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ABSTRACT

Studies strongly indicate that the United States will face widespread electrical power constraints in the 1990s. In many cases, the demand for increased power will occur during peak and intermediate demand periods. While natural gas is currently plentiful and economically attractive for meeting peak and intermediate loads, the development of a coal-fired peaking option would give utilities insurance against unexpected supply shortages or cost increases. This paper discusses a conceptual evaluation of using thermal energy storage (TES) to improve the economics of coal-fired peak and intermediate load power generation.

The use of TES can substantially improve the economic attractiveness of meeting peak and intermediate loads with coal-fired power generation. In this case, conventional pulverized coal combustion equipment is continuously operated to heat molten nitrate salt, which is then stored. During peak demand periods, hot salt is withdrawn from storage and used to generate steam for a Rankine steam power cycle. This allows the coal-fired salt heater to be approximately one-third the size of a coal-fired boiler in a conventional cycling plant. The general impact is to decouple the generation of thermal energy from its conversion to electricity.

While not commercially available, molten nitrate salt TES has been extensively investigated as part of the U.S. Department of Energy's Solar Thermal Program (1). The concept has been the subject of bench-scale experimental investigations, several detailed design studies, and small-scale field demonstrations. Although significant problems remain, the balance of opinion is that commercialization of molten nitrate salt TES is technically feasible.

The present study compares a conventional cycling pulverized coal-fired power plant to a pulverized coal-fired plant using nitrate salt TES. The study demonstrates that a coal-fired salt heater is technically feasible and should be less expensive than a similar coal-fired boiler. The results show the use of nitrate salt TES reduced the levelized cost of power by between 5% and 24%, depending on the operating schedule.

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

INTRODUCTION

Studies give increasingly strong indications that the United States will face widespread electric power generating capacity constraints in the 1990s with most regions of the country experiencing capacity shortages by the year 2000 (2). In many cases, the demand for increased power will occur during intermediate and peak demand periods. Much of this demand is expected to be supplied by oil- and natural gas-fired Brayton cycle gas turbines and combined cycle plants. While natural gas is currently plentiful and reasonably priced, the availability of an economical long-term coal-fired option for peak and intermediate load power generation will give electric power utilities an option in case either the availability or cost of natural gas should deteriorate.

A number of demand-side and system-wide energy storage options for intermediate and peak capacity exist; but, when new generating capacity is unavoidable, the only mature nonpetroleum option is a cycling coal-fired power plant. The study documented in this paper was conducted by the Pacific Northwest Laboratory[a] to evaluate an alternative method of using coal to generate peak and intermediate load power. The approach uses a continuously operating, coal-fired heater to heat molten nitrate salt, which is then stored. During peak demand periods, the hot salt is used as a heat source for a conventional Rankine cycle steam power plant.

RESULTS OF PREVIOUS EVALUATIONS

A series of studies on thermal energy storage for near-term utility applications was conducted by the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the National Aeronautics and Space Administration (NASA) in the late 1970s (3,4,5). The results of these studies were not favorable for thermal storage. The studies screened a large number of TES systems that could be coupled with an 800-MWe coal or a 1140-MWe light water nuclear reactor. These studies were limited to TES concepts that did not require any modifications to the coal-fired or nuclear steam generators.

Molten nitrate salt TES was included as one thermal storage option in these studies. The concept used the exhaust of the high-pressure turbine for charging storage. During peak demand periods, heat was extracted from storage and used to generate steam for a separate low-pressure turbine. The high-pressure turbine exhaust steam was at a temperature of 300°C (572°F). The maximum storage temperature was approximately 280°C (536°F). During discharge, low-pressure steam was generated at 251°C (484°F) for peak power production. The decision to use high-pressure turbine exhaust for charging storage had several negative impacts on nitrate salt TES. First, nitrate salts have a higher maximum temperature [450°C to 566°C (842°F to 1050°F) depending on the salt mixture] than other thermal storage media, such as heat transfer oils, but they often are more expensive. By operating storage at 280°C (536°F), the benefits of the molten salt were not attained; the small change in molten salt temperature between charge and discharge conditions meant that a very large molten salt inventory was required to provide the desired storage. Second, the low temperature of the steam produced during discharge resulted in low steam cycle efficiency when operating from storage. In addition, extra thermal energy had to be stored to compensate for the poor efficiency of the discharge steam cycle, further increasing the size of the storage system. The overall result was that the nitrate salt TES option had an excessively high capital cost and poor performance. The results apparently discouraged further studies of the use of molten salt TES for power generation.

In the last 10 years, significant changes have decisively altered the situation. These include:

- improved plant integration--The decision in early studies to concentrate on TES concepts that do not modify the steam generator is understandable given the emphasis on near-term applications, but this ground rule had a serious negative impact on nitrate salt TES. Alternate methods for integrating storage have been developed that avoid the difficulties associated with using high-pressure turbine exhaust for charging storage. The proposed concept uses direct heating of salt to 566°C (1050°F) in a coal-fired salt heater. During discharge, steam is generated at conditions typical of modern coal-fired power plants resulting in no performance penalty when operating from storage. Improved plant integration results in reduced capital cost due to the increased temperature difference between the hot and cold salt and superior performance due to the improved steam conditions.

- improved storage systems--The earlier studies were based on first-generation TES concepts. During the last 10 years, substantial progress has been made on TES design, particularly nitrate salt systems. The DOE Solar Thermal Program funded the development and field testing of low-cost nitrate salt TES. In general, nitrate salt has proved to be economical and reliable. The concept exceeded all cost goals; current estimates predict energy-related costs of $15/kWht (6) in 1986 dollars. The comparable cost estimate from the earlier studies is approximately $90/kWht in 1986 dollars. The cost reduction is due to the use of lower-cost nitrate salts and improved energy storage density by increasing the temperature difference between the hot and cold salt.

- advanced coal combustion technologies--A number of new coal combustion technologies are being developed, and several are near commercialization, e.g., integrated coal gasification combined-cycle power plants and fluidized bed combustion. These technologies offer new opportunities for integrating TES, which is particularly important because several advanced coal combustion technologies result in power plants that are difficult to cycle or operate at part load.

These three developments indicated that utility applications for TES should be re-evaluated and that the potential exists for TES technology to make a substantial contribution toward lowering electrical generation costs and providing new peak generation capabilities.

CONCEPT DESCRIPTION

Thermal energy storage can be integrated with conventional and advanced coal technologies in a number of ways. This study was focussed on using conventional pulverized coal combustion technology.

The concept evaluated in this study uses a pulverized coal-fired salt heater to heat molten nitrate salt from 280°C (536°F) to 566°C (1050°F). The hot molten salt is returned to a hot salt tank for storage. During peak demand periods, hot salt is withdrawn from the hot salt tank and used as a heat source for a steam generator. The molten salt is then returned to the cold molten salt storage tank. The steam generator produces steam for a conventional steam cycle. Turbine inlet steam conditions are 538°C (1000°F) and 16,500 kPa (2400 psi). The concept is shown in Figure 1.

The coal-fired salt heater operates continuously, charging storage. The steam generator and turbine only operate when electric power is being generated. This allows the salt heater to be much smaller than the size of a coal-fired boiler in a conventional cycling coal-fired power plant. In addition, the salt heater would not be cycled, avoiding the difficulties associated with cycling a coal-fired boiler. The general impact of the concept is to decouple (on a temporal basis) the generation of thermal energy and its conversion to electricity.

The storage medium is a mixture of sodium nitrate (60 wt%) and potassium nitrate (40 wt%). Thermal energy is stored as sensible heat in this molten salt. This salt mixture freezes at a temperature near 240°C (464°F). Consequently precautions must be taken to ensure that the temperature of the molten salt never drops below the freezing

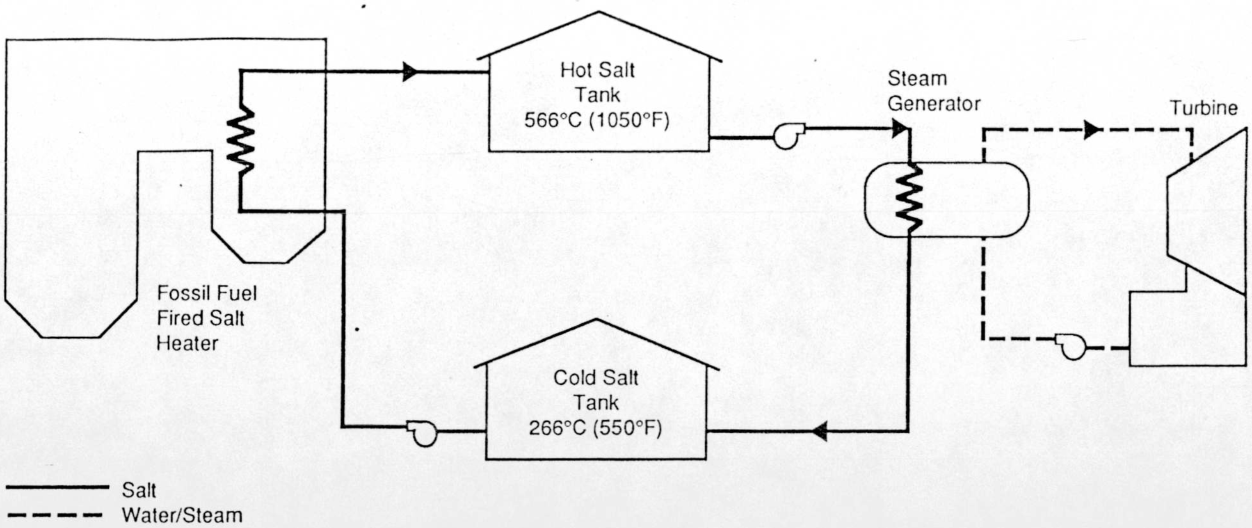

Figure 1--Coal-Fired Peaking Power Plant Using Thermal Energy Storage

point. The maximum salt temperature is 566°C (1050°F) and is determined by the chemical stability of the salt.

While not used to produce power commercially, nitrate salt TES was extensively investigated as part of the U.S. Department of Energy's (DOE) Solar Thermal Program. The concept was the subject of bench-scale experimental investigations, several detailed design studies, and small-scale field demonstrations. While significant problems remain, the general technical opinion of experts is that commercialization of molten nitrate salt TES is technically feasible (7).

METHODOLOGY

The general approach used in this study consisted of developing a conceptual design and cost estimate for the coal-fired plant with TES and comparing this data to the costs for a conventional cycling pulverized coal-fired plant operated during peak and intermediate demand periods. The comparison was made for a range of plant operating schedules. Table 1 summarizes the assumed operating schedules and gives several key design features of the thermal storage concept required to meet these schedules.

The range of operating schedules was selected to include nominal capacity factors ranging from 20% to 40%. Two weekly operating schedules were assumed. In the first case, the plant was assumed to operate for 5 days per week. The second case involved operation for 7 days per week with a shorter daily operating period.

In all cases, the peak plant net output was assumed to be 500 MWe for both the conventional plant and the coal-fired plant with TES. This resulted in all plant configurations having a similar steam cycle, steam turbine, and switch gear. The significant design variations occurred in the coal-handling and coal-firing equipment. As the capacity factor decreases, the size and cost of the coal-handling and coal-firing equipment in the TES option will decrease. The size and cost of the TES subsystem will increase. The size and cost of the coal-firing equipment in the conventional design will not vary with capacity factor.

TABLE 1. PLANT OPERATING SCHEDULES

Days of Operation per Week	Hours of Operation per Day	Approximate Capacity Factor, %	Approximate Size of Storage, MWht	Equivalent Size of Coal Firing Equipment for TES System, MWe
5	8	20	6763	167
5	12	30	7591	250
5	16	40	6741	330
7	6	20	5698	120
7	9	30	7139	188
7	12	40	7591	250

The economic evaluation was conducted by calculating and comparing the levelized energy cost (LEC) of conventional coal-fired power plant to a coal-fired power plant with molten salt TES. Levelized cost analysis combined initial cost, annually recurring cost, and system performance characteristics with financial parameters to produce a single figure-of-merit (the LEC) that is economically correct and can be used to compare the projected energy costs of alternative power plant concepts.

Initial capital costs were first identified in the literature for a conventional 500-MWe coal-fired power plant at a relatively detailed level. For example, the turbine plant cost was distributed into costs such as those for the turbine generator, condensing system, feed heating system, instrumentation and control, and other turbine plant equipment. Each individual cost element for the entire plant was divided into two element categories: variable elements (those related to the coal-fired capacity) and fixed elements (those related to the power-generation capacity). Some elements were split into both fixed and variable parts. The capacity and cost of the variable elements depend on the plant's designed power generation schedule and are lower for the coal-fired power plant with molten salt TES than for the conventional plant. The capacity and cost of the fixed elements are the same for both coal-fired power plants with molten salt TES and conventional coal plants.

Individual cost elements were then assigned to coal-handling, boiler, emissions-handling, power generation, and balance-of-plant (BOP) components. Equations estimating the cost of each of these components as a function of power-generation or coal-firing capacity were derived from power plant economy-of-scale studies described in the literature.

Molten salt storage and steam generator costs were obtained from research reports on solar thermal power systems. Molten salt heater costs were scaled from conventional boiler costs based on their different heat transfer tubing designs. Finally, molten salt piping designs and cost estimates were prepared by Pacific Northwest Laboratory.

Estimates for fixed, variable, and consumable operation and maintenance (O&M) elements were developed in a manner similar to the initial capital costs, i.e., O&M cost elements were separated into coal-firing related and power generation related parts and estimating equations for each part were developed as a function of plant power rating. Current and future coal cost estimates were derived from projections made by several energy forecasting organizations.

A more detailed description of the methodology used in this study is presented in Drost et al. (8).

RESULTS

The conceptual design of the coal-fired power plant with TES involved the selection and sizing of major components. In most cases, the equipment installed in a coal-fired power plant with TES is similar to that used in a cycling coal plant other than size. The new components are associated with the nitrate salt storage system and include the coal-fired salt heater, nitrate salt storage system, salt transport system, and the salt heated steam generators. The last three components have been extensively investigated as part of DOE's Solar Thermal Program and the designs developed for the coal-fired power plant with TES are based on the results of numerous design studies conducted for nitrate salt heating solar central receiver power plants. Therefore, the present study focused on the coal-fired salt heater.

The conceptual design of the coal-fired salt heater was conducted by comparing a conventional coal-fired boiler to a coal-fired salt heater and modifying the design of the coal-fired boiler to adjust for the differences between sensible heating of a molten salt and steam generation. The design study identified three major differences between a coal-fired salt heater and a coal-fired boiler. These include:

- heat transfer--Heat transfer in a molten salt heater is comparable to conventional boilers for most heat transfer surfaces and superior to conventional boilers for superheaters and reheaters.
- wall thickness--The low pressure experienced in the molten salt heater allows the use of thin wall tubing with the associated savings in tube cost, reduced temperature difference across the tube walls, and reduced stresses.
- flow rate--The molten salt heater requires a substantially higher mass and volume flow rate than a conventional boiler. This results in an increase in parasitic pumping power.

The results of the preliminary design study suggest that a coal-fired salt heater is technically feasible and may have a number of advantages when compared to a conventional coal-fired boiler. Calculations showed that the salt heater will be approximately equivalent to a steam boiler (with the same thermal rating) in size, performance, and cost.

The conceptual designs of the other TES-related components were based on designs developed for solar thermal applications. The designs of the coal-fired salt heater, TES system, salt transport system, and the salt-heated steam generator are presented in more detail in Drost et al. (8).

The performance of the coal-fired power plant with TES was compared to the conventional cycling coal-fired power plant. The results showed that the two plants had nearly identical heat rates of approximately 10,200 Btu/kWe. The start-up losses associated with cycling the conventional plant approximately balanced the added parasitic losses associated with molten salt TES system.

The availability of the two designs were also compared. The results suggested that the coal-fired power plant with TES would have a higher plant availability than the conventional cycling plant. This is due to the improved availability of small (approximately 100 MWe) coal-fired power plants when compared to larger coal-fired plants. This observation is in agreement with the plant availabilities reported in EPRI's Technical Assessment Guide (9).

Levelized energy cost estimates were prepared for a conventional coal-fired power plant with TES and a conventional cycling coal-fired power plant operating at six power generation schedules. The results are presented on Table 2.

The results show the coal-fired plant with molten salt TES has an LEC lower than the corresponding conventional coal-fired plant for the generation schedules assumed. The concept using coal-fired plants with molten salt TES looks more attractive at lower plant capacity factors (fewer operating hours per day) where the coal-firing equipment is downsized and, hence, the benefit of incorporating TES is greater.

The key factors contributing to the reduction in LEC for the coal-fired plant with molten salt TES are an increase in plant availability caused by the use of smaller capacity coal-firing equipment and a decrease in the initial capital cost. Initial costs, annually recurring costs, availability, annual power output, and LEC are compared in Table 3 for a plant operating 5 days per week and 12 hours per day. Initial capital costs decreased by $45 million as reductions in coal handling, emissions handling and balance-of-plant costs, and elimination of the boiler exceeded the additional costs of the salt systems. Fuel costs increased for the coal-fired plant with molten salt TES in proportion to the 7% increase in plant availability.

Although the levelized energy cost estimates indicate promise for the coal-fired plant with molten salt TES, the results should be used with caution. A considerable amount of uncertainty is associated with many of the key inputs to the analysis. Future efforts should be directed towards improving our understanding of these factors and narrowing the range of uncertainty for individual elements in the overall comparison.

CONCLUSIONS

The significant conclusions from this evaluation of TES for utility power generation are summarized below:

- Molten nitrate salt TES is technically feasible--While acknowledging that problems exist with certain aspects of salt handling, these appear to be resolvable. The overall judgement, both of this study and similar evaluations in the solar thermal area, is that molten nitrate salt TES is technically feasible and it is reasonable to assume that the technology can be successfully commercialized.

- Coal-fired salt heater is technically feasible--Given the similarity between a coal-fired salt heater and a coal-fired boiler, it was concluded that a coal-fired salt heater is technically feasible. While requiring further analysis and development, the results of this preliminary study suggest that a coal-fired molten salt heater can be successfully developed.

- Using TES in a conventional coal-fired power plant produces lower cost power--The results of this study show that a coal-fired power plant with molten salt TES produces lower cost power than a conventional cycling coal plant over the range of operating schedules, but substantial uncertainties exist in several key inputs to the levelized energy costs.

TABLE 2. LEVELIZED ENERGY COST RESULTS

Generating Schedule		Coal	Coal/TES Plants	
days/week	hours/day	Plant	3-Year Construction	4-Year Construction
5	8	0.146	0.120	0.118
5	12	0.106	0.097	0.095
5	16	0.086	0.083	0.082
7	6	0.140	0.108	0.107
7	9	0.102	0.088	0.087
7	12	0.083	0.076	0.075

TABLE 3. SUMMARY COST AND PERFORMANCE COMPARISON: CONVENTIONAL COAL VERSUS COAL/TES

Cost Item	Conventional Coal Plant	Coal/TES Plant
Initial capital		
coal-firing	411	150
salt systems	-	236
power generation	202	202
balance-of-plant	149	130
other	29	28
total	791	746
Annual operation and maintenance		
fuel	17.0	18.1
non-fuel	19.4	19.1
total	36.4	37.2
Annual availability	0.712	0.759
Annual energy output, GWhe	1111	1184
Levelized energy cost, $/kWhe	0.106	0.097

While not the subject of this paper, molten salt TES may also be useful when integrated with advanced coal combustion technologies. The use of molten salt with advanced coal combustion technologies, such as integrated coal gasification combined-cycle power plants and fluidized bed combustion, improves the flexibility of these technologies by letting them provide peak and intermediate load power. If technically feasible, direct-contact salt heating would be particularly attractive for applications with coal gasification combined-cycle plants.

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