the given meteorological input values of insolation and ambient temperature, the performance model calculates hourly performance values of HTF mass flow and temperatures, collected solar thermal energy, thermal energy fed into the storage, thermal energy taken from the storage, heat losses of solar field, piping and storage, dumped energy, and electric gross and net power. The model also considers thermal inertia of the solar field, storage, and the HTF system under transient insolation conditions.

The following modifications of the performance model were necessary to properly consider the system changes for a molten salt HTF:

- Ability to use a fluid other than VP-1,
- Allowing operation temperatures higher than 400°C,
- Modeling a direct 2-tank storage system and new operation strategy,
- Improvement of heat loss model, and
- Change of freeze protection mode.

IMPACTS OF SALT HTF ON PERFORMANCE

The use of salt as HTF in the solar field has the following main effects on the performance of the plant:

- Molten salt can operate at higher temperatures than the synthetic oil used in the current SEGS plants in California. Consequently, higher steam temperatures can be achieved in the Rankine cycle leading to higher cycle efficiency.
- The mass flow in the solar field is considerable lower with molten salt, which leads to a lower pressure loss in the piping. Both effects combined – low mass flow and low pressure loss – lead to relatively low pumping parasitics compared to a VP-1 solar field.
- Because of the higher outlet temperature the average temperature in the solar field also increases. Consequently, the heat losses of the solar field are higher, and the solar field efficiency decreases.
- The freezing point of HitecXL is rather high (about 120°C). Therefore, more thermal energy is consumed in freeze protection operation. The solar field temperature must be kept well above 120°C throughout the night. That also leads to additional heat losses.

The impact of these four effects is illustrated in Fig. 2, which shows the annual net electric output for a VP-1 plant with 6 hours storage and the change of performance if the effects are considered separately. The VP-1 case uses solar salt in the storage system, an oil-to-salt heat exchanger to transfer heat to the salt storage, and a steam cycle pressure of 66 bar to optimize performance. Combining these effects leads to the performance of a plant with HitecXL (calcium nitrate salt mixture) as HTF. In case of the salt HTF, the investigation was done for a maximum temperature of 450°C.

The improvements in performance are significantly higher than the penalties due to the higher temperature and freezing point. The largest improvement is caused by the lower parasitics in the solar field, an effect that was not initially expected in this evaluation. It is also important to note that the higher heat losses cause only a slight decay of the performance. The biggest penalty resulted from the freeze protection operation.

IMPACTS OF SALT HTF ON ECONOMICS

Figure 3 directly compares the changes in the plant economics if a calcium nitrate salt is used as HTF instead of VP-1. The initial bars show the impact on LEC of adding 6 hours of thermal storage to a plant using VP-1 as the HTF. These plants require the use of a heat exchanger to transfer thermal energy to and from the two-tank and thermocline storage systems. The LEC can be reduced 6% by the integration of a 2-tank molten salt storage system with a state-of-the-art SEGS, and more if a thermocline storage system is used. Replacing the HTF with the calcium nitrate salt would again reduce the LEC, by an additional 9%. If operation temperatures up to 500°C are feasible, the improvement would be 13%. It is interesting to observe that the relative improvement would be of the same order if a thermocline system is considered instead of a 2-tank storage with either HTF or temperature level.

Figure 4 shows the relative influences of the effects responsible for the improvement with a calcium nitrate salt HTF. This Figure presents data for the salt base case, that is, a configuration with 55 MWe gross; 450°C solar field output temperature; 2-tank solar salt storage with 6 hours capacity; and nominal emissivity. The reduction of investment cost is just 2.2% with a correspondingly small effect on the LEC. The most important effect is the performance improvement. The annual electricity output increases by 8.7%, leading to a reduction of the LEC of \$10/MWh$_e$. Less than half of this improvement is caused by the better performance of the Rankine cycle at higher temperatures while the other portion comes from the lower parasitic consumption of the solar field. The higher solar field and piping thermal losses are, of course, included in the analysis. These improvements are partly diminished by higher O&M costs, due to more costly maintenance associated with freeze protection equipment and salt-driven maintenance of valves and ball joints.

These results project that the potential reduction in levelized electricity cost by switching from VP-1 to a ternary salt HTF at 450°C in a trough plant with 6 hours storage is slightly over 1 cent/kWh. This would be a very significant gain for a trough power plant, and can be realized over and above cost reductions owing to collector field cost reductions. If the higher temperature of 500°C proves to be possible, the potential cost reduction could be more than 1.5 cents/kWh. These relative gains are generally true for either 2-tank salt storage or thermocline systems.

FINAL OBSERVATIONS

Table 5 provides summary data on the performance and economic improvements potentially possible by use of a salt HTF in the solar field and storage system. The less expensive Solar Salt is used for storage if the HTF is VP-1, whereas calcium nitrate salt is used for the HTF and storage in the salt HTF cases. Assuming a 2-Tank system and a maximum operation temperature of 450°C, the LEC can be reduced by 14.2% compared to a state-of-the-art parabolic trough plant, such as the SEGS plants in California. If higher temperatures are possible, the improvement may be as high as 17.6%. Further cost reductions are possible with a thermocline storage system.

Table 5 Summary of Parametric Results for Salt HTF Analysis

Case ID	VP-1 No Sto	VP-1 66bar 2T	VP-1 66bar TC	Salt 450°C 2T	Salt 450°C TC	Salt 500°C 2T	Salt 500°C TC
Solar Field Size [m²]	270,320	427,280	427,280	425,100	425,100	425,100	425,100
Investment Cost [M$]	110,291	175,251	169,546	171,405	159,556	164,583	156,158
Thermal Storage Cost [M$]	0	21,330	15,897	19,674	8,390	14,141	6,117
Annual O&M cost [k$/yr]	3,583	4,088	4,088	4,282	4,282	4,282	4,282
Net Electric [GWh]	107.5	169.2	169.1	183.9	182.9	185.7	184.4
Mean Solar to electric efficieny	14.64%	14.58%	14.57%	15.92%	15.84%	16.08%	15.97%
LEC [USD/MWh]	**139.7**	**131.5**	**128.1**	**119.9**	**113.9**	**115.1**	**111.0**
LEC Reduction	-	5.9%	8.3%	14.2%	18.5%	17.6%	20.6%
Thermal Storage Cost $/kWh el	0.0	64.6	48.2	59.6	25.4	42.9	18.5
Thermal Storage Cost $/kWh th	0.0	23.7	17.7	23.6	10.1	17.4	7.5

From a technology viewpoint, R&D is required in several areas. A few of the more important needs are:

- Thermocline storage offers an important potential for cost reduction in trough plants with storage, even with a VP-1 HTF system.

- In the solar field, a significant challenge is the simplification and cost reduction of the heat tracing and sealing of ball joints and HCEs.
- Selective surface development is required for durability and good performance at the temperature levels needed for use of a salt HTF.
- Prototype testing at small commercial-level capacities will be required for validation of both thermocline storage and a salt HTF solar field loop.

ACKNOWLEDGMENTS

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NOMENCLATURE FOR FIGURES

NoSto=no thermal storage ; 66=66 bar steam pressure ; 2T=two-tank thermal storage ; TC=thermocline thermal storage

REFERENCES

[1] H. R. Reilly, G. Kolb, "An Evaluation of Molten-Salt Power Towers Including Results of the Solar Two Project", SAND2001-3674, November 2001.

[2] D. Kearney, B. Kelly, R. Cable, N. Potrovitza, U. Herrmann, P. Nava, R. Mahoney, J. Pacheco, D. Blake, H. Price, "Evaluation of a Molten Salt Heat Transfer Fluid in a Parabolic Trough Solar Field", Proceedings of Solar 2002, Reno, Nevada, June 2002.

[3] D. Kearney, B. Kelly, R. Cable, N. Potrovitza, U. Herrmann, P. Nava, R. Mahoney, J. Pacheco, D. Blake, H. Price, "Engineering Aspects of a Molten Salt Heat Transfer Fluid in a Trough Solar Field", Proceedings of 11th SolarPaces International Symposium on Concentrating Solar Power and Chemical Energy Technologies, Zurich, Switzerland, September 2002.

[4] Nexant Inc., "USA Trough Initiative: Nitrate Salt HTF Rankine Cycle, Steam Generator, and Thermal Storage Analyses", prepared for NREL, March 2001.

[5] J. E. Pacheco, S. Showalter, W. Kolb, "Development of a Molten Salt Thermocline Thermal Storage System for Parabolic Trough Plants", Solar Forum 2001, Washington DC, April 2001.

[6] J. Pacheco, W. Kolb, "Comparison of an Impedance Heating System to Mineral Insulated Heat Trace for Power Tower Applications", Proceedings of ASME International Solar Energy Conference, Washington, DC, April 1997.

[7] Pilkington Solar International (now Flabeg Solar International), "Solar Steam System Investment Costs", prepared for NREL, October 1999, Subcontract No. AAR-9-29442-05.

[8] H. Price, P. Svoboda, D. Kearney, "Validation of the FLAGSOL Parabolic Trough Solar Power Plant Performance Model", Proceedings of the ASME/JSME/JSES International Solar Energy Conference, Maui, Hawaii, March 1995.

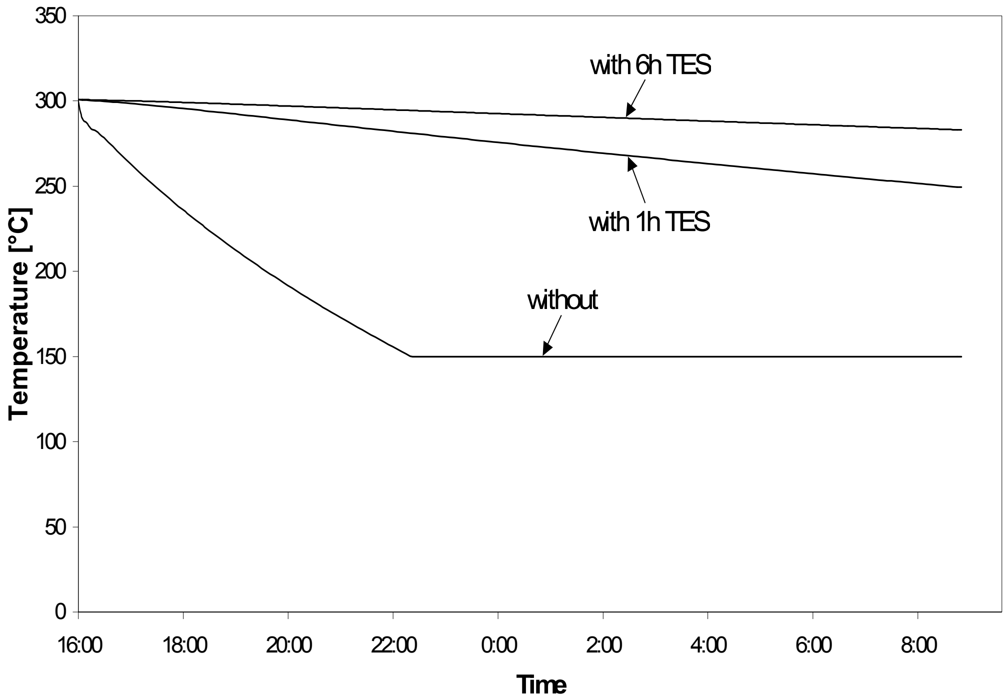

Figure 1. Solar field cooling curves with Salt HTF

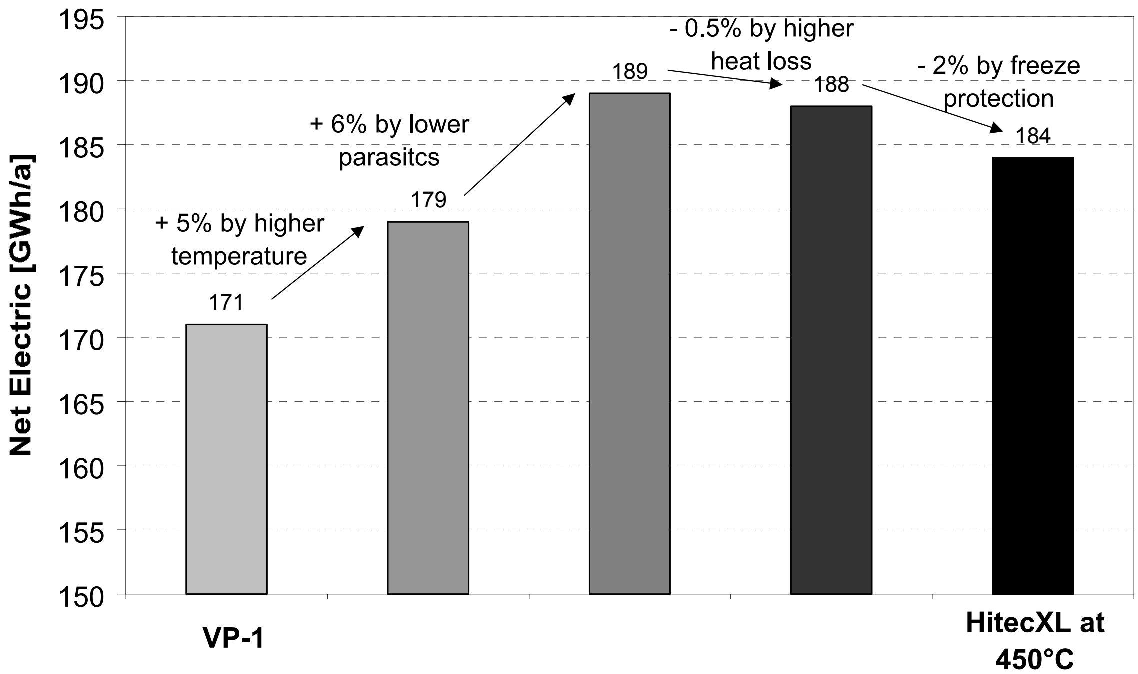

Figure 2. Impact of salt HTF on performance for a 55 MW plant with 6h storage

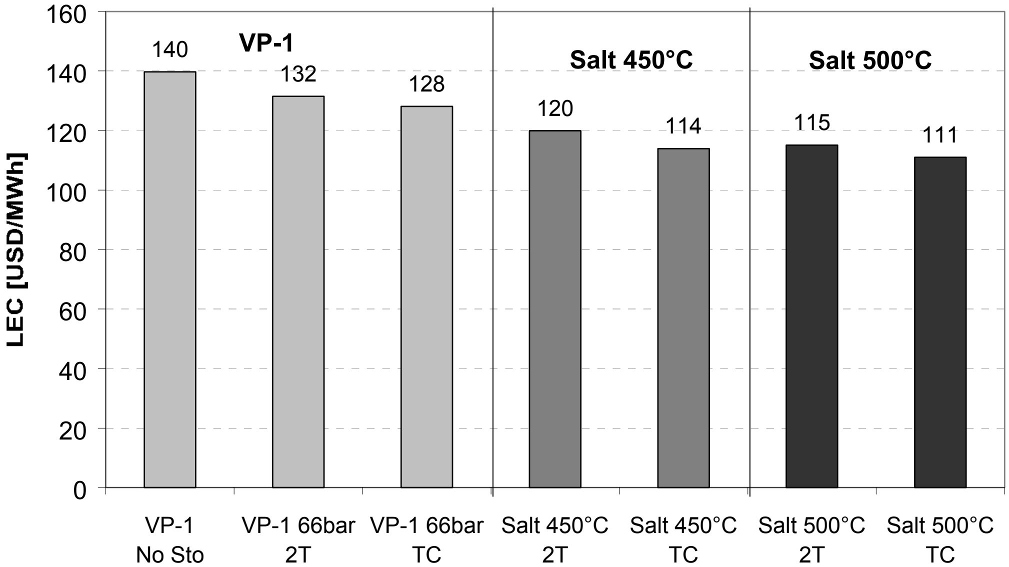

Figure 3. LEC Gains from Use of Calcium Nitrate Salt as HTF

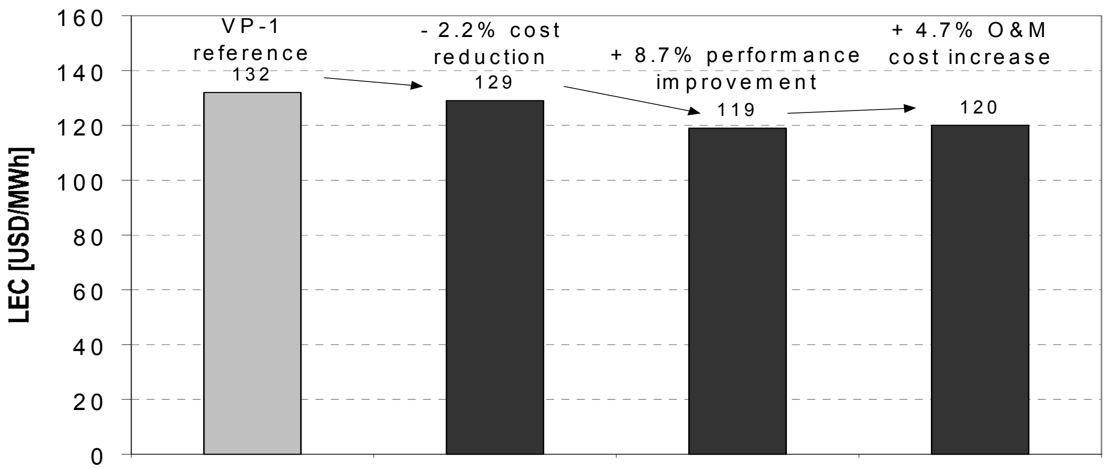

Figure 4. Individual effects on LEC of molten salt HTF for system with 6 hour 2-tank thermal storage and 450°C outlet