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EVALUATION 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, but reasonable, cost inputs. The two leading candidates were the so-called solar salt (a binary salt consisting of 60% $NaNO_3$ and 40% KNO_3) and a salt sold commercially as HitecXL (a ternary salt consisting of 48% $Ca(NO_3)_2$, 7% $NaNO_3$, and 45% KNO_3).

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.

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 1 shows the final parametric conditions discussed in this paper.

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

Table 1. Parametric operating conditions for analyses

Power block type:	Steam Rankine cycle	
Power block capacity:	50 MW 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
Power Block	Capacity, MW	55 gross
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. 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.

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 2, with the freezing points indicated in the square brackets. Thermal storage equipment is not included in this comparison.

Table 2. Effective Storage Fluid Cost

Salt	Temperature Rise	Cost per Kg	Storage Cost
	°C	$/kg	$/kWh
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	1.19	15.2
	150	1.19	20.1
	100	1.19	30.0
Therminol VP-1 (d)	100	3.96	57.5

a) 7:53 Na:K Nitrate, 40 Na Nitrite
b) 60:40 Na:K Nitrate
c) 42:15:43 Ca: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 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. While the detailed engineering results cannot be elucidated in this short paper, 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 conditions, 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 [2,3].

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.

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 [4] 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 components in a molten salt HTF system. The results showed that a 10% variation 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 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 [5].

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. 1, 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 2 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 3 the relative influences of the effects responsible for the improvement with a salt HTF. This is shown in Fig. 3 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. 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 3 provides summary data on the performance and economic improvements potentially possible by use of a salt HTF in the solar field and storage system. 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%.

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.

Though not directly associated with a molten salt HTF system, but of significant importance to current oil-based HTF systems, is the observation that 2-tank molten salt storage systems appear ready for commercial application in trough plants.

ACKNOWLEDGMENTS

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Key for Figures:

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

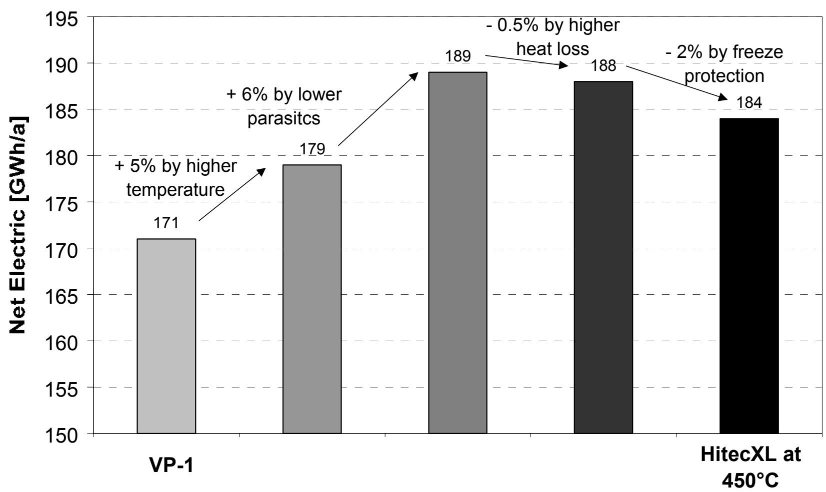

Figure 1. Impact of salt HTF on performance for a 55 MW plant with 6h storage

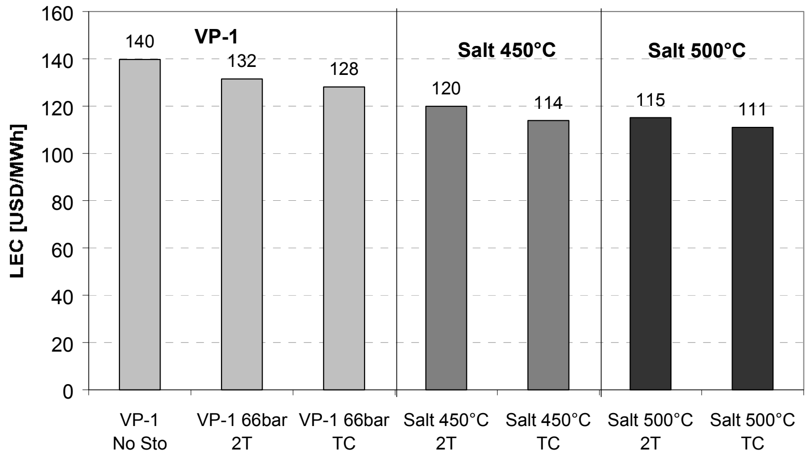

Figure 2. LEC Gains from Use of Calcium Nitrate Salt as HTF

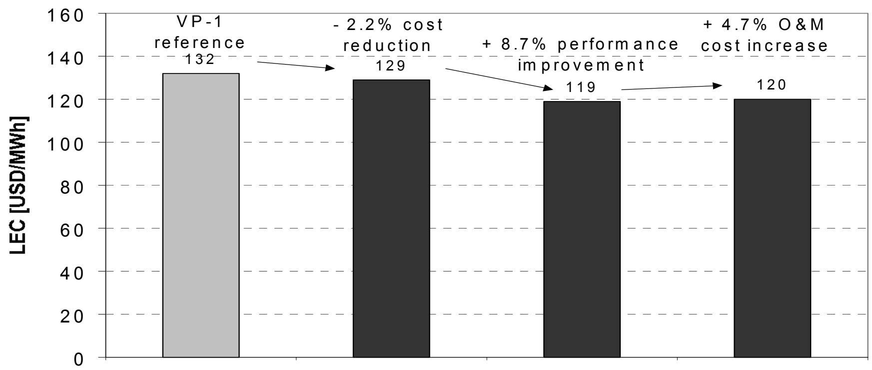

Figure 3. Individual effects on LEC of molten salt HTF for system with 6 hour 2-tank thermal storage and 450°C outlet

Table 3. 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