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APPLICATIONS OF COGENERATION WITH THERMAL ENERGY STORAGE TECHNOLOGIES

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ABSTRACT

The Pacific Northwest Laboratory[2] (PNL) leads the U.S. Department of Energy's Thermal Energy Storage (TES) Program. The program focuses on developing TES for daily cycling (diurnal storage), annual cycling (seasonal storage), and utility-scale applications [utility thermal energy storage (UTES)]. Several of these storage technologies can be used in a new or an existing power generation facility to increase its efficiency and promote the use of the TES technology within the utility and the industrial sectors.

The UTES project has included a study of both heat storage and cool storage systems for different utility-scale applications. The study reported here has shown that an oil/rock diurnal TES system, when integrated with a simple gas turbine cogeneration system, can produce on-peak power for \$0.045 to \$0.06 /kWh, while supplying a 24-hour process steam load. The molten salt storage system was found to be less suitable for simple as well as combined-cycle cogeneration applications. However, certain advanced TES concepts and storage media could substantially improve the performance and economic benefits.

In related study of a chill TES system was evaluated for precooling gas turbine inlet air, which showed that an ice storage system could be used to effectively increase the peak generating capacity of gas turbines when operating in hot ambient conditions.

1. BACKGROUND

The U.S. Department of Energy's Thermal Energy Storage (TES) Program under the direction of the Pacific Northwest Laboratory (PNL) focuses on developing different types of storage system technologies that are applicable to utility-scale power plants. Natural-gas-fired gas turbine technologies, such as simple cogeneration and combined-cycle power plants, are becoming the generation options of choice because of there relatively low capital cost, operational flexibility,

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reduced environmental impact, and increasing thermal efficiency. Thermal energy storage for utility applications includes a range of technologies that can further improve the efficiency, flexibility, and economics of gas turbine operations. The following is an overview of the integration of TES technologies with cogeneration plants, as well as results of the technical and economic assessments of TES applied to gas turbine systems.

2. TES SYSTEM TECHNOLOGIES

Brief descriptions of the different TES system technologies that were considered in this study are provided in this section. The selection of a specific storage system will depend on the quality and quantity of recoverable thermal energy and on the nature of the thermal load to be supplied from the storage system. The TES systems and technologies for gas turbine applications can be categorized by the media storage temperature. Heat storage systems can be used to store thermal energy at high temperatures (566 °C) from sources like the exhaust from a gas turbine or an engine. High-temperature TES options include oil/rock storage, molten nitrate salt storage, and combined molten salt and oil/rock storage. On the other hand, chill storage technologies store thermal energy at temperatures below ambient temperature and can be used for cooling the air entering gas turbines. An example of a chill storage concept is the diurnal ice storage system.

2.1 Heat Storage Systems

Heat storage systems are used to store thermal energy at intermediate temperatures (such as in an oil/rock system) for hot water/process heat recovery applications and at high temperatures (such as in molten nitrate salt systems) for steam production for process applications or for additional power generation using steam turbines as in a combined-cycle application.

2.1.1 Oil/Rock Storage

An oil/rock TES system (Drost et al. 1990) consists of a single, large tank that is filled with a mixture of oil (i.e., low-cost heat transfer oils that can operate at temperatures between 38°C and 304°C), and low-cost filler such as river rock (see Figure 1). Hot oil is maintained at the top of the tank and cold oil at the tank bottom. This arrangement stratifies the fluid in the tank, resulting in minimal mixing between the hot and cold regions. During normal operation, cold oil is removed from the bottom of the tank, heated in the heat recovery oil heater, and returned to the top of the storage tank. Thermal energy is, therefore, stored in the mixture of oil and rock. An oil/rock TES system is relatively less expensive than other heat storage systems, but the upper end of its temperature range is limited by the oil's stability considerations. Oil/rock storage has been successfully demonstrated in solar thermal applications.

2.1.2 Molten Nitrate Salt Storage

Molten nitrate salt is an excellent storage medium for high-temperature TES applications (566°C). Current molten salt TES concepts use a mixture of sodium nitrate (60 wt%) and potassium nitrate (40 wt%) that can operate up to 566°C. This mixture freezes at 240°C, so molten nitrate salt systems must operate at temperatures above 288°C to provide freeze protection. The minimum operating temperature limits the amount of waste heat that can be recovered from a combustion turbine's exhaust because the exhaust can be cooled to only approximately 315°C. Typically, molten nitrate salt systems use separate hot and cold salt tanks (see Figure 2).

Molten nitrate salt TES has been extensively investigated for solar thermal power generation applications. Investigations have included bench-scale testing, detailed design studies, and field demonstrations. Based on the results of these investigations, the U.S. Department of Energy and a group of electric utilities are sufficiently confident of the concept's technical feasibility to embark on the $40 million Solar II demonstration (100-MWth system) of molten nitrate salt central receiver technology. This suggests that molten nitrate salt TES is technically ready for a power plant application demonstration.

2.1.3 Combined Storage

The advantages of both storage concepts just described can be retained by using a combination of molten nitrate salt TES for high-temperature storage and oil/rock TES for intermediate-temperature storage. If the thermal end-use requires high-temperature steam production, the molten nitrate salt TES or a combined molten nitrate salt and oil/rock TES can be used. Alternatively, if the end-use thermal energy is below 288°C, the oil/rock TES may be the preferred option.

Alternative nitrate salts that can operate between 510°C and 120°C have been identified (e.g., ternary mixture of $LiNO_3$ - $NaNO_3$ - KNO_3 with weight percents of 30%, 18%, and 52%, respectively, that melts at 120°C; or a mixture of $Ca(NO_3)_2$ - $NaNO_3$ - KNO_3 with proportions of 30%, 24%, and 46%, respectively, that melts at 160°C). Using these nitrate salts would retain the benefits of both storage concepts by allowing the turbine exhaust to be cooled to near stack conditions. However, these salts tend to be more expensive than the conventional molten salt and will require additional research before a large-scale application is justified. Successful development of an alternative nitrate salt TES system could eliminate the need for a combined molten salt and oil/rock TES system to cover the entire temperature range.

2.2 Chill Storage Systems

Chill storage systems are mainly used to increase the generating capacity of flow-through devices, such as gas turbines, during hot ambient conditions (as exists during the summer seasons) by cooling the air to close-to-design inlet temperatures and thereby increasing the density of the incoming air.

2.2.1 Diurnal Ice Storage

Diurnal ice storage is a form of chill storage system. Currently, the most common application for this type of storage system is in commercial office buildings where conventional heating, ventilating, and air-conditioning (HVAC) equipment is combined with a cool storage unit to shift chiller operation from on-peak (daytime) to off-peak (night-time) periods. The storage unit is charged using the chiller during off-peak hours when electricity rates are lowest and discharged during on-peak hours when the rates are highest, thus reducing the cost of electricity used for cooling.

The principal element of a cool storage system is the storage tank. Other ancillary equipment includes circulation pumps, piping, valves, and controls. Chilled water and/or ice are the two most common storage media, but eutectic salts also have attractive features. Water and ice storage are popular because they are well understood and integrate easily with standard chilled water distribution systems. The energy absorption density of ice is approximately seven times that of water, resulting in smaller storage tanks. However, ice generation requires more expensive refrigeration equipment and a lower storage temperature, resulting in a lower chiller coefficient of performance (COP). Eutectic salts have an energy storage density between that of water and ice, and freeze at temperatures consistent with conventional chiller operation. The eutectic salts, however, are more expensive than water and are usually combined with a chilled water storage system to reduce storage tank size.

The two basic diurnal ice storage systems are ice building and ice harvesting. As the name implies, ice building systems form ice directly on coils submerged in a tank of water by flowing a subzero temperature fluid (refrigerant or water/glycol mixture) through the coils. Ice forms around the coils during the charging cycle and is subsequently melted by circulating water during the discharge cycle. Ice harvesting systems also have ice forming directly on evaporator surfaces, but the ice is periodically removed by passing hot defrosting vapor through the evaporator. This loosens the ice and allows it to drop into the remaining water/ice mixture in the storage tank. During discharge, the ice is melted, which cools the circulating water.

3. TES SYSTEM APPLICATIONS

Two different TES system applications, cogeneration and gas turbine inlet air cooling TES, are discussed in this section. Each application results in an overall improvement in energy efficiency and an effective utilization of the available energy.

3.1 Cogeneration

Several emerging issues may limit the number of useful applications of cogeneration. One issue is a daily mismatch between the demand for electricity and the thermal energy load to be supplied. Increasingly, utilities are requiring cogenerators to provide dispatchable power (power that needs to be supplied on demand) while most industrial thermal loads are relatively constant during the day.

Diurnal TES can decouple the generation of electricity from the production of thermal energy, allowing the cogeneration facility to supply dispatchable power. Diurnal TES stores thermal energy recovered from the exhaust of the prime mover (gas turbine) to meet daily variations in the demand for electric power and thermal loads.

The concept for integrating TES in a natural-gas-fired cogeneration facility is shown in Figure 3. The facility consists of a 1) gas turbine prime mover, 2) heat recovery salt heater, 3) thermal energy storage system, and 4) salt-heated steam generator. The gas turbine is operated during peak demand periods, and the exhaust heat is used to heat molten salt in a heat recovery salt heater. Cold salt (288°C) is pumped from the cold salt tank through the heat recovery salt heater (where it is heated to between 510°C and 538°C) before being pumped to the hot salt storage tank. Hot salt is continuously removed from the hot salt tank and used as a heat source to meet the constant thermal load. A cogeneration plant with a TES system sized for an 8-hour peak demand period would provide a 30-MWe peaking capacity, compared to a similar conventional cogeneration facility that would provide a 10-MWe baseload.

TES allows a cogeneration facility to provide dispatchable electric power, which is sold to the local utility, while providing a constant thermal load. The cost of power produced by cogeneration and cogeneration/TES systems designed to serve a fixed process steam load has been evaluated (Somasundaram et al. 1992). The value of the process steam was set at the levelized cost estimated for steam from a conventional stand-alone boiler. Power costs for combustion turbine and combined-cycle power plants were also calculated for comparison. The results for an assumed steam load show that the conventional cogeneration system and the cogeneration plant combined with the oil/rock TES system, have lower levelized costs of producing steam compared to the conventional boiler plant operation, if the selling price of electricity is above $0.06/kWh. The breakeven price for the sale of electricity (with the same steam costs for the three plant options) ranges from $0.035/kWh for the conventional cogeneration system to approximately $0.045/kWh to 0.06/kWh for the combined system. This represents a 25% to 40% reduction in the cost of peak power when compared to $0.08/kWh for a gas turbine plant; it is a 14% to 35% reduction compared to a peak power cost of approximately $0.07/kWh for a combined-cycle plant.

After the different heat storage systems for the TES/cogeneration application are compared, the oil/rock TES system remains the most attractive option for the assumed thermal load quality. A higher quality of the assumed thermal load (e.g., at higher pressures and temperatures) will favor the molten nitrate salt TES system because it can achieve a higher temperature range. The economies-of-scale with respect to the costs of the gas turbine, the oil/salt heater, oil/rock or salt storage system, and the heat recovery steam generator, as well as the magnitude of energy loss from the storage system, also favor the larger-sized system components. Further cost reductions may result from optimization of individual components in the combined plant configurations and TES system improvements gained from future research and development.

3.1.1 Modeling using TRNSYS

In addition to the sizing and economic analyses described above, an attempt is underway to simulate the demand and supply of thermal and electric load profiles for an integrated cogeneration/TES system using TRNSYS. TRNSYS is a modular transient system analysis program developed and supported by the Solar Energy Laboratory, at the University of Wisconsin-Madison under contract to the U.S. Department of Energy (Solar Energy Laboratory 1994). The simulations of a single stratified tank model for an oil TES system was undertaken first. Two scenarios as to heat recovery steam generators were explored. A single evaporator/economizer pair worked well for a constant steam load, but multiple (in this case, four) sets of evaporators/economizers were modelled for variable steam load cases. The multiple heat exchangers model was clearly superior to the single evaporator/economizer case for steam load profiles that had diurnal (day/night) variations and a weekday/weekend variation over a 7 day period. In addition, the overall model stability related to simulation time-step size and the relative error tolerance, as well as the storage tank size were optimized. Future directions in this simulation exercise will be to incorporate actual site data (loads and weather conditions) and to conduct a two-tank (separate cold and hot tanks) molten salt TES system simulation study.

3.2 Gas Turbine Inlet Air Cooling

The degradation of gas turbine generating capacity during periods of high ambient temperature can be a significant problem, especially for summer peaking utilities. As the ambient air temperature increases, the density of inlet air, the generating capacity, and the efficiency of the gas turbine all decrease. A review of data on existing gas turbine installations shows that the summer capacity of a typical gas turbine is between 15% and 25% lower than the winter capacity of the same gas turbine. Traditionally, evaporative cooling has been used to cool gas turbine inlet air. However, it can reduce the temperature of the inlet air to only the wet-bulb temperature. Further reductions in inlet air temperature will require additional cooling.

Several approaches have been proposed or utilized to reduce the temperature of the gas turbine inlet air. One approach uses off-peak electric power to drive a vapor compression cycle ice maker, producing ice that is then stored. During on-peak electricity demand, the stored ice is used to cool the gas turbine inlet air to approximately 4.4°C. Such a diurnal ice TES system has been installed at Lincoln Electric System's Rokeby Station (Antoniak et al. 1992). The system consists of a refrigeration unit, ice/water storage tank, and an air cooling heat exchanger. During off-peak periods, cold water from the bottom of the storage tank is pumped to three ice-making units located on the top of the tank. The cold water is frozen, and the ice is stored in the tank. Off-peak electric power is used to drive the ice makers. During periods of high ambient temperature, cold water is pumped from the tank and used to cool the gas turbine inlet air. The inlet air passes through the shell side of a heat exchanger, while chilled water passes through the tube side. Indirect heat transfer is used to protect the gas turbine from impurities in the chilled water. The heat exchanger is sized to reduce the temperature of the inlet air from 38.3°C to 4.4°C with a pressure drop of 1.67 kPa. Reducing the inlet air temperature to 4.4°C increases the peak capacity of the Rokeby gas turbine from 53 MWe to 64 MWe. The 20% increase in the gas turbine capacity is obtained at a cost of approximately $165/kWe. This represents a 58% reduction in the cost of adding peaking capacity by installing new gas turbines, which have been estimated to cost $387/kWe (EPRI 1989).

4. BENEFITS OF TES APPLICATIONS

The use of TES in advanced power plant applications has five key benefits:

- High-temperature TES allows a natural-gas-fired cogeneration facility to produce dispatchable power while meeting constant thermal loads.
- High-temperature TES integrated in a natural-gas-fired cogeneration facility allows all power generation to occur during periods of peak demand. The installed capacity of the prime mover is substantially larger than for a conventional cogeneration facility. A cogeneration plant with a TES system sized for an 8-hour peak demand period would provide 30 MWe of peaking capacity compared to a similar conventional cogeneration facility that would provide 10 MWe of baseload.
- For gas-fired cogeneration, all natural gas is used to fire the combustion turbine (compared to direct natural-gas-firing of the waste heat steam generator). This results in high-efficiency operation by ensuring that all natural gas is used to produce both electric power and thermal energy.
- Cool storage or chill energy storage systems provide an alternative economic means of precooling gas turbine inlet air to avoid reduction in generating capacity during operation in the hot summer months.
- A simple-cycle gas turbine cogeneration plant integrated with a TES system has a lower emission (of NOx and CO on a kg/MWh basis) than a non-TES system with the same cycle. This is caused by the lower heat rates of larger turbines used (also producing more power) for the TES systems compared to the non-TES systems.

5. CONCLUSIONS AND RECOMMENDATIONS

Thermal energy storage (heat or cool) for gas turbine power plant applications will enhance the efficiency, flexibility, and economics of the natural-gas-fired gas turbine technologies currently being promoted for intermediate- and peak-load generation applications. The heat storage systems help decouple the production of electric power from that of process heat loads, while the chill storage systems can be used to precool the gas turbine inlet air. The different TES systems that have been discussed are only a sampling of some of the emerging technologies now being developed and evaluated.

The next step is to conduct large-scale demonstration studies of the integrated systems (advanced power plant designs with TES systems) and disseminate the benefits and performance data to the utility industry.

In the cogeneration plant applications, certain advanced TES concepts could substantially improve the performance and economic benefits. Some of these concepts include direct-contact salt heating, lower-freezing-point salts (or salts with an extended temperature range such as the ternary mixtures referred to in Section 2.1.3), dual storage media (as in the combined storage of salt and oil/rock systems discussed in Section 2.1.3), and advanced storage tank designs. The direct-contact heat exchanger (DCHX) design involves transfer of heat between the molten salt and the turbine exhaust gases by direct counter-current contact of the two fluids through a packed tower. This 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. The current status of research on DCHX systems shows that only preliminary modeling and experiments have been performed to quantify the heat transfer aspects of packed bed towers. A more fundamental analysis and extensive experimentation with large beds and wide ranges of temperatures and flow rates have to be performed before any commercialization of a DCHX system for TES applications can be achieved.

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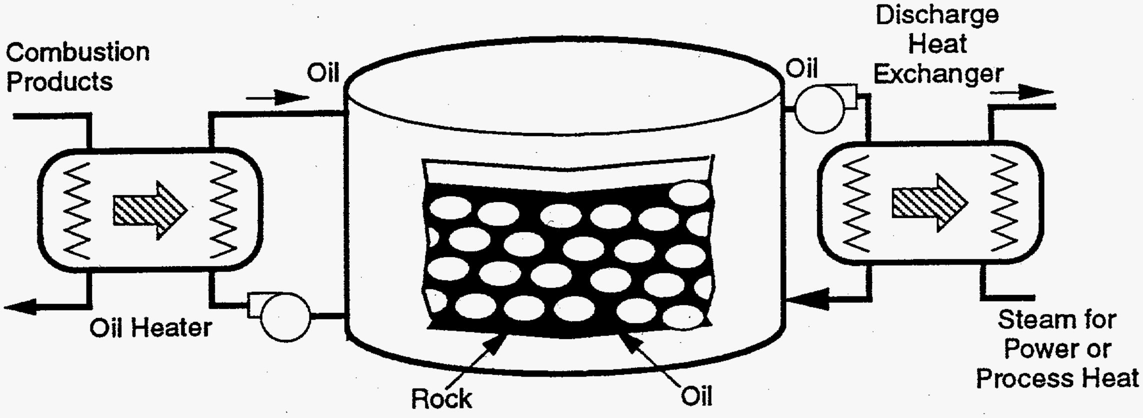

Figure 1. Oil/Rock TES Technology

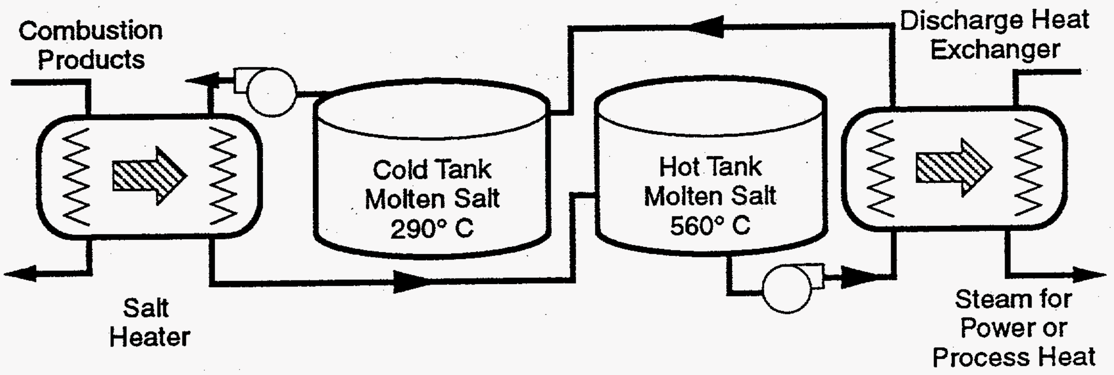

Figure 2. Molten Nitrate Salt TES Technology

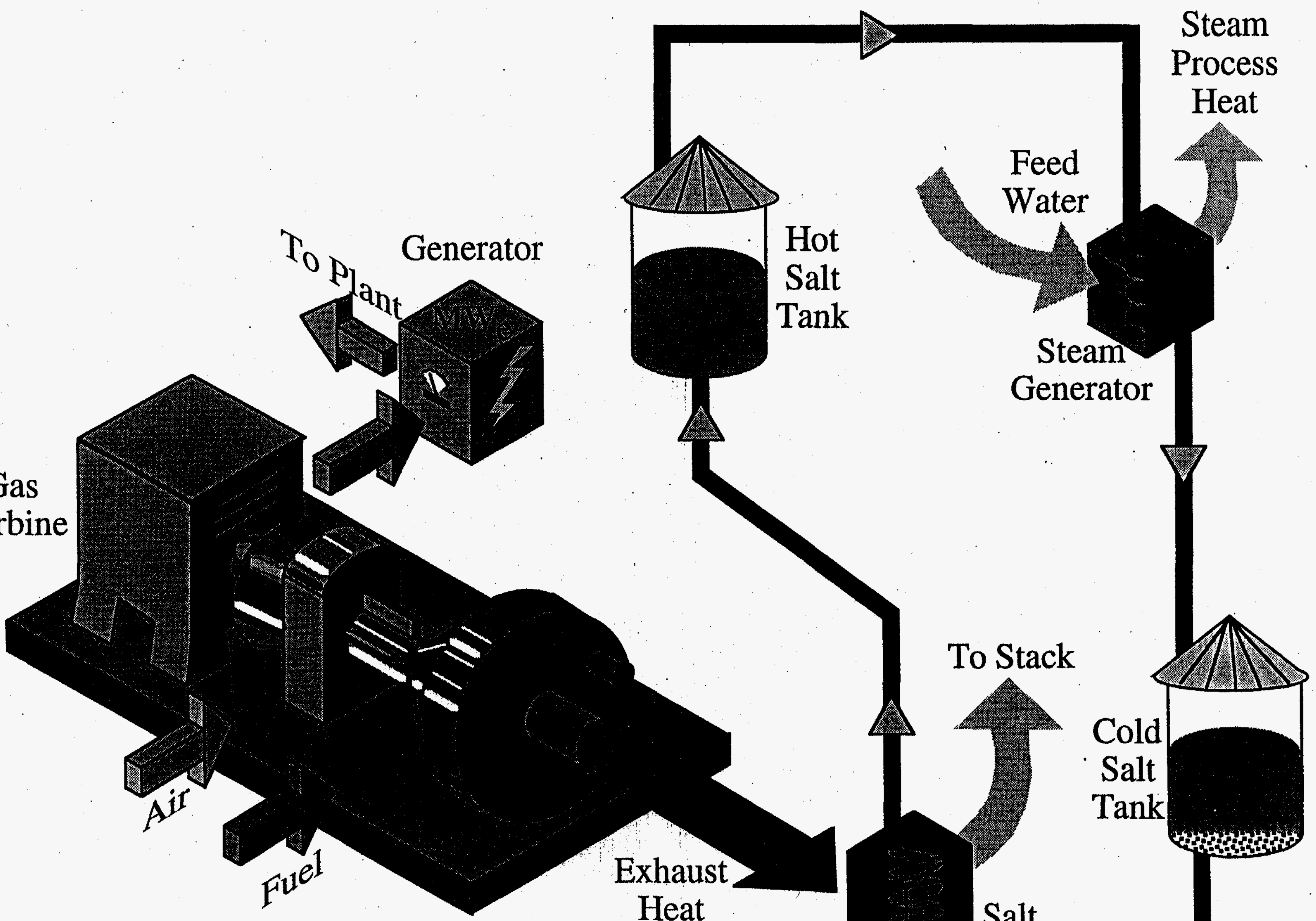

Figure 3 Schematic of a Cogeneration Plant Integrated with Molten Salt TES.