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M. K. Drost
D. R. Brown

Z. I. Antoniak
S. Somasundaram

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Pacific Northwest Laboratory
Richland, Washington 99352

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THERMAL ENERGY STORAGE FOR AN INTEGRATED COAL GASIFICATION COMBINED-CYCLE POWER PLANT

Kevin Drost, Zen Antoniak, Daryl Brown, and Sriram Somasundaram

Pacific Northwest Laboratory^(a)
Richland, Washington 99352

ABSTRACT

This study investigates the use of molten nitrate salt thermal energy storage in an integrated gasification combined-cycle power plant allowing the facility to economically provide peak- and intermediate-load electric power. The results of the study show that an integrated gasification combined-cycle power plant with thermal energy storage can reduce the cost of coal-fired peak- or intermediate-load electric power by between 5% and 20% depending on the plants operating schedule. The use of direct-contact salt heating can further improve the economic attractiveness of the concept.

INTRODUCTION

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 allow the use of an integrated coal gasification combined-cycle (IGCC) power plant to produce peak- and intermediate-load electric power.

IGCC technology is an efficient, environmentally sound and economical method of providing coal-fired electric power but the technology is generally limited to base-load applications due to the difficulty in cycling the gasifier. The use of TES can substantially improve the economic attractiveness of coal-fired, peak- and intermediate-power generation by allowing the use of an IGCC plant to meet peak- and intermediate-loads. In this case, the gasification equipment in the IGCC plant is continuously operated to produce low Btu fuel gas that is then used to drive a gas turbine. The thermal energy in the fuel gas and turbine exhaust heat is used to heat molten nitrate salt,

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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. The resulting power plant has a base-load component (electric power produced by the gas turbine) and an intermediate- or peak-load component (produced by the Rankine power cycle).

CONCEPT

While the IGCC concept has many attractive features, it has only been considered for base-load applications because the concept has several characteristics that make the concept unattractive for peak- and intermediate-load applications. These include: 1) poor turn-down capability in the gasifier; 2) poor part-load performance, and 3) long gasifier start-up time. The incorporation of a molten salt TES system into an IGCC plant would allow flexible power production in an intermediate or peaking mode.

During this study, several schemes were identified for integrating TES in an IGCC plant. After a preliminary evaluation, one scheme was selected for detailed evaluation. This concept is shown in Figure 1. A continuously operating Texaco gasifier supplies intermediate-Btu fuel gas to a gas turbine, which is also operated continuously, generating base-load electric power. Thermal energy in the gas turbine exhaust and hot fuel gas is used to charge a TES system.

The TES system consists of a high-temperature and low-temperature TES. The high-temperature TES uses molten nitrate salt as the storage medium. Cool salt stored in the cold salt tank at 280°C (536°F) is continuously pumped through the high-temperature section of the gas turbine waste heat recovery heater and the radiant and convective fuel gas coolers, where the salt is heated to 566°C (1050°F) and is then returned to the hot salt storage tank. The low-temperature TES stores thermal energy in a dual medium of oil and rock. The oil and rock are contained in a storage tank and the oil inlet and outlet are positioned to allow the formation of a thermocline in the tank. 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.

During peak demand periods, hot molten salt is used as a heat source to produce 538°C (1000°F) and 16.54 MPa (2400 psi) steam in a steam generator. The steam is then used to produce electricity in a conventional steam Rankine power cycle. The thermal energy stored in the low-temperature TES is used to preheat the feedwater after it leaves the condenser and to produce process steam for other applications in the IGCC plant.

The high-temperature storage medium is a mixture of sodium nitrate (60 wt%) and potassium nitrate (40 wt%). Thermal energy is stored as sensible heat in the 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 point. The maximum temperature of the salt is 566°C (1050°F) and is determined by the chemical stability of the mixture.

Figure 1. Schematic arrangement of an integrated gasification combined-cycle power plant with thermal energy storage

Although 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 salt TES is technically feasible [1,2].

The low-temperature storage medium is a mixture of a heat transfer oil, such as Caloria HT-45^(a) (25% by volume) and rock (75% by volume). Thermal energy is primarily stored as sensible heat in the rock with the oil acting as a heat transfer 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. In this case, the lower density hot oil will remain in the top of the tank while the higher density cool oil occupies the bottom of the tank, forming a hot and 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. The maximum oil temperature is approximately 304°C (580°F) and is determined by the chemical stability of the oil.

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 [3].

METHOD OF ANALYSIS

The general approach used in this study consisted of developing a conceptual design and cost estimate for the IGCC plant using TES and comparing this data to the cost for a base case that consists of an IGCC base-load power plant and either a cycling pulverized coal-fired or a natural gas fired combined-cycle power plant providing intermediate-load electric power generation. The comparison was complicated because the IGCC plant with TES has a base-load power generating component supplied by the gas turbine and a peak-load power generating component from the steam Rankine power cycle. Therefore, the comparison was conducted by assigning a value to the base-load power and subtracting this from the costs associated with producing the peak- or intermediate-load power. The comparison was made for a range of plant operating schedules. Table 1 summarizes the assumed operating schedules and gives several key design requirements for the TES system enabling the IGCC plant to meet the proposed operating schedule.

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 be operated for 5 days per week. The second case involved operation for 7 days per week but with a shorter daily operating period. In all cases, the peak plant net output was assumed to be 500 MWe for both the conventional coal-fired base case and the IGCC plant with TES.

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TABLE 1. Planned Generating Schedules

<u>Schedule Number</u>	<u>Operating Days/Week</u>	<u>Base-Load Hours/Day</u>	<u>Peaking Hours/Day</u>
1	5	24	8
2	5	24	12
3	5	24	16
4	7	24	6
5	7	24	9
6	7	24	12

The main element of this study was the development of a conceptual design of an IGCC power plant with TES. The conceptual design process served two purposes. First, the design was detailed sufficiently to allow the development of a preliminary capital cost estimate. In addition, the design process identified problems that might impact the technical feasibility of the concept.

The integration of TES in an IGCC plant is a challenging design problem because a large number of options exist for combining the two technologies. A comprehensive review of the design options was not attempted but two integration concepts were identified and briefly evaluated. The first concept was described above and involves operating the gas turbine continuously to produce base-load power and operating the Rankine steam power cycle intermittently to produce intermediate-load power. The second scheme was intended to only produce intermediate-load power. In this case, the gasifier operated continuously and the fuel gas was used to directly heat salt during off-peak periods. During peak demand periods, the fuel gas was used to fire a gas turbine with the waste heat in the exhaust also being used to charge storage. The thermal energy in storage was used during peak demand periods to generate steam for the Rankine steam power cycle. The first approach was selected for further evaluation because this concept made the maximum use of the combined cycle, increasing the plant efficiency. This arrangement was then used as the basis for the conceptual design and economic evaluation. Neither design was the subject of rigorous design optimization. While the arrangements selected for evaluation are reasonable, it is possible that additional investigations of concept arrangements and optimization studies would result in more attractive plant designs.

The economic evaluation was conducted by calculating and comparing the levelized energy cost (LEC) of an IGCC/TES power plant to reference power plants supplying the same mix of base-load and intermediate-load power output. Levelized cost analysis combines 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 plants. The specific economic methodology employed was that defined in Brown et al. [4].

RESULTS

The conceptual design process characterized the major plant components in sufficient detail to allow the development of a meaningful cost estimate. Design parameters were identified for the heat recovery salt heater, convective and radiant fuel gas coolers, heat recovery oil heater, molten salt storage, oil/rock storage, salt heated steam generator, and oil heated feedwater heater and process steam generator. The results of the design characterization in Drost [5].

Initial capital cost, annual operation and maintenance costs, and annual performance characteristics were combined with the economic methodology and assumptions to produce LEC estimates. LEC estimates were prepared for the six planned generating schedules identified in Table 1. Two reference plant systems were evaluated for comparison to the IGCC/TES power plants. Both systems are based on an IGCC plant supplying the base-load portion of the power. A cycling pulverized coal (PC) power plant is presumed to supply the intermediate-load power in the first reference system; intermediate-load power for the second reference system is presumed to come from a gas-fired combined-cycle (CC) plant. The reference system LECs were set equal to the weighted average LEC of the individual LECs calculated for IGCC and PC or CC power plants. The weighting was based on the relative amount of base-load and intermediate-load power produced; approximately 47% of the total annual power output for each production schedule is classified as intermediate. Cost and performance assumptions for PC and CC power plant LEC calculations are shown in Table 2. Financial assumptions are the same as for IGCC/TES plants. Gas for the CC plant was presumed to cost \$2.25/MMBtu in mid-1987\$ and escalate at 4%/yr in excess of general inflation.

Levelized energy cost results for IGCC/TES, IGCC/PC, and IGCC/CC power plants are shown in Table 3 for each of the six planned operating schedules. The results indicate that the LEC for the IGCC/TES plant is less than for

TABLE 2. Reference Power Plant Cost and Economic Assumptions
(all costs in mid-1987\$)

<u>LEC Input</u>	<u>IGCC Plant</u>	<u>PC Plant</u>	<u>CC Plant</u>
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, \$/kWe-year	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

Sources: [6,7,8]

TABLE 3. Levelized Energy Cost Results; Median Fuel Escalation Rates
(mid-1987 levelized \$/kWh)

<u>Generation Schedule</u>	<u>Power Plant</u>		
	<u>IGCC/TES</u>	<u>IGCC/PC</u>	<u>IGCC/CC</u>
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

the IGCC/PC power plant, but greater than the IGCC/CC power plant for the assumed baseline fuel escalation rates (1%/yr real escalation for coal; 4%/yr real escalation for gas). If a higher fuel escalation scenario is presumed (2%/yr real escalation for coal; 6%/yr real escalation for gas), the IGCC/TES plant LEC is in most cases lower than both IGCC/PC and IGCC/CC plants, as shown in Table 4. Also note that the IGCC/TES plant is most attractive for the planned production schedules with fewer peaking hours per day (i.e., at lower annual capacity factors). 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 summarized comparison of capital cost and performance characteristics is provided in Table 5.

Two sensitivity studies were conducted to evaluate the impact on IGCC/TES plant LEC resulting from decreases in the cost of two key molten salt components. The first study examined the effect of reducing the molten salt TES cost by presuming that a less expensive TES media could be identified. The second study investigated 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.

TABLE 4. Levelized Energy Cost Results; High Fuel Escalation Rates
(mid-1987 levelized \$/kWh)

<u>Generation Schedule</u>	<u>Power Plant</u>		
	<u>IGCC/TES</u>	<u>IGCC/PC</u>	<u>IGCC/CC</u>
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

TABLE 5. Comparative Cost and Performance Data

<u>Generation Schedule</u>	<u>Power Plant</u>			
	<u>IGCC/TES</u>	<u>IGCC</u>	<u>PC</u>	<u>CC</u>
	<u>Capital Cost, 1987\$/kWe</u>			
1	1556	1660	1582	534
2	1650	1660	1582	534
3	1721	1660	1582	534
4	1419	1660	1582	534
5	1559	1660	1582	534
6	1650	1660	1582	534
<u>Availability, %</u>				
All	83.2	83.2	71.2	90.3
<u>Heat Rate, Btu/kWh</u>				
1	9181	9322	10192	8394
2	9182	9322	10192	8394
3	9175	9322	10192	8394
4	9192	9322	10192	8394
5	9180	9322	10192	8394
6	9182	9322	10192	8394

The reference total direct installed capital cost for the complete molten salt TES system, including salt media, containment, and ancillary equipment is \$11/kWh. A little more than half of this total, or about \$6/kWh, represents the cost of the molten salt media. The impact of reducing TES media costs was examined by presuming alternative media costs of \$0/kWh and \$3/kWh. For the 5 days/week, 16 hours/day operating schedule, the total salt storage cost including indirect costs, sales tax, and contingency is about \$49,000,000 for media costs of \$6/kWh. If media costs could be reduced to \$3/kWh or \$0/kWh, the corresponding total TES costs would be about \$35,000,000 and \$22,000,000, respectively. The plant LEC would be lowered from \$0.0692/kWh for the baseline case to \$0.0686/kWh and \$0.0680/kWh for the alternative cases.

In the baseline IGCC/TES power plant design, the cost for the gas turbine exhaust salt heater is based on a conventional finned-tube design. The second sensitivity study investigated the cost impact of using a direct-contact heat exchanger design instead. This latter design exchanges heat between the molten salt and turbine exhaust gases by direct counter-current contact of the two fluids through a packed tower. A discussion of current experience and theory with direct-contact heat exchanger design and performance is presented in Drost [5].

The direct-contact 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 the 5 day/week, 16 hour/day production schedule, the direct installed cost of the finned-tube heat exchanger was estimated to be approximately \$33,000,000 based on estimating relationships presented in Foster-Pegg [9]. The estimated direct installed capital cost of the direct-contact heat exchanger, based on three separate sources [10,11,12], was approximately \$6,000,000. The reduction in capital cost lowered the LEC from \$0.0692/kWh for the baseline case to \$0.0668/kWh for the direct-contact heat exchanger design. The primary technical uncertainty with direct-contact salt heating is chemical compatibility between gas turbine exhaust constituents and the molten nitrate salt.

CONCLUSIONS

The results of this study have led to a number of conclusions and suggestions for further research. The significant conclusions from this evaluation of TES for application with IGCC are summarized below.

- Molten nitrate salt 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 commercialized.
- An IGCC plant with molten salt TES can substantially reduce the cost of coal-fired peak- and intermediate-load power--The results of this study show that an IGCC plant with molten salt TES produces lower cost peak- and intermediate-load power than the conventional coal-fired alternative over a range of operating schedules.
- 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 medium, and advanced tank designs have the potential to substantially improve the performance and economics of combining IGCC with TES.

The results of this study show that thermal energy storage has substantial promise when used in an integrated gasification combined-cycle power plant but to advance the technology, additional research is needed, as described below.

- Resolve remaining technical issues associated with molten salt TES--The remaining technical issues associated with molten salt handling need to be resolved and demonstrated in field tests.

- Conduct a more detailed evaluation of using molten salt TES with IGCC technology--The evaluation documented in this report was a scoping study and could not address second-order issues. Before proceeding with a technology development program, a more detailed evaluation should be conducted. This evaluation should include a vendor developed design and cost estimate.
- Develop advanced molten salt TES technology--Several advanced concepts such as direct-contact salt heating, low freezing point salts, dual storage medium, and advanced tank designs require research and development. If successful, these concepts have the potential to substantially improve the performance and economics of an already attractive concept.
- Conduct a large-scale field test of molten salt TES--The acceptance of TES technology by the utility industry will depend on a successful large-scale field test of the concept including direct-contact salt heating. A meaningful technology development program must result in such a field test.

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