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Site-Specific Investigations of Aquifer Thermal Energy Storage for Space and Process Cooling

August 1991

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SITE-SPECIFIC INVESTIGATIONS OF
AQUIFER THERMAL ENERGY STORAGE FOR
SPACE AND PROCESS COOLING

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SUMMARY

The Pacific Northwest Laboratory (PNL) has completed three preliminary site-specific feasibility studies that investigated using aquifer thermal energy storage (ATES) to reduce space and process cooling costs. Chilled water stored in an ATES system could be used to meet all or part of the process and/or space cooling loads at the three facilities investigated. Water pumped from a set of supply wells is cooled and then injected into a set of storage wells. Later, the storage wells are pumped and the cool water is used to meet a process or space cooling load.

The primary objective of this study was to identify prospective sites and determine the technical and economic feasibility of implementing chill ATES technology. If the preliminary feasibility studies showed promise, more detailed feasibility studies, allowing an implementation decision, would be recommended. A secondary objective was to identify site-specific factors promoting or inhibiting the application of chill ATES technology so that other potentially attractive sites could be more easily identified and evaluated and R&D initiated to reduce the impact of inhibiting factors.

A previous study developed and screened a list of potential entry market applications for chill ATES. Large industrial structures, in general, and automotive plants, in particular, were identified as attractive opportunities. Cooling systems at Ford Motor Company Plastic Products Division plants in Sandusky, Ohio, (Sandusky plant) and Seline, Michigan (Seline plant), and the General Motors Corporation Delco Products Division plant in Dayton, Ohio, (Dayton plant) were evaluated in this study.

The preliminary feasibility studies considered several different chill ATES system designs, as well as alternative thermal energy storage and conventional cooling system technologies. The general approach was to calculate and compare the total life-cycle cost of each of the cooling system alternatives. The economic figure-of-merit was the levelized cost of cooling in $\$/10^6$ kJ.

Where available, site-specific design information (characterizing the general aquifer conditions, cooling loads, and conventional cooling system) was acquired via written and oral communications with site energy managers.

PNL specified ATES system design, cost, and performance characteristics; any missing data for other systems; and the financial assumptions required to complete the economic analysis. Most of the key modeling assumptions were based on conditions actually known to exist at the three plants. These included local climatic conditions, peak hourly and annual cooling loads, maximum flow rate per well, well cost, well depth, transportation distances, cooling water reject temperature, and electricity cost. Two other key chill ATES variables, aquifer thermal recovery efficiency and well spacing, were set at generically applicable values that would have to be confirmed by further analysis of the site geohydrology.

The results of the preliminary site feasibility studies indicated that seasonal or diurnal chill ATES systems could be significantly less expensive than a conventional electrically-driven, load-following chiller system at the Seline plant, depending on the cooling water loop return temperature and presumed future electricity escalation rate. For the other two sites investigated, a chill ATES system would be economically competitive with conventional chillers if onsite aquifer characteristics were improved. Well flow rates at the Sandusky plant were adequate, but the expected thermal recovery efficiency was too low. The reverse of this situation was found at the Dayton plant, where the thermal recovery efficiency was expected to be adequate, but well flow rates were too low.

The availability of a suitable aquifer is an obvious requirement for any ATES system. The economic feasibility of chill ATES requires shallow, low-cost, thermally efficient, productive wells. Future feasibility studies should begin by investigating the geohydrologic characteristics of prospective sites because the lack of suitable aquifer conditions is a constraint inhibiting implementation of the ATES concept.

The importance of the target cooling conditions (temperature and humidity) for chill ATES application cannot be overemphasized when considering the potential feasibility of a chill ATES system. Process cooling conditions in excess of 40°C (100°F) are usually more economically served by evaporative cooling towers. Typical office environment cooling conditions [low 20s (°C) with low to moderate humidity] require low cooling water loop return temperatures in humid climates that generally make chill ATES less attractive.

In between these two endpoints, cooling with chill ATES systems has its greatest competitive advantage.

Tempering the indoor air within large manufacturing facilities to approximately 50% relative humidity at 27°C (80°F) has several attributes that make it especially attractive as a possible application of ATES for space cooling. Strict temperature and humidity control is not required; relatively large cooling loads allow the capture of strong economies-of-scale in chill ATES systems; and higher cooling water return temperatures substantially improve chill ATES economics by increasing the amount of cooling that can be accomplished per unit of chilled water supplied to the building cooling water loop.

Constructing a winter cooling mechanism (e.g., evaporative cooling tower, air cooler, spray pond, cooling pond) allows greater siting flexibility, but could be more expensive than using natural sources of winter chill (e.g., lakes, ponds, rivers). The cost and performance of these alternative cooling sources should be investigated for alternative design conditions (e.g., source temperature, source availability, transmission distance, peak thermal load).

Both seasonal and diurnal chill ATES systems should be considered at prospective sites. The best chill ATES system will depend on the prevailing electric rate structure and load profile, as well as local aquifer conditions. Seasonal chill ATES systems could displace all or part of a facility's cooling load, while diurnal chill ATES systems could provide the same service as other diurnal chill storage technologies.

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1.0 INTRODUCTION

The Pacific Northwest Laboratory (PNL)^(a) has completed three preliminary site-specific feasibility studies that investigated using aquifer thermal energy storage (ATES) to reduce space and process cooling costs. Chilled water stored in an ATES system could be used to meet all or part of the process and/or space cooling loads at the three facilities investigated. The work was sponsored by the U.S. Department of Energy's (DOE) Office of Energy Management.

Aquifer thermal energy storage is a technology that allows relatively low-grade thermal energy sources to be stored and retrieved for future use on a seasonal or diurnal basis. Water pumped from a set of supply wells is heated or cooled and then injected into a set of storage wells. Later, the storage wells are pumped and the warm or cool water can be used to meet a thermal load (see Figure 1.1). The principal advantages of ATES are the use of existing aquifer formations as both the media and physical containment components of a storage system, the use of water as the heat transfer medium, and the concept's ability to store energy on a seasonal or diurnal basis. The concept is limited, however, to locations where the energy source, energy application, and a suitable aquifer are in close proximity to each other.

The ultimate goal of DOE's Thermal Energy Storage Program is to successfully transfer ATES technology to industrial and commercial sectors. The primary objective of this study was to identify prospective sites and determine the technical and economic feasibility of implementing chill ATES technology. A secondary objective was to identify site-specific factors promoting or inhibiting the application of chill ATES technology so that other potentially attractive sites could be more easily identified and evaluated.

A previous study (Hattrup and Weijs 1989) developed and screened a list of potential entry market applications for chill ATES. Several initial screening criteria were used to identify promising chill ATES applications.

(a) PNL is operated for the U.S. Department of Energy by Battelle Memorial Institute.

SEASONAL THERMAL ENERGY STORAGE

FIGURE 1.1. Aquifer Thermal Energy Storage

These include the existence of an energy availability/usage mismatch, the existence of many similar applications or commercial sites, the ability to utilize proven technology, the type of location, market characteristics, the size of and access to capital investment, and the number of decision makers involved (Hattrup and Weijo 1989). During the course of the study, additional screening criteria were identified. They included a requirement that the reliability of the ATES system should not be of overriding importance, that a wide range of temperature variability should be acceptable, and that relatively high application temperatures would be allowable.

The application that best met the above description was the cooling of large industrial structures that are not currently being air conditioned. Because many auto assembly plants fit this description, a preliminary investigation of the feasibility of commercializing chill ATES in automotive assembly facilities was completed. The results suggested that automotive assembly facilities represent a good entry market for chill ATES, if the system is cost-effective (Hattrup and Weijo 1989). As a result, this study was undertaken to identify and evaluate prospective chill ATES applications in the automotive industry.

The balance of the report contains two main sections. Section 2.0 describes the site identification process. Site feasibility is addressed in Section 3.0. Overall study conclusions and recommendations are then presented in Section 4.0.

2.0 SITE IDENTIFICATION

The site identification process served two purposes: 1) obtaining participants for preliminary feasibility studies and 2) developing valuable insights that should facilitate future efforts to identify and evaluate prospective chill ATES sites and the technology transfer/commercialization process in general. The results of the former are presented in Section 2.1 and the latter in Section 2.2.

2.1 PARTICIPANT SOLICITATION

The initial goal of this study was to identify several sites that were actively considering cooling systems and would be willing to provide the site-specific design data required to conduct the preliminary feasibility studies. The states of Ohio, Michigan, and Indiana were selected as the primary focus of recruitment activities based on the expected availability of suitable aquifers and the concentration of auto manufacturing plants in this region. An analysis of auto industry data revealed that nearly 70% of the employees and 58% of the plants in the industry are located in these three states (Motor Vehicle Manufacturers Association 1988). The close proximity of prospective sites would enhance subsequent technology transfer efforts if a successful demonstration system were implemented. The climatic and geohydrologic conditions would more likely be similar and the system would be more accessible for inspection by other site energy managers in the auto industry.

Before the plants were contacted, briefing material explaining the chill ATES concept and a list of the data required for conducting the preliminary feasibility study were developed. These materials, reproduced in the Appendix, were mailed to plant engineers who indicated an initial interest in chill ATES technology. Recruiting contacts were attempted with approximately 90 plants, but only about 40 plant engineers were successfully contacted. In the remaining cases, it was either not possible to identify the appropriate person to contact or phone messages were never returned. Repeated attempts were usually required to establish the initial contact.

Of the approximately 40 plants contacted, 22 were willing to review an information packet on chill ATES technology, which included the technology brief and the data requirements for conducting the preliminary feasibility study. Follow-up contacts were usually made about 2 weeks later to ascertain the level of interest in the preliminary feasibility study. Of the 22 that received the ATES information package, only 6 plant engineers said they were willing to participate. Several of the individuals who declined to participate cited the fact that the data required for the preliminary feasibility study was not readily available. Of the six plants that indicated they would participate, only two plants (the Ford Motor Company Plastic Products Division plant in Sandusky, Ohio, and the General Motors Corporation Delco Products Division plant in Dayton, Ohio) eventually provided the information necessary to complete the preliminary feasibility studies. The results of these studies were presented to corporate-level energy managers within Ford and General Motors, however, so significantly broader exposure was ultimately obtained. Unfortunately, all three of the Chrysler plants originally indicating interest later declined to participate.

2.2 LESSONS LEARNED

Part of the site characterizing information received from the Dayton plant included a map of the groundwater resources for their local county. The map was extremely useful for assessing the prospects for ATES at the Dayton plant and the surrounding area. The map had adequate detail to identify the near-surface geologic formations and expected well flow rates and depths. Future site recruitment efforts would probably be more efficient if potentially suitable aquifers were identified first and prospective applications within the suitable aquifer areas identified second. Groundwater maps for concentrated manufacturing regions should logically be reviewed first.

Many of the individuals who reviewed the ATES information package declined to participate in the preliminary feasibility studies. The reasons given were varied, but included the following: 1) too busy to generate the information, 2) insignificant benefits attributable to space or process cooling, 3) the building was too big to cool, 4) not currently cooling so any

system would only increase costs, 5) a general lack of interest in the technology, 6) dim prospects for the plant's future, 7) difficulty in generating the data required for the preliminary feasibility study, and 8) concerns about ecological and regulatory issues relating to use of groundwater.

Environmental concerns (technically justified or not) may be a significant barrier to implementation of chill ATES because of increasing concern with environmental issues. In one instance, company concern about public acceptance or reaction to the use of aquifers was particularly strong. In this case, the plant engineer contacted was initially enthusiastic about chill ATES technology and reviewed the technology brief and the list of data requirements. Subsequent review by divisional management terminated further interest because of a previous experience in one of the division's other plants where severe negative public opinion was generated from the proposed use of an aquifer as a cooling source. Groundwater was to be pumped, directly used for space cooling, and then rejected to a river or sewer. Unfortunately, the aquifer had been previously contaminated by another company and strong objections were made to rejecting the water to either a nearby river or the sewer. ReInjection to the aquifer was apparently not considered as the project was dropped to avoid additional bad publicity.

One of the lessons learned as a result of this effort is that when trying to transfer an energy efficient technology into the private sector, it is important that the targeted application actually allows the technology to reduce energy consumption. By targeting the application of space conditioning in large manufacturing facilities that don't typically do any space conditioning, the costs of a cooling system have to be justified based on non-energy issues, such as improved product quality and increased worker productivity. The attitude of some plant engineers was it would be nice to have, but we've gotten by without any cooling system for years. Although it would generally be more difficult for chill ATES systems to be economically competitive in a retrofit situation, there would be several advantages to targeting applications that are already being cooled. Such facilities would already have data on their cooling load requirements and information on system capital and operating costs, which would allow a valuable comparison with chill ATES.

Without an existing air conditioning system the plants don't readily know what their cooling load would be. Where cooling systems already exist, site energy managers could be shown the potential savings available by utilizing chill ATES systems. However, it should be noted that corporate level energy managers at Ford did show interest in space conditioning of large manufacturing facilities.

Future chill ATES assessment activities may want to focus on newer plants that already have air-conditioning systems. It might also be wise to contact local utilities and heavy industry in areas that have good aquifers to enlist their help in identifying candidate sites for preliminary feasibility studies. Because more and more utilities are interested in shaving summer peak electrical loads, they might be willing to help the candidate site define the information required for the preliminary feasibility study, particularly for diurnal systems.

The Sandusky plant represented an especially interesting opportunity for implementing a chill ATES system because Ford was actively considering installing a new space and process cooling system that incorporated eutectic salt storage. The Sandusky plant, built in 1955, was not currently air conditioned. The new system was to condition the air within the manufacturing facility to approximately 27°C (80°F) at moderate humidity and more effectively meet current process cooling loads.

Ford cited three principal reasons for considering adoption of a space cooling system for their manufacturing facility: 1) worker productivity, 2) electronic malfunctions related to operation in a high-temperature environment, and 3) other adverse effects on production processes caused by overheating. Ford first considered using well water as the cooling source and was primarily interested in cooling the process equipment. After becoming aware of eutectic salt storage as a means to reduce peak electricity charges associated with load-following chiller operation, they decided to investigate cooling the entire structure.

Ford indicated that they are not actively looking at providing cooling for all of their large production facilities. Each plant is different and has different air conditioning needs. Smaller electronics plants need a

temperature-controlled environment for the processes they house, which dictates the use of air conditioning in those plants. The increased use of solid-state technology on the production floors of larger plants could possibly create a need for space cooling. On the other hand, General Motors noted that electronic system designs could be modified to operate in higher temperature environments.

As noted above, Ford originally investigated the possibility of using naturally cool groundwater for supplemental process cooling. At the Sandusky plant, Ford currently uses water from an onsite, 6 hectare (15 acre) lake for cooling injection molding processes. However, during the summer months, the water in the quarry can reach 27°C (80°F), which is too hot to effectively cool the process. Test drilling indicated that wells producing 1.5 m³/min (400 gpm) were possible, but Ford was concerned about having to reinject or dispose of the aquifer water because it would have to be treated to control precipitation of dissolved minerals.

3.0 SITE EVALUATION

The general approach was to calculate and compare the total life-cycle cost of each of the cooling system alternatives. The economic figure-of-merit was the levelized cost of cooling in $\$/10^6$ kJ. Levelized cost analysis combines initial cost, annually recurring cost, and system performance characteristics with financial parameters to produce a single figure-of-merit (the levelized energy cost or LEC) that is economically correct and can be used to compare the projected energy costs of alternative cooling system concepts. The specific economic methodology employed was that defined in Brown et al. (1987). Some of the key inputs to the LEC analysis conducted for this study are shown in Table 3.1.

Where available, site-specific design information characterizing the general aquifer conditions, cooling loads, and conventional cooling system was acquired via written and oral communications with site energy managers. PNL specified chill ATES system design, cost, and performance characteristics; any missing data for other systems; and the financial assumptions required to complete the economic analysis. Most of the key modeling assumptions were based on conditions actually known to exist at the three plants. These included local climatic conditions, peak hourly and annual cooling loads, maximum flow rate per well, well cost, well depth, transportation distances, cooling water reject temperature, and electricity cost. Two other key chill ATES variables, aquifer thermal recovery efficiency and well spacing, were set at generically applicable values that would have to be confirmed by further analysis of the site geohydrology.

Initial capital and annually recurring costs for a chill ATES system were estimated with a computer spreadsheet tool, called AQUACOOL, developed specifically for this project. The development of AQUACOOL and its relationship to previous chill ATES system cost analyses conducted at PNL is discussed in more detail in the following subsection. Initial capital and annually recurring cost data for non-ATES cooling systems were either set equal to known site-specific conditions or estimated by PNL based on published information sources.

TABLE 3.1. Key Levelized Energy Cost Inputs

Initial Costs		
Site exploration	Heat exchanger	Cooling tower
Piping	Wells	Pumps
Chiller		
Recurring Costs		
Operating and maintenance	Electricity	Operating overheads
Design and Performance Factors		
Source temperature	Source availability	Peak thermal load
Annual thermal load	Load reject temperature	Well life
Well spacing	Well flow rate	Well depth
Thermal efficiency	Transmission distance	
Financial Assumptions		
Nominal discount rate		9.3%
General inflation rate		3.1%
Capital inflation rate		3.1%
Operation and maintenance inflation rate		3.1%
Electricity inflation rate		3.1 to 9.3%
Investment tax credit		0%
Property and insurance tax rate		2.0%
Combined State and Federal income tax rate		39.1%
System economic life		20 yr
System depreciable life		7 yr
System construction period		1 yr
Price year		1989
First year of system operation		1990

3.1 AQUACOOOL

A computer spreadsheet model called AQUACOOOL was developed for this study to estimate the initial capital and annually recurring costs of chill ATES systems providing chilled water for space or process cooling. AQUACOOOL was developed from the results of previous chill ATES computer simulations generated by the computer model AQUASTOR (Brown 1983). AQUASTOR can simulate ATES district heating systems using stored hot water or ATES district cooling systems using stored chilled water. The model simulates the technical design and cash flows associated with exploration, development, and operation of

ATES supply and distribution systems. AQUASTOR is described in detail in Huber, Brown, and Reilly (1982). AQUACOOL was developed in preference to using AQUASTOR primarily because the latter had not been maintained for immediate use and a significant investment would have been required to make it available. In addition, the AQUACOOL spreadsheet operates quickly and easily with adequate accuracy for conducting preliminary feasibility studies. A sample of the input and output sections of the AQUACOOL spreadsheet is shown in Figure 3.1.

Two modeling approaches were considered for developing AQUACOOL. The first alternative was to develop a correlation of cost for each chill ATES system component as a function of all of the design variables via a multivariable regression analysis. The second alternative was to develop correlations of relative cost for each chill ATES system component (relative to the cost for a specified baseline design condition) as a function of the individual design variables, one at a time. The second alternative was chosen because the multivariable approach would be considerably more difficult to apply and, given the limited, non-random sample data set available for regression analysis, would not likely produce more reliable cost predictions.

For the approach chosen, the combined impact on a cost component of changing two or more design variables at the same time was estimated by multiplying the individual adjustment factors. The general relationship is shown in Equation (3.1):

$$\text{Adjusted Cost} = \text{Base Cost} * (F1 * F2 * \dots * F14)^x \quad (3.1)$$

Each cost component has 14 adjustment factors corresponding to 14 individual design and cost variables. The value of "x" in Equation (3.1) was initially set at 1.0 and then adjusted during calibration procedures.

Initial capital and annually recurring costs originally estimated by AQUASTOR were recorded as a function of alternative values for 14 design variables. Individual cost components are shown in Table 3.2. Individual design variables with corresponding ranges of values and reference system values are identified in Table 3.3. Normalized component costs were

AQUACCOOL VERSION 1.1 - April 25, 1991

SYSTEM DESCRIPTION INPUTS

Source temperature	1.7 to 7.2°C (35 to 45°F)
System peak thermal load	1 to 50 MWt
Single well maximum flow rate	23 to 230 Mg/hr
Well life	2 to 30 yr
System thermal load factor	0.1 to 0.4
Total transmission piping length	2000 to 40000 m
Well cost	6 to 60 \$/m
Electricity cost	2 to 15 cents/kWh
Load reject temperature	13 to 18°C (55 to 65°F)
Well depth	60 to 460 m
Aquifer thermal efficiency	63 to 90%
Source availability	60 to 120 days
Well spacing	2 to 10 hectares
User heat exchanger	0 = no; 1 = yes

Regression equations were developed based on cost data covering the variable ranges indicated. Extrapolate at your own risk.

Input well cost and electricity cost in current year dollars.

CHEMICAL ENGINEERING PLANT COST INDICES

	Reference Date Jan 1980	Current Date Jan 1989
Heat exchangers and tanks	274.9	368.0
Pipes, valves, and fittings	317.6	458.1
Engineering and supervision	204.3	342.6

SYSTEM COST SUMMARY

INITIAL COSTS	ANNUAL COSTS
Site exploration	Wells
Heat exchangers	Pumps, piping, and heat exchangers
Transmission piping	Electricity
Wells	Overhead
Wellfield pumps and piping	
Distribution piping	
Total Initial Costs	Total Annual Costs

FIGURE 3.1. Sample of AQUACCOOL Spreadsheet

TABLE 3.2. Cost Components

<u>Initial Capital</u>	<u>Annually Recurring</u>
Site exploration	Well maintenance
Heat exchangers	Piping maintenance
Transmission piping	Pump maintenance
Wells	Heat exchanger maintenance
Well field piping	Pumping electricity
Pumps	Overhead

TABLE 3.3. Design Variables

<u>Variable</u>	<u>Reference Value</u>	<u>Range of Values</u>
Source temperature	4.4°C	1.7 to 7.2°C
Peak thermal load	5 Mwt	1 to 50 Mwt
User heat exchanger	yes	yes or no
Annual load factor	0.25	0.10 to 0.40
Well depth	122 m	60 to 460 m
Well life	30 yr	2 to 30 yr
Well flow rate	68 Mg/hr	23 to 230 Mg/hr
Source availability	90 days	60 to 120 days
Thermal efficiency	90%	63 to 90%
Load reject temperature	15.6°C	13 to 18°C
Electricity cost	\$0.05/kWh	\$0.02 to \$0.15/kWh
Well cost	\$330/m	\$6 to \$60/m
Transmission distance	6000 m	2000 to 40000 m
Well spacing	10 hectares	2 to 10 hectares

calculated by dividing the actual component cost for each design variable value by the component cost for the reference design variable value. This established the adjustment factor for discrete values of individual design variables. Regression analysis was used to develop functional relationships defining the adjustment factor for each cost component and design variable combination. Individual adjustment factors were combined for each cost component, as shown in Equation (3.1).

After assembling the combined cost adjustment equations for each cost component, costs estimated by the trial AQUACOOL model were compared to costs predicted by AQUASTOR for 20 simulation cases not used in developing the cost adjustment factors. Statistics summarizing the comparison of AQUACOOL and AQUASTOR predicted costs are presented in Table 3.4. The results of the comparison indicated that AQUACOOL was adequately matching AQUASTOR predictions for annually recurring costs, but consistently overestimated initial capital costs. Therefore, the initial capital cost equations in AQUACOOL were modified to bring estimated costs in line with AQUASTOR results.

The costs estimated by AQUASTOR/AQUACOOL are for a complete, installed system. Direct material and construction costs, indirect construction costs, and construction contingency are included. Annually recurring costs include an allowance for overhead in addition to direct operating and maintenance costs. Costs originally estimated in 1980 dollars by AQUASTOR were updated to a user-specified year using Chemical Engineering Plant Cost Indices published monthly in Chemical Engineering. Costs estimated by AQUACOOL were separately adjusted to reflect changes in fundamental design assumptions incorporated in the original AQUASTOR simulations. This included the substitution of non-insulated PVC pipe for insulated steel pipe and the use of plate-and-frame heat exchangers instead of shell-and-tube heat exchangers.

TABLE 3.4. Calibration Statistics

<u>Ratio</u>	<u>AQUACOOL/AQUASTOR Initial Capital Cost Ratio</u>	<u>AQUACOOL/AQUASTOR Annually Recurring Cost</u>
Average	1.069	1.007
Minimum	0.971	0.878
Maximum	1.190	1.148
Standard deviation	0.051	0.082
Variance	0.003	0.007

3.2 PRELIMINARY FEASIBILITY STUDIES

Three site-specific preliminary feasibility studies were conducted. The primary objective of the studies was to determine the technical and economic feasibility of implementing chill ATES technology at the three locations. If the preliminary feasibility studies showed promise, more detailed feasibility studies, allowing an implementation decision, would be recommended. A secondary objective was to identify site-specific factors promoting or inhibiting the application of chill ATES technology so that other potentially attractive sites could be more easily identified and evaluated and R&D initiated to reduce the impact of inhibiting factors.

3.2.1 The Sandusky Plant

The feasibility study investigated storing chilled water in an ATES system for subsequent application to process and/or space cooling loads. Six cooling systems were evaluated. Four systems used chill ATES in various modes. One non-ATES storage system and one non-storage system were also evaluated for comparison. Each of the six systems is described briefly below.

- Seasonal ATES. A seasonal ATES system supplies chilled water to meet all of the space and process cooling loads for the months of April through November. No conventional chillers are used in this system. Water withdrawn from supply wells is cooled by quarry water during the winter to approximately 5.6°C (42°F) and then injected into storage wells. From April through November, water is withdrawn from the storage wells on demand to meet space and process cooling loads.
- Diurnal ATES. A diurnal ATES system serves as a daily chilled water storage "tank." On the peak cooling demand day of the year, conventional chillers operate continuously at their maximum capacity. Water withdrawn from supply wells is cooled by excess chiller capacity during the first part of the day and injected into storage wells. In the afternoon, chilled water withdrawn from the storage wells is used to supplement the chiller capacity to meet the total process and space cooling load. Lesser amounts of water are chilled and stored in the ATES system on non-peak days.
- Process ATES. A process ATES system supplies chilled water to meet all of the process cooling load for the months of April through November. Water withdrawn from supply wells is cooled by quarry water during the winter to approximately 5.6°C (42°F) and then injected into storage wells. From April through November, water is withdrawn from the storage wells on demand to meet the process cooling load. The space cooling load is met by conventional load-following chillers.

- Seasonal/Diurnal ATES. A seasonal/diurnal ATES system supplies chilled water to meet all of the space and process cooling loads occurring during peak hours for the months of April through November. Conventional chillers serve the off-peak cooling loads. Water withdrawn from supply wells is cooled by excess chiller capacity during off-peak hours and injected into storage wells. During peak hours from April through November, chilled water withdrawn from the storage wells is used to meet the total process and space cooling load.
- Diurnal Salt Thermal Energy Storage (TES). A diurnal eutectic salt TES system provides daily chill storage capacity. On the peak cooling demand day of the year, conventional chillers operate continuously at their maximum capacity. Water cooled by excess chiller capacity during the first part of the day is used to freeze the eutectic salt. In the afternoon, warm water cooled by melting the eutectic salt is used to supplement the chiller capacity to meet the total process and space cooling load. On non-peak days the eutectic salt TES system is less than fully charged.
- Load-Following Chillers. As the name suggests, this system consists of conventional chillers that operate in a load-following mode to meet the total process and space cooling load without any seasonal or diurnal storage augmentation. Load-following chillers were considered to be the reference case.

Design, cost, and performance characterizations for non-ATES systems and components were acquired from data presented in a proprietary feasibility study of diurnal eutectic salt TES prepared for Ford Sandusky by Transphase Systems, Inc.^(a) and from written and oral communications with Mr. Bob Gulas and Mr. Dick Smith of Ford Sandusky. Chill ATES system design, cost, and performance assumptions were specified by PNL, as were the financial assumptions required to complete the economic analysis.

Most of the key chill ATES modeling assumptions were based on conditions actually known to exist at the Sandusky plant. These include the maximum flow rate per well, well cost, well depth, cooling source water temperature, and the distance between the cooling source and the central cooling water distribution point. Another key variable, the aquifer thermal recovery efficiency, was assumed to be 90% for the purposes of conducting the comparative economic analyses. The probability of achieving this level of efficiency is discussed separately below. Key design and cost attributes at the Sandusky plant are summarized in Table 3.5.

(a) Transphase Systems Inc., Huntington Beach, California.

TABLE 3.5. Sandusky Plant Design Conditions

<u>Design Variables</u>	<u>Value</u>
Source temperature	4.4°C
Source availability	90 days
Peak thermal load	
process cooling	5.14 MWt
space cooling	13.94 MWt
Annual thermal load factor	0.219
Transmission piping length	
Seasonal ATES	1900 m
Diurnal ATES	200 m
Electricity cost (effective)	\$0.045/kWh
Load reject temperature	15°C
Thermal efficiency	90%
User heat exchanger	no
Well spacing	2 hectares
Well depth	114 m
Well cost	\$88/m
Well flow rate	91 Mg/hr
Well life	30 yr

Initial calculations indicated that diurnal ATES and diurnal salt TES systems would be competitive with load-following chillers; hence, these systems were evaluated in more detail. A seasonal ATES system was also evaluated for comparison. Sensitivity analyses were conducted for the ATES system cooling water reject temperature and load-following chiller system electricity cost escalation rate. Initial capital and annually recurring cost estimates for each of the cooling systems evaluated are summarized in Table 3.6.

The levelized energy cost results, presented in Tables 3.7, 3.8, and 3.9, indicate that diurnal ATES would be a strong competitor to load-following chillers at higher cooling water reject temperatures and would have a significant advantage over load-following chillers if electricity costs were to escalate at 2% or more per year in excess of general inflation. The seasonal

TABLE 3.6. Sandusky Plant System Cost Estimates

System	Initial Capital Costs (1000s of 1989 \$)			1st Year Operation Maintenance Costs (1000s of 1989 \$)	
	ATES	Chiller	Salt TES	Electricity	Other
Seasonal ATES, 15°C reject temperature	7265	-	-	290	649
Seasonal ATES, 18°C reject temperature	5267	-	-	208	488
Seasonal ATES, 21°C reject temperature	4265	-	-	161	397
Load-following chiller	-	2062	-	567	165
Diurnal salt TES	-	1602	1536	436	251
Diurnal ATES, 15°C reject temperature	1178	1602	-	502	249
Diurnal ATES, 18°C reject temperature	823	1602	-	483	212
Diurnal ATES, 21°C reject temperature	633	1602	-	473	190

Note: Chiller system energy consumption for load-following chiller, diurnal salt TES, and diurnal ATES systems = 7.11×10^{-5} kWh per kJ of cooling, i.e., coefficient of performance = 3.91.

**TABLE 3.7. Reference Cooling System Levelized
Energy Costs**

System	LEC
Seasonal ATES	\$13.40
Diurnal ATES	\$8.10
Diurnal salt TES	\$8.00
Load-following chillers	\$7.30

Notes: Levelized energy costs in 1989 \$/10⁶ kJ
Cooling water reject temperature = 15°C
Electricity cost real escalation rate = 0%/yr

TABLE 3.8. Alternative ATES System Levelized Energy Costs

<u>Cooling Water Reject Temperature</u>	<u>Seasonal ATES LEC</u>	<u>Diurnal ATES LEC</u>
15°C	\$13.40	\$8.10
18°C	\$9.80	\$7.40
21°C	\$7.90	\$6.90

Notes: Levelized energy costs in 1989 $\$/10^6$ kJ
Electricity cost real escalation rate = 0%/yr

**TABLE 3.9. Alternative Load-Following Chiller
Levelized Energy Costs**

<u>Electricity Cost Real Escalation Rate</u>	<u>LEC</u>
0%/yr	\$7.30
2%/yr	\$8.20
4%/yr	\$9.20
6%/yr	\$10.50

Note: Levelized energy costs in 1989 $\$/10^6$ kJ

ATES system is projected to be less attractive than diurnal ATES, but would also have a significant advantage over load-following chillers if higher reject temperatures were allowed and if higher electricity cost escalation rates were expected. On the other hand, if future electricity costs are projected to escalate at the rate of general inflation and the design cooling water reject temperature is fixed at 15°C (59°F), the seasonal ATES system looks unattractive while the two diurnal storage systems show no competitive advantage over load-following chillers. Note that given the level of uncertainty in the analysis, the projected levelized energy costs (in Table 3.7) for the two diurnal systems and the load-following chiller system should be considered equal.

In the first sensitivity case, the cooling water reject temperature was allowed to increase from the reference condition of 15°C (59°F) to 18°C (65°F) and 21°C (70°F). The levelized energy cost results shown in Table 3.8

demonstrate how dramatically chill ATES system costs are reduced if higher cooling water reject temperatures are allowed. The significant savings are attributable to an increase in the energy density per unit of water, which reduces the size and cost of ATES equipment while meeting the same thermal load. Increasing the cooling water reject temperature would require additional heat transfer area in the space and process cooling heat exchangers, but would also reduce cooling water distribution piping and pumping costs. These cost effects were not included in this evaluation. Increasing the cooling water reject temperature would probably be most effectively implemented for process cooling where the reduction in heat exchanger approach temperature and increased heat transfer area requirements would be relatively minor compared to the space cooling application.

The second sensitivity analysis examined the impact of various electricity cost escalation rates on the levelized energy cost of load-following chillers. For the reference calculations, the cost of electricity was assumed to escalate at the rate of general inflation, i.e., 0%/year in real terms. The cost of electricity represents more than one-half of the total levelized energy cost for load-following chillers, so increases in the expected future cost of electricity have a dramatic impact on the levelized energy cost of this technology, as shown in Table 3.9. Higher future electricity costs would not have nearly the impact on the levelized energy cost of a seasonal ATES system, which uses less electricity, but is more capital-intensive.

The levelized energy cost calculations described above were based on an assumed aquifer thermal efficiency of 90%. At this efficiency and a natural aquifer temperature of 13°C (55°F), water injected at a temperature of 5.6°C (42°F) should be recoverable at 6.1°C to 6.7°C (43°F to 44°F). A separate evaluation of the geohydrology at the Sandusky plant indicates that a high thermal efficiency is unlikely. Although the well flow rates (1.5 m³/min) are adequate to support a chill ATES system, the limestone formations underground are not conducive to a thermally efficient chill ATES system. Water injected into this type of formation would not usually be retrieved without significant mixing with the natural groundwater, which would degrade the recovery temperature. However, it should be noted that site testing would have to be

conducted to confirm or replicate this expectation. In addition, conditions instigating mixing are less detrimental to diurnal storage than seasonal storage.

3.2.2 The Dayton Plant

The feasibility study investigated storing chilled water in ATES systems for subsequent application to a space cooling load. Each ATES system supplies chilled water to meet all of the space cooling load in the Dayton plant's administration and engineering building. Water withdrawn from supply wells is cooled by passing through an evaporative cooling tower or by heat exchange with onsite lake water. Onsite and nearby offsite aquifers were considered, as were alternative assumptions regarding cooling source temperature, storage injection period, and well flow rates. Thus, 16 different chill ATES systems were evaluated, representing unique combinations of the variables summarized in Table 3.10. A conventional load-following, electrically-driven chiller system was also evaluated to establish a reference for comparison. Both new construction and continued operation scenarios were evaluated for the chiller system at future real electricity cost escalation rates ranging from 0 to 6%/year.

Site-specific design information was acquired via written and oral communications with Mr. Art Collins of Delco. Cost and performance assumptions were specified by PNL, as were the financial assumptions required to complete the economic analysis. Most of the key modeling assumptions were based on conditions actually known to exist at the Dayton plant. These include local

TABLE 3.10. ATES System Variables for the Dayton Plant

- Onsite or offsite aquifer
- Cooling tower or natural lake cooling source
- 1.7°C (35°F) chilling source for a 70-day storage period or 4.4°C (40°F) chilling source for a 100-day storage period
- 0.13 or 0.289 m³/min per onsite well
- 0.38 or 1.9 m³/min per offsite well

climatic conditions; peak hourly and annual cooling loads; maximum flow rate per well; well cost; well depth; distances between the Administration and Engineering Building and the offsite aquifer and onsite pond; cooling water reject temperature; and electricity cost. Two other key variables, aquifer thermal recovery efficiency and well spacing, were assumed to be 90% and 500 ft, respectively. These assumptions are reasonable to make for a preliminary feasibility study, but would have to be confirmed by further analysis of the site geohydrology as part of a more detailed feasibility study. Key design and cost attributes at the Dayton plant are summarized in Table 3.11. Initial capital and annually recurring cost estimates for each of the cooling systems evaluated are summarized in Table 3.12.

The levelized energy cost results, presented in Tables 3.13 and 3.14, indicate that a seasonal chill ATES system with wells located in an offsite aquifer could be economically competitive with a conventional chiller system. The levelized energy costs shown for the conventional chiller systems are probably understated because the evaluation of both chill ATES and chiller systems was based on an overall average cost of electricity per kWh, rather than explicitly evaluating the demand and energy charge components. Chiller energy consumption is concentrated during the peak demand period of the day and would likely result in a higher average cost of electricity per kWh than the energy demand profile for the chill ATES system. A more detailed examination of electricity consumption and cost, and consideration of diurnal energy storage systems would be warranted, but Delco indicated they did not want to pursue an offsite aquifer location and the onsite aquifer well productivity is too poor for chill ATES to be economically attractive (as shown in Table 3.13).

The results shown in Table 3.13 highlight the importance of having productive wells. The levelized energy cost varies by about a factor of four between the best and worst systems, with well productivity being the key distinguishing factor. In fact, the offsite systems show significantly better economics because of higher well flow rates despite having much greater transport piping costs.

TABLE 3.11. Dayton Plant Design Conditions

<u>Design Variables</u>	<u>Values</u>
Source temperature	1.7°C or 4.4°C (35°F or 40°F)
Source availability	70 or 100 days
Peak thermal load	3.34 MWt
Annual thermal load factor	0.30
Transmission piping length	
onsite aquifer, cooling tower	200 m
onsite aquifer, lake water	1700 m
offsite aquifer, cooling tower	3300 m
offsite aquifer, lake water	4900 m
Electricity cost (effective)	\$0.045/kWh
Load reject temperature	15.6°C (60°F)
Thermal efficiency	90%
User heat exchanger	no
Well spacing	2 hectares
Well depth	35 m onsite 11 m offsite
Well cost	\$236/m onsite \$394/m offsite
Well flow rate	7.9 or 17 Mg/hr onsite 23 or 113 Mg/hr offsite
Well life	30 yr

Operating with a 1.7°C (35°F) chilling source and a 70-day storage period appears to be slightly preferred over having a 4.4°C (40°F) source and 100-day storage period. Two opposing effects are at work here. A cooler storage temperature increases the chilling capacity per unit of water, thus reducing the total amount of water that must be stored and the size and cost of equipment, all else equal. However, the shorter storage period increases the water flow rate and the size and cost of equipment, all else equal. Transportation distances, well flow rates, and well costs, among other factors, affect this tradeoff.

TABLE 3.12. Dayton Plant System Cost Estimates

Aquifer Location	Cooling Source	Source Conditions	Flow Rate per Well m ³ /minute	Initial Capital (a)	1st Year Operation and Maintenance (a)	
					Electricity	Other
Onsite	Tower ^(b)	1.7°C @ 70 days	0.13	5586	36	438
Onsite	Tower	1.7°C @ 70 days	0.28	3118	34	281
Onsite	Tower	4.4°C @ 100 days	0.13	6057	45	457
Onsite	Tower	4.4°C @ 100 days	0.28	3372	43	293
Onsite	Lake	1.7°C @ 70 days	0.13	6350	37	483
Onsite	Lake	1.7°C @ 70 days	0.28	3881	35	322
Onsite	Lake	4.4°C @ 100 days	0.13	6719	46	504
Onsite	Lake	4.4°C @ 100 days	0.28	4034	44	332
Offsite	Tower	1.7°C @ 70 days	0.38	2892	29	283
Offsite	Tower	1.7°C @ 70 days	1.9	1342	25	131
Offsite	Tower	4.4°C @ 100 days	0.38	3121	36	296
Offsite	Tower	4.4°C @ 100 days	1.9	1439	32	135
Offsite	Lake	1.7°C @ 70 days	0.38	3670	29	327
Offsite	Lake	1.7°C @ 70 days	1.9	2120	26	161
Offsite	Lake	4.4°C @ 100 days	0.38	3800	37	335
Offsite	Lake	4.4°C @ 100 days	1.9	2118	33	162
Continued Operation of Current Chiller System				0	126	38
Purchase and Operation of a New Chiller System				475	94	38

(a) 1000s of 1989 \$

(b) The costs for the cooling tower cases are based on using an existing tower to cool aquifer water in the winter. Purchasing a new tower would add from \$175,000 to \$250,000 to the initial cost.

Cooling the aquifer water in an evaporative cooling tower was found to be less expensive than cooling with lake water in a shell-and-tube or plate-and-frame heat exchanger. Using a cooling tower avoids the cost of piping to and from the lake and the cooling tower alone is not expected to cost more than a heat exchanger. However, freezing water could create operational problems for the cooling tower.

The results presented in Table 3.14 show the impact of various electricity cost escalation rates on the LEC of load-following chillers for continued operation or replacement (new construction) of the current equipment. The cost of electricity represents more than one-half of the total

TABLE 3.13. Levelized Energy Cost Results - ATEs Systems

<u>Aquifer Location</u>	<u>Cooling Source</u>	<u>Source Temperature, °C</u>	<u>Storage Period, days</u>	<u>Flow Rate per Well, m³/minute</u>	<u>Levelized Energy Cost^(a)</u>
Onsite	Tower ^(b)	1.7	70	0.13	34
Onsite	Tower	1.7	70	0.28	21
Onsite	Tower	4.4	100	0.13	37
Onsite	Tower	4.4	100	0.28	23
Onsite	Lake	1.7	70	0.13	39
Onsite	Lake	1.7	70	0.28	25
Onsite	Lake	4.4	100	0.13	42
Onsite	Lake	4.4	100	0.28	27
Offsite	Tower	1.7	70	0.38	20
Offsite	Tower	1.7	70	1.9	9
Offsite	Tower	4.4	100	0.38	22
Offsite	Tower	4.4	100	1.9	10
Offsite	Lake	1.7	70	0.38	25
Offsite	Lake	1.7	70	1.9	13
Offsite	Lake	4.4	100	0.38	26
Offsite	Lake	4.4	100	1.9	13

(a) Levelized energy costs in 1989 \$/10⁶ kJ.

(b) The levelized energy costs for the cooling tower cases are based on using an existing tower to cool aquifer water in the winter. Purchasing a new tower would add about \$1/10⁶ kJ to the levelized energy cost.

TABLE 3.14. Levelized Energy Cost Results - Chiller Systems^(a,b)

<u>Electricity Cost Real Escalation Rate</u>	<u>Continued Operation</u>	<u>New Construction</u>
0%/yr	5.1	5.9
2%/yr	5.9	6.4
4%/yr	6.8	7.1
6%/yr	8.1	8.1

(a) Levelized energy costs in 1989 \$/10⁶ kJ.

(b) Chiller coefficient of performance (COP) assumed to be 3.0 for continued operation and 4.0 for new construction.

levelized energy cost for load-following chillers, so increases in the expected future cost of electricity have a dramatic impact on the levelized energy cost of this technology. Higher future electricity costs would not have nearly the impact on the levelized energy cost of a full ATES system, which uses less electricity, but is more capital-intensive. The current chillers at the Dayton plant are over 20 years old and were assumed to have a COP of 3.0. Replacement equipment should be able to achieve a COP of about 4.0. Note that a new chiller system could be an attractive option for Delco, especially if electricity costs are expected to escalate in excess of inflation and the actual COP of the current system is less than the assumed value of 3.0.

3.2.3 The Seline Plant

The Seline plant is another Ford facility within their Plastics Division. Ford representatives indicated that the loads at this plant and a nearby plant in Milan were similar to the Sandusky plant and ATES cooling should be considered in Seline and Milan as well. Both plants are located in Southeastern Michigan, about 24 km (15 miles) apart.

Unfortunately, Ford was unable to provide plant-specific data for the Seline or Milan plants. Aquifer characteristics in Seline and Milan were found to be similar and advantageous for ATES development. Wells drilled in a glacial till aquifer formation to a depth of around 38 m (125 ft) could generally be expected to produce 3.8 to 5.3 m³/min (1000 to 1400 gpm), according to Larry Wight of Lane Northern Company, a local well drilling contractor. Mr. Wight indicated that a well of this type could be expected to cost about \$50,000 to drill and develop.

Well depth, flow rate, and cost characteristics identified above for the Seline area were combined with the other design conditions and system cost estimates for the Sandusky plant (see Tables 3.5 and 3.6) to generate a proxy for the Seline plant. The resulting levelized energy costs for seasonal and diurnal ATES systems are shown in Table 3.15.

The data presented in Table 3.15 show that the Seline aquifer conditions result in a 33% reduction in seasonal ATES system costs and a 10% reduction in

diurnal ATES system costs compared to the Sandusky plant (see Table 3.8). Note that the overall cost reduction for the diurnal ATES system is tempered by the inclusion of non-ATES components in its system. Seasonal or diurnal ATES systems at Seline are projected to be less expensive than load-following chillers, except for the seasonal ATES system at a 15°C (59°F) cooling water reject temperature and 0%/year real electricity price escalation rate. Seasonal or diurnal ATES systems show significant advantage over load-following chillers at higher cooling water reject temperatures and/or higher real escalation rates for electricity.

TABLE 3.15. Seline ATES System Levelized Energy Costs

<u>Cooling Water Reject Temperature</u>	<u>Seasonal ATES LEC</u>	<u>Diurnal ATES LEC</u>
15°C	\$8.90	\$7.10
18°C	\$6.70	\$6.60
21°C	\$5.50	\$6.40

Notes: Levelized energy costs in 1989 \$/10⁶ kJ.
Electricity cost real escalation rate = 0%/yr

4.0 CONCLUSIONS AND RECOMMENDATIONS

Site-generic discussion is presented in Section 4.1. Matters specifically pertaining to the preliminary feasibility studies are presented in Sections 4.2, 4.3, and 4.4.

4.1 SITE-GENERIC

Tempering the indoor air within large manufacturing facilities has several attributes that make it especially attractive as a possible application of ATES for space cooling.

1. Space conditioning in a manufacturing environment does not require the strict temperature and humidity control criteria that many commercial cooling applications have. Flexibility in meeting the cooling load removes some of the concern in implementing an innovative cooling technology.
2. The relative large cooling loads associated with such facilities allow reductions in the unit costs of ATES systems via strong economies-of-scale.
3. Tempering conditions substantially improve ATES economics by increasing the amount of cooling that can be accomplished per unit of chilled water supplied to the building cooling water loop.

Tempering is defined here as conditioning indoor air to approximately 50% relative humidity at 27°C (80°F) in contrast to the cooler and less humid conditions usually required in commercial buildings. Air conditioning of large manufacturing facilities is currently atypical of U.S. industrial practice, but may become more common in the future because of 1) concerns for worker comfort, 2) the prospect of improved labor productivity, and/or 3) more restrictive operating requirements for computers and other electronic manufacturing equipment.

The importance of the target cooling conditions (temperature and humidity) for chill ATES application cannot be overemphasized when considering the potential feasibility of a chill ATES system. Process cooling conditions in excess of 40°C (100°F) are usually more economically served by evaporative cooling towers. Typical office environment cooling conditions [low 20s (°C) with low to moderate humidity] require low cooling water loop return

temperatures in humid climates that generally make chill ATES less attractive. In between these two endpoints, cooling with ATES systems should have its greatest competitive advantage.

The availability of a suitable aquifer is an obvious requirement for any ATES system. The economic feasibility of ATES for cooling requires shallow, low-cost, thermally efficient, productive wells. Future feasibility studies should begin by investigating the geohydrologic characteristics of prospective sites because the lack of suitable aquifers is a significant constraint inhibiting implementation of the chill ATES concept.

Constructing a winter cooling mechanism (e.g., evaporative cooling tower, air cooler, spray pond, cooling pond) allows greater siting flexibility, but could be more expensive than using natural sources of winter chill (e.g., lakes, ponds, rivers). The cost and performance of these alternative cooling sources should be investigated for alternative design conditions (e.g., source temperature, source availability, transmission distance, peak thermal load).

Both seasonal and diurnal chill ATES systems should be considered at prospective sites. The best chill ATES system will depend on the prevailing electric rate structure and load profile, as well as local aquifer conditions. Seasonal chill ATES systems could displace all or part of a facility's cooling load, while diurnal chill ATES systems could provide the same service as other diurnal chill storage technologies.

4.2 THE SANDUSKY PLANT

The principal conclusions and recommendations of the preliminary feasibility study of space and process cooling using ATES at the Sandusky plant are summarized below.

1. The geohydrologic characteristics at the Sandusky plant are inadequate for a chill ATES system.
2. Diurnal ATES would be a strong competitor to load-following chillers at cooling water reject temperatures higher than the reference condition [15°C (59°F)] and would have a significant advantage over load-following chillers if electricity costs were to escalate at 2% or more per year in excess of general inflation.

3. Seasonal ATES is projected to be less attractive than diurnal ATES, but would also have a significant advantage over load-following chillers if higher cooling water reject temperatures were allowed and if higher electricity cost escalation rates were expected.
4. None of the alternative systems were projected to have an economic advantage over load-following chillers for the reference study conditions.
5. Future electricity cost escalation in excess of general inflation (assumed equal to general inflation for the reference assumption) makes all storage concepts more attractive and would change the technology rankings if future electricity costs escalated rapidly.
6. Increasing the cooling water reject temperature from 15°C (59°F) to 18°C or 21°C (65°F or 70°F) would likely make chill ATES an attractive option, especially for process cooling, if an appropriate aquifer were available.
7. The geohydrology at other facilities with cooling loads similar to the Sandusky plant should be investigated to identify prospective chill ATES applications.

4.3 THE DAYTON PLANT

The principal conclusions and recommendations of the preliminary feasibility study of space cooling using ATES at the Dayton plant are summarized below.

1. Onsite well productivity is too poor for chill ATES to be economically attractive.
2. If access to an offsite aquifer approximately 1.6 km (1 mile) north of the plant boundary is possible, chill ATES economics become much more attractive and a more detailed analysis of seasonal and diurnal ATES would be warranted.
3. Chill ATES would be more attractive if applied to a facility with a cooling load and cooling water reject temperature higher than required for the Administration and Engineering Building. For example, chill ATES is probably best suited for tempering the indoor air in large production facilities. With a peak load of only 3.34 Mwt, the economies-of-scale available to larger chill ATES systems are not captured in the application evaluated. In addition, the low cooling water reject temperature required for humidity control in an office environment works against chill ATES system economics.
4. Operating with a 1.7°C (35°F) chilling source and a 70-day storage period appears to be slightly preferred over having a 4.4°C (40°F) source and 100-day storage period.

5. Evaporative cooling towers would be preferred to using onsite lake water and a heat exchanger as the means of chilling the aquifer water, provided potential freezing problems in the cooling towers can be avoided.
6. A new chiller system could be an attractive option for Delco, especially if electricity costs are expected to escalate in excess of inflation and the actual COP of the current system is less than the assumed value of 3.0.
7. The geohydrology at other Delco/General Motors' Corporation facilities with large cooling loads should be investigated to identify prospective chill ATES applications.

4.4 THE SELINE PLANT

The principal conclusions and recommendations of the preliminary feasibility study of space and process cooling using ATES at the Seline plant are summarized below.

1. Shallow, productive aquifers in the Seline and Milan, Michigan areas significantly enhance the potential attractiveness of an ATES system.
2. Seasonal or diurnal ATES systems at Seline could be significantly less expensive than load-following chillers, depending on the cooling water reject temperature, future electricity escalation rate, and the similarity of the Sandusky and Seline plants.
3. The preliminary results indicate that further investigation of ATES feasibility based on the actual design conditions at Seline is warranted.

REFERENCES

Brown, D. R. 1983. Aquifer Thermal Energy Storage Costs With a Seasonal Chill Source. PNL-4587, Pacific Northwest Laboratory, Richland, Washington.

Brown, D. R., J. A. Dirks, M. K. Drost, G. E. Spanner, and T. A. Williams. 1987. An Assessment Methodology for Thermal Energy Storage Evaluation. PNL-6372, Pacific Northwest Laboratory, Richland, Washington.

Hattrup, M. P., and R. O. Weijs. 1989. Commercialization of Aquifer Thermal Energy Storage Technology. PNL-6845, Pacific Northwest Laboratory, Richland, Washington.

Huber, H. D., D. R. Brown, and R. W. Reilly. 1982. User Manual for AQUASTOR: A Computer Model for Cost Analysis of Aquifer Thermal Energy Storage Coupled With District Heating or Cooling Systems, Volumes I and II. PNL-4236, Pacific Northwest Laboratory, Richland, Washington.

The Motor Vehicle Manufacturers Association of the United States, Inc. 1988. Information Handbook U.S. Motor Vehicle Manufacturing Facilities. Detroit, Michigan, and Washington, D.C.

APPENDIX

MATERIAL SUPPLIED TO INTERESTED PLANT ENGINEERS

Aquifer Thermal Energy Storage for Space Heating and Cooling

Increase product quality and process and worker productivity using Aquifer Thermal Energy Storage (ATES) to temper industrial work spaces.

Large high bay manufacturing and assembly spaces may be heated or cooled economically by an ATES system using waste heat or stored winter chill. ATES is a method of using groundwater in aquifers to economically store heat or chill for long periods of time. For example, an ATES system could store water chilled during winter until it is withdrawn for space cooling in the summer. Waste heat can also be stored and used later for space or process heating.

The U.S. Department of Energy has conducted an extensive 10-year research program on ATES. These activities have developed ATES to the point where the technology is ready for large-scale demonstration. Research has determined the effect of aquifer geophysical and geochemical characteristics on ATES performance. These studies have also identified the aquifer characteristics required for a successful installation. This information has been incorporated in computer codes developed to evaluate and design aquifer storage systems.

Concept Description

A typical ATES chill storage system uses cold winter conditions to cool aquifer water to near freezing. The cold water is pumped into an underground aquifer. There it is stored until summer, when the cold water is pumped out of the aquifer and used for cooling commercial or industrial buildings. ATES chill could also be used for cooling industrial processes. The water is returned to the aquifer and stored until the next winter when the cycle is repeated.

An ATES heating system works in a similar manner. Waste heat from an industrial process or a solid waste incinerator is used for year-round heating of aquifer water. The hot water is stored in the aquifer until winter, when the water is pumped out of the aquifer and the heat is extracted for space heating. The water is then returned to the aquifer for the next cycle.

Where ATES Works Best

The economics of a specific application depend on local conditions. A number of studies show that ATES can be economically attractive for space heating and cooling of large industrial facilities. Important local factors include the availability and characteristics of an aquifer, the type and quantity of energy needed, the availability of winter chill or waste heat, and the cost of alternative energy sources.

ATES shows most promise for use in larger industrial applications located in these 10 water resource areas of the United States: the mid-Atlantic, the south-Atlantic Gulf, Ohio, the upper and lower Mississippi, North Dakota, the Missouri Basin, Arkansas, the Texas Gulf, and California.

Experimental Results

Aquifer research in the United States has been supplemented by two successful field tests. A test at the University of Minnesota has demonstrated the technical feasibility of using ATES to store high-temperature water (100°C). Energy recovery

efficiencies have consistently exceeded 65%. The second test at the University of Alabama has successfully demonstrated the use of ATES for storing winter chill. The ATES system has provided the complete cooling load for a student recreation center. These installations have demonstrated the basic soundness of the technology.

A new chill storage system has recently been installed at a U.S. Postal Service mail processing center on Long Island, and a new chill ATES system is being designed for space cooling at an automobile manufacturing plant in Alabama. These installations will further demonstrate the soundness of the technology and provide additional information on ATES system operation.

Commercial Use

Additional large-scale demonstrations are needed because larger installations are calculated to show greater savings. Increased demonstration of the economics of the technology will generate greater confidence on the part of potential users and provide valuable information about the operation of ATES systems.

Want More Information?

The success of an ATES application will depend on your local conditions. If you have a potential application for ATES heat or chill storage, we can help you evaluate it and suggest steps you can take to ensure the success of your project.

If you have any questions, please call:

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Preliminary Feasibility Study Data Requirements

1. Cooling Source Temperature or Storage Charging Temperature

2. Cooling Source Availability or Storage Charging Period

These two variables define the average temperature of chilled water injected into the aquifer and the aquifer charging period. The cooling source could be naturally chilled water withdrawn from nearby rivers or lakes. Alternatively, a cooling tower, air cooler, or cooling pond could be used to chill water or another heat transfer fluid (e.g., an ethylene glycol/water mixture). Knowledge of the local climate can allow these two variables to be estimated.

3. System Peak Hourly Thermal Load

4. Annual System Load Factor or Annual System Load

These two variables define the system thermal capacity and annual operating capacity factor. Knowing two of the above three datums defines the third: $\text{annual system load factor} = \text{annual system load} / (\text{system peak hourly thermal load} * 8760 \text{ hours})$.

5. Well Flow Rate

6. Well Life

7. Well Cost

8. Well Depth

The maximum sustainable flow rate from a single well, the expected well life given normal maintenance procedures, the well depth (depth to aquifer plus aquifer thickness), and the total cost (i.e., drilling, casing, well development) of putting in a well with these characteristics must be defined.

9. Transmission Piping Length

Transmission piping runs from the supply wellfield to the cooling source mechanism, from there to the storage wellfield, from there to the interface point with the building cooling water piping system, and from there back to the supply wellfield. These distances will be a function of the physical layout at a particular site. The minimum length of transmission piping is limited by the required separation between the supply and storage wellfields.

10. Electricity Cost

The average effective cost/kWh needs to be estimated in addition to understanding the specific rate structure.

11. Cooling Water or Load Reject Temperature

This is the return temperature in the application cooling water loop, after the cooling water has picked up energy from the space or process being cooled.

12. Aquifer Thermal Efficiency

13. Well Spacing

These two variables are a function of the volume of water injected and the following aquifer-related variables: aquifer thickness, aquifer material, aquifer stratification (the number and type of different layers within the aquifer), and the aquifer regional flow rate. Some of this data may be found in well drillers log books. Standard assumptions can be made where information is lacking.

14. Secondary Heat Exchanger Requirement

A heat exchanger may or may not be required at the interface between the ATES system and the application cooling water piping system. State and local regulations will have to be reviewed to determine if the groundwater can be used directly for cooling or whether the ATES system must be isolated from the cooling water piping system. A related question is whether regulations require water withdrawn from an aquifer to be injected back into the aquifer or sent to a sewer system.

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