CONF-901251--1

PNL-SA-18826

PNL-SA--18826

DE91 005049

THERMAL ENERGY STORAGE FOR COAL-FIRED POWER GENERATION

M. K. Drost
S. Somasundaram
D. R. Brown
Z. I. Antoniak

November 1990

Presented at
Fossil-Fuel Plant Cycling Conf.
Washington, D.C.
December 4-6, 1990

Work Supported by
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

THERMAL ENERGY STORAGE FOR COAL-FIRED POWER GENERATION

M. K. Drost
S. Somasundaram
D. R. Brown
Z. I. Antoniak

Pacific Northwest Laboratory[a]
Richland, Washington 99352

ABSTRACT

This paper presents an engineering and economic evaluation of using thermal energy storage (TES) with coal-fired conventional and combined cycle power plants. The use of thermal energy storage can substantially improve the economic attractiveness of meeting intermediate loads with coal-fired power generation. In the first case, conventional pulverized coal combustion equipment was assumed to continuously operate to heat molten nitrate salt which was then stored in a tank. During intermediate-load demand periods, hot salt was withdrawn from storage and used to generate steam for a Rankine steam power cycle. This allowed the coal-fired salt heater to be approximately one-third the size of a coal-fired boiler in a conventional cycling plant. The use of nitrate salt TES also reduced the levelized cost of power by between 5% and 24% depending on the operating schedule.

The second case evaluated the use of thermal energy storage with an integrated gasification combined cycle (IGCC) power plant. In this concept, the nitrate salt was heated by a combination of the gas turbine exhaust and the hot fuel gas. The IGCC plant also contained a low-temperature storage unit that uses a mixture of oil and rock as the thermal storage medium. Thermal energy stored in the low-temperature TES was used to preheat the feedwater after it leaves the condenser and to produce process steam for other applications in the IGCC plant. This concept study also predicted a 5% to 20% reduction in levelized cost of power compared to other coal-fired

(a) Pacific Northwest Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

alternatives. If significant escalation rates in the price of fuel were assumed, the concept could be competitive with natural-gas-fired intermediate-load power generation. A sensitivity analysis of using a direct-contact heat exchanger instead of the conventional finned-tube design showed a significant reduction in the installed capital cost.

INTRODUCTION

Studies give increasingly strong indications that the United States will face widespread electrical power-generating capacity constraints in the 1990s, with most regions of the country experiencing capacity shortages by the year 2000. In many cases, the demand for increased power will occur during intermediate and peak demand periods (United States Energy Association 1988). Much of this demand is expected to be met by oil- and natural gas-fired Brayton cycle 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 another option in case either the availability or cost of natural gas should deteriorate.

This study was conducted by Pacific Northwest Laboratory (PNL) to evaluate alternative methods of using coal to generate peak and intermediate load power. The approach was to review the technical and economic feasibility of using thermal energy storage (TES) with a conventional coal-fired power plant and an integrated gasification combined cycle (IGCC) power plant.

CONCEPT DESCRIPTION

Thermal energy storage can be integrated with conventional and advanced coal technologies in a number of ways. The first concept evaluated in this study used a pulverized coal-fired salt heater to heat molten nitrate salt from 288°C (550°F) to 566°C (1050°F). The hot molten salt was returned to a hot salt tank for storage. During peak demand periods, hot salt was withdrawn from the tank and used as a heat source for a steam generator. The molten salt was then returned to the cold molten salt storage tank. The steam generator produced steam for a conventional steam cycle. Turbine inlet steam conditions were 538°C (1000°F) and 16,500 kPa (2400 psi). The concept is shcwn in Figure 1.

The coal-fired salt heater was operated continuously to charge the storage system. The steam generator and turbine only operate when electric power was being generated. This allowed the salt heater to be much smaller than 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 was to decouple (on a temporal basis) the generation of thermal energy and its conversion to electricity.

The storage medium was a mixture of sodium nitrate (60 wt%) and potassium nitrate (40 wt%). Thermal energy was stored as sensible heat in this molten salt. This salt mixture freezes at a temperature near 240°C (464°F).

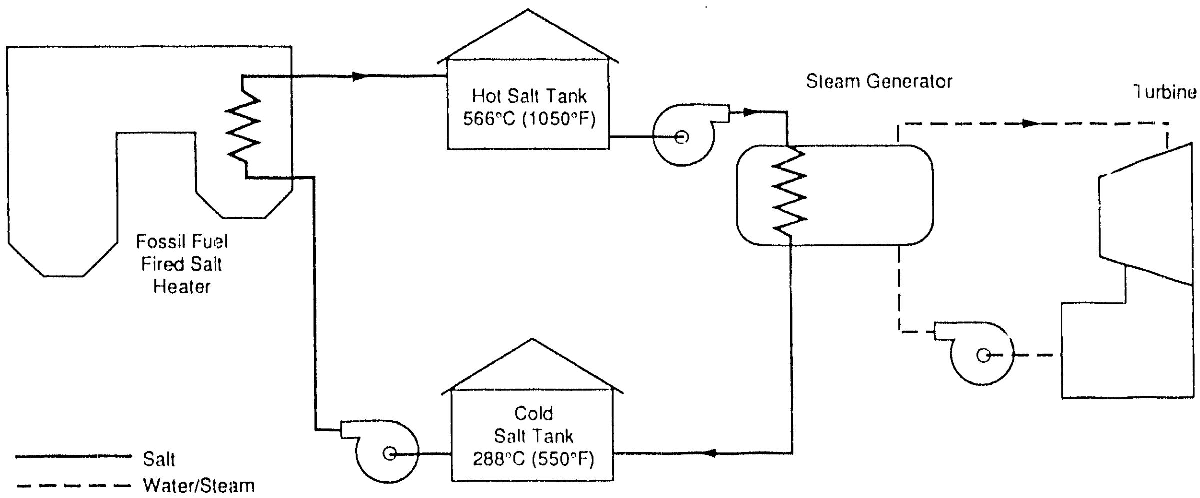

FIGURE 1. Coal-Fired Peaking Power Plant Using Thermal Energy Storage

Consequently precautions must be taken to ensure that the temperature of the molten salt never drops below the freezing point. The maximum salt temperature was 566°C (1050°F) and was limited by the chemical stability of the salt.

In addition to conventional coal-firing technology, TES can also be used with advanced coal-fired schemes, such as an IGCC plant. The IGCC power plant is an attractive option for the expanding current and near-term capacity needs of the utility industry. IGCC plants can be built as modular units with phased construction, they use coal which is abundant and has been historically stable in price, and they can significantly reduce air pollutant emissions when compared to conventional coal-fired power plants. While the IGCC concept has many attractive features, it has only been considered for base load applications. Some of the reasons include: 1) poor turn-down capability in the gasifier portion, 2) poor part-load performance, and 3) long start-up times required for the gasifier. The incorporation of molten salt TES would allow for flexible power production in an intermediate or peak mode.

The design concept for the IGCC plant involves a continuously operating Texaco[a] gasifier supplying intermediate-Btu fuel gas to a gas turbine, which also generates base load electric power on a continuous basis. A molten salt TES system interposed between the gasifier/gas turbine and the steam generator in an IGCC plant provides a cycling capability (see Figure 2). Instead of generating steam directly, the heat from the fuel gas coolers and turbine exhaust is used to heat molten nitrate salt, which is then stored. The gas turbine is operated whenever the gasifier operates. The TES serves to decouple the steam generator and turbine from the rest of the plant, allowing steam power production as needed for intermediate-load power generation. In addition to the high-temperature molten salt storage system, the IGCC plant also uses low-temperature heat storage. This system uses a storage medium that consists of a mixture of a heat transfer oil such as Caloria HT-45[b] (25 vol%), and rock (75 vol%) contained in a storage tank. Thermal energy is stored as sensible heat (primarily in the rock) and the oil acts as a heat transfer

(a) Texaco Inc., White Plains, New York.

(b) Trademark of the Exxon Corporation, Houston, Texas

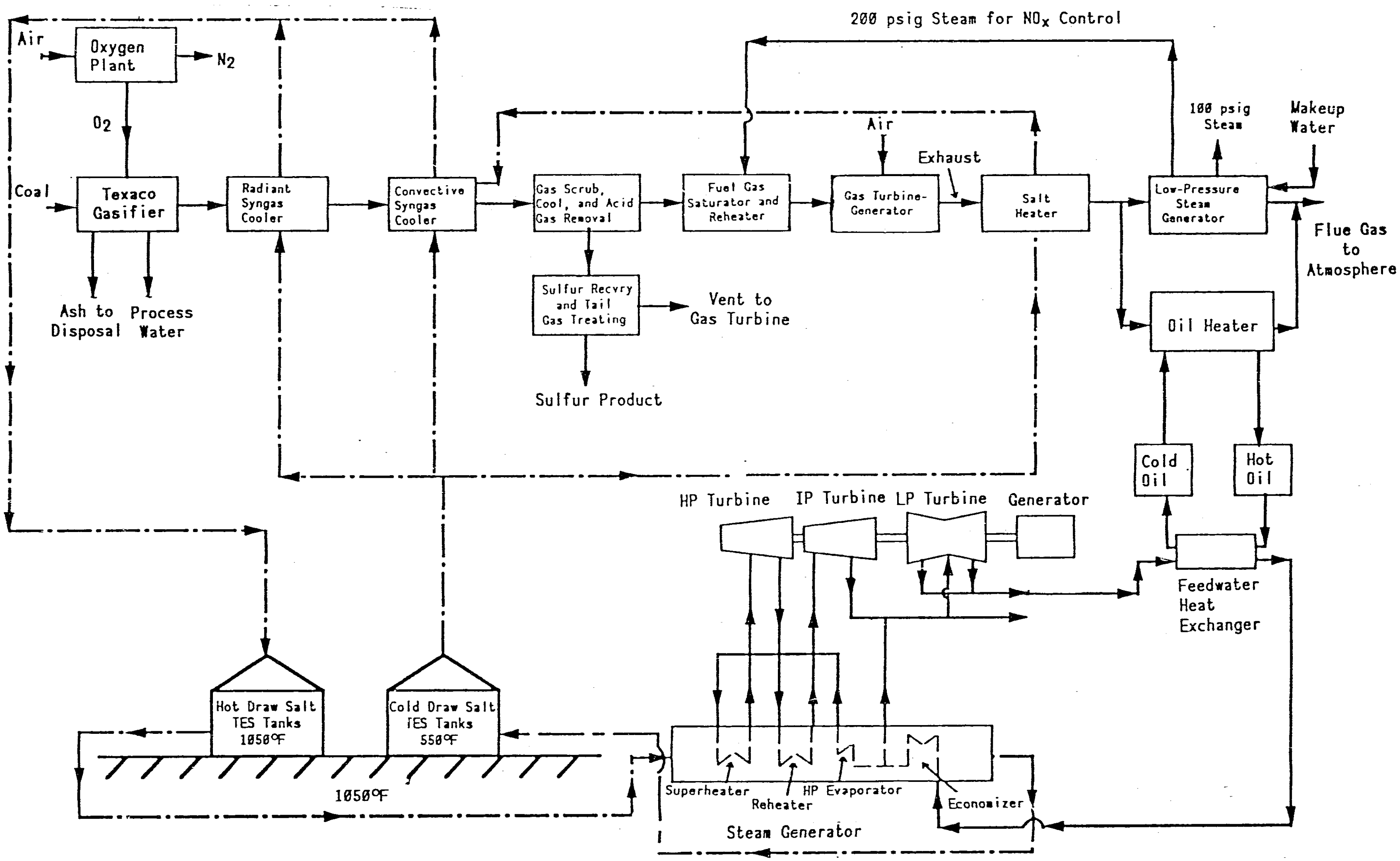

FIGURE 2. IGCC Power Plant with Molten Salt TES System

fluid. The storage tank is arranged so that hot oil is always added or removed from the top of the tank, while cold oil is added or removed from the bottom of the tank, maintaining a hot and a cold region separated by a thermocline. This eliminates the need for a separate hot and cold tank as is used with the molten salt TES system. Low-temperature oil from the bottom of the tank at 121°C (250°F) is pumped to the low-temperature section of the gas turbine waste heat recovery heater, where it is heated to 288°C (550°F). The oil is then returned to the top of the oil/rock storage tank. The thermal energy stored in the low-temperature TES system is used to preheat the feedwater after it leaves the condenser and to produce process steam for other applications in the IGCC plant.

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.

As with the molten salt TES, oil and rock TES was extensively investigated as part of the DOE Solar Thermal Program. One large scale demonstration has been successfully completed at the Barstow Solar Thermal Power Plant. Oil and rock TES has been proven to be technically feasible and in this study it was assumed to be commercially available.

METHODOLOGY

The general approach used in this study was to develop a conceptual design and a cost estimate for a coal-fired plant with TES (Case 1) and an IGCC plant with TES (Case 2) and to compare these to the cost for a base case. The base case consists of a conventional cycling pulverized coal-fired plant (Case 1) and a combination of an IGCC base load power plant and either a cycling coal-fired plant or a natural-gas-fired combined-cycle plant to provide intermediate load (Case 2). The latter comparison was complicated by the fact that the IGCC plant with TES had an IGCC base load power plant and a steam Rankine power cycle to provide intermediate load power generation.

The comparison was made for a range of plant operating schedules. Table 1 summarizes the assumed operating schedules and gives the corresponding capacity factors.

TABLE 1. Plant Operating Schedules

Generation Schedule	Days of Operation Per Week	Hours of Operation Per Day	Capacity Factor, %
1	5	8	20
2	5	12	30
3	5	16	40
4	7	6	20
5	7	9	30
6	7	12	40

The range of operating schedules was selected to include nominal capacity factors ranging from 20% to 40%. Two weekly operating schedules were evaluated. 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 both Case 1 and Case 2, the peak plant net output was assumed to be 500 MWe for both the conventional plant and the 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 decreased, the size and cost of the coal-handling and coal-firing equipment in the TES option decreased, while the size and cost of the TES subsystem increased. The size and cost of the coal-firing equipment in the conventional design did not vary with capacity factor.

The economic evaluation was conducted by calculating and comparing the levelized energy cost (LEC) of a conventional coal-fired power plant to a coal-fired power plant with molten salt TES, in Case 1, while comparing that of IGCC/TES power plants to reference power plants supplying the same mix of base load and intermediate duty power output, in Case 2. 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.

RESULTS

CONVENTIONAL COAL-FIRED POWER PLANTS

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 was similar to that used in a cycling coal plant, except for its size. The new components were 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. Because the last three components have been extensively investigated as a part of DOE's Solar Thermal Program, the conceptual design of the coal-fired power plant with TES focused on the coal-fired salt heater. The results of this evaluation suggested that a coal-fired salt heater was technically feasible and may have a number of advantages (viz. thinner tube walls) when compared to a conventional coal-fired boiler. Calculations showed that the salt heater was approximately equivalent to a steam boiler (with the same thermal rating) in size, performance, and cost. The design details of the other subsystems are presented in more detail in Drost et al. (1989).

The performance of the coal-fired power plant with TES was compared to the conventional cycling coal-fired power plant. The two plants had nearly identical heat rates of approximately 10,200 Btu/kWh, because the start-up losses associated with cycling the conventional plant were approximately equal to the parasitic losses associated with the molten salt TES system. The availability was higher for the coal-fired power plant with TES because of the improved availability of smaller (approximately 100 MWe) coal-fired power plants.

The levelized energy cost estimates were also prepared for comparison purposes at six power generation schedules and are given in Table 2.

TABLE 2. Levelized Energy Cost Results (mid-1987 levelized $/kWhe)

Generating Schedule, days/week	Generating Schedule, hours/day	Coal Plant	Coal/TES Plants 4-Year Construction	Coal/TES Plants 3-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

The results show that the coal-fired plant with TES has a lower LEC compared to the conventional coal-fired plant for all the generation schedules considered. As Table 2 shows, the plant with 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 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 have decreased by $45 million as reductions in coal handling, emissions handling, balance-of-plant costs, and the elimination of the boiler exceeded the additional costs of the salt systems.

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, primarily data on capital costs, plant availability, and fuel escalation rates. Future efforts should be directed toward improving our understanding of these factors and narrowing the range of uncertainty involved.

TABLE 3. Summary Cost and Performance Comparison: Conventional Coal Versus Coal/TES

Plant Generation Schedule: 5 days/week; 12 hours/day
(all costs in millions of mid-1987 dollars, except LEC)

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

IGCC POWER PLANTS

The proposed integration of TES in an IGCC power plant requires modifications to the radiant fuel gas cooler, the convective fuel gas cooler, and the heat recovery steam generator (HRSG) to allow the components to heat molten salt (and oil in the case of the HRSG). The design considerations for the molten salt TES system are identical to those discussed earlier for a conventional coal-fired plant. The low-temperature oil/rock TES system is contained in one or more carbon steel tanks that are appropriately insulated to reduce heat loss. All piping is assumed to be Schedule 40 carbon steel with calcium silicate insulation. The tanks are enclosed in dikes to contain oil spills. A fluid maintenance system filters the oil to remove suspended solids, distills a side stream to remove high boiling polymeric compounds, and adds fresh makeup fluid to replace decomposed fluid. Details of these results are reported in Drost et al. (1990).

The heat rate of the IGCC plant with molten salt TES will be different from that for a conventional IGCC plant. Parasitic losses associated with the TES system will tend to increase the heat rate, but this effect is more than offset by the improved efficiency of the steam cycle. The result is that the net heat rate of the IGCC plant with TES is approximately 9,180 Btu/kWh as compared to 9,322 Btu/kWh for a conventional IGCC plant.

The LEC estimates were prepared for comparison of the IGCC/TES power plants with two reference plant systems. Both systems use an IGCC plant to supply the base load portion of the power. A cycling pulverized coal (PC) power plant is presumed to supply the intermediate duty power in the first reference system; a gas-fired combined cycle (CC) plant is presumed to supply the intermediate duty power for the second reference system. The reference system LECs were set equal to the weighted average of the individual LECs calculated for the IGCC plant with a PC or a CC system, based on the relative amount of base load and intermediate duty power produced. The cost and performance assumptions for PC and CC power plant LEC calculations are shown in Table 4.

TABLE 4. Reference Power Plant Cost and Economic Assumptions (all costs in mid-1987 dollars)

LEC Input	IGCC Plant	PC Plant	CC Plant
Initial capital, $/kWe	1520.0	1525.0	447.0
Land, $/kWe	3.9	3.9	3.9
Startup, $/kWe	53.5	36.5	36.4
Working capital, $/kWe	82.4	16.7	16.7
Fixed O&M[a], $/kWe-yr	43.1	25.8	6.6
Variable O&M, mills/kWh	2.6	5.9	1.7
Heat rate, Btu/kWh	9322	10192	8394
Availability, %	83.2	71.2	90.3

(a) O&M = operation and maintenance

The LEC results are shown in Table 5 for each of the six assumed operating schedules. The LEC for the IGCC/TES plant is less than the IGCC/PC power plant, but greater than the IGCC/CC power plant for baseline fuel escalation rates assumed (1%/yr real escalation for coal; 4%/yr real escalation for gas). For higher fuel escalation rates (2%/yr real escalation for coal; 6%/yr real escalation for gas), the IGCC/TES plant LEC is lower than both IGCC/PC and IGCC/CC plants for all the generation schedules except the first (see Table 6).

TABLE 5. Levelized Energy Cost Results: Median Fuel Escalation Rates (mid-1987 levelized $/kWh)

Generation Schedule	Power Plant IGCC/TES	IGCC/PC	IGCC/CC
1	0.0892	0.0996	0.0717
2	0.0758	0.0809	0.0670
3	0.0692	0.0715	0.0647
4	0.0760	0.0911	0.0652
5	0.0656	0.0732	0.0608
6	0.0600	0.0643	0.0585

TABLE 6. Levelized Energy Cost Results: High Fuel Escalation Rates (mid-1987 levelized $/kWh)

Generation Schedule	Power Plant IGCC/TES	IGCC/PC	IGCC/CC
1	0.0946	0.1054	0.0934
2	0.0811	0.0867	0.0887
3	0.0745	0.0773	0.0863
4	0.0814	0.0969	0.0869
5	0.0710	0.0791	0.0824
6	0.0653	0.0701	0.0801

The fundamental advantages of the IGCC/TES plant are its reduced capital cost at lower annual capacity factors (where the gasification-related components are downsized and, hence, the capital cost benefit of incorporating TES is greater), higher availability compared to a PC plant, and a lower heat rate compared to either IGCC or PC plants.

A sensitivity study was conducted to investigate the potential cost reductions associated with substituting a direct-contact gas turbine exhaust/molten salt heat exchanger for the conventional finned-tube heat exchanger design assumed for the baseline conditions. The direct-contact design exchanges heat between the molten salt and the turbine exhaust gases by direct counter-current contact of the two fluids through a packed column (bed). This type of a heat exchanger offers better overall heat transfer between the two fluid streams and a significant reduction in equipment cost compared to the finned-tube heat exchanger design. For instance, the direct installed capital cost of a direct-contact heat exchanger was estimated to be only one-fifth of that for a finned-tube heat exchanger, and this lowered the LEC from \$0.0692/kWh for the baseline case to \$0.0668/kWh for the direct-contact design. However, a great deal of uncertainty exists in predicting the performance of direct-contact salt/gas heat exchangers, and uncertainty in performance is directly translated to uncertainty in design and cost.

CONCLUSIONS

Significant conclusions from this evaluation of TES for utility power generation are summarized below.

- 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 (by between 5% and 24% depending on the operating schedule) than a conventional cycling coal plant.

- Molten salt TES also enhances advanced coal combustion technologies. The use of TES with advanced coal combustion technologies, such as an IGCC plant, improves the flexibility of these technologies by letting them provide peak and intermediate load power at a cost that is between 5% and 20% less than the best coal-fired alternative. This concept also can reduce LEC compared to the natural gas-fired alternative if significant escalation rates in the price of fuel are assumed.

- 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.

- Advanced molten salt TES concepts can substantially improve performance and economics. Several advanced concepts such as direct-contact salt heating, low-freezing-point salts, dual storage media, and advanced tank designs, have the potential to substantially improve the performance and economics of combining IGCC with TES.

- To reduce the uncertainties with the various inputs to the concepts studied, additional research is needed to address several issues. These issues include a more detailed evaluation of using molten salt TES with IGCC technology, development of advanced molten salt TES technology, and conducting a large-scale field test of molten salt TES.

REFERENCES

Drost, M. K., Z. I. Antoniak, D. R. Brown, and K. Sathyanarayana. 1989. Thermal Energy Storage for Power Generation. PNL-7107, Pacific Northwest Laboratory, Richland, Washington.

Drost, M. K., Z. I. Antoniak, D. R. Brown, and S. Somasundaram. 1990. Thermal Energy Storage for Integrated Gasification Combined-Cycle Power Plants. PNL-7403, Pacific Northwest Laboratory, Richland, Washington.

United States Energy Association. 1988. U.S. Energy '88: Countdown to the Next Crisis, Second Annual Assessment of U.S. Energy Policy and Prospects. U.S. Energy Association, U.S. Member-Committee of the World Energy Conference, April 1988.

- END -

DATE FILMED

02 / 20 / 91