Aquifer Thermal Energy Storage Costs With a Seasonal Chill Source

D. R. Brown

January 1983

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

AQUIFER THERMAL ENERGY STORAGE COSTS
WITH A SEASONAL CHILL SOURCE

D. R. Brown

January 1983

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

Seasonal thermal energy storage (STES) involves storing thermal energy, such as winter chill, summer heat, and industrial waste heat, for future use in heating and cooling buildings or industrial processes. Widespread development and implementation of STES would significantly reduce the need to generate primary energy in the U.S. In fact, 1980 data indicate that STES is suitable for providing 5 to 10% of the nation's energy with major contributions in the commercial, industrial, and residential sectors.

Research efforts in STES under Pacific Northwest Laboratory management are underway in two areas: aquifer thermal energy storage (ATES) and STES technology assessment and development (STES/TAD). Aquifer thermal energy storage is predicted to be the most cost-effective technology for seasonal storage of low-grade thermal energy. Approximately 60% of the U.S. is underlain with aquifers potentially suitable for underground energy storage.

A major determinant of ATES commercialization is, of course, its economic feasibility. Studies conducted by the Pacific Northwest Laboratory have sought to determine the economic competitiveness of various ATES configurations with the more conventional heating and cooling technologies. The study described in this report investigated the costs for thermal energy delivered by ATES systems coupled to a seasonal chill source. Life cycle costs are determined for a base system under selected financial conditions. A parametric analysis of ATES system costs is documented for various ATES technical conditions and performance parameters. Results indicate that utilization of ATES as the sole source of chill will be an economic option only under relatively limited conditions. Of course, the economic appeal of ATES for chill will change as financial conditions and energy costs change. Depending on these changes and the characteristics of the application, ATES for chill can be a promising technology for economic conservation of energy.

John R. Raymond
Project Manager
Aquifer Thermal Energy Storage Project

PREFACE

This report serves as a companion document to the results previously presented in Aquifer Thermal Energy Storage Costs With A Seasonal Heat Source (Reilly, Brown, and Huber 1981). The analytical approach taken in this analysis of chill storage in aquifers is essentially the same as that used in the analysis of heat storage in aquifers. Many of the modeling assumptions employed in both chill and heat storage analyses are identical. Changes in modeling assumptions generally reflect the intrinsic differences between heat and chill storage in aquifers. For example, chill storage assumptions for parameters such as supply temperature, aquifer efficiency, and building reject temperature must obviously be different from appropriate assumptions for heat storage. Minimizing the number of changes in assumptions between the two studies should allow for equitable judgments about the relative benefits of heat and chill storage in aquifers. Although comparisons are made in this report between the results of chill and heat storage analyses, the information presented within does not presume prior knowledge of the costs of heat storage in aquifers.

SUMMARY

The cost of energy supplied by an aquifer thermal energy storage (ATES) system from a seasonal chill source was investigated. The work was performed in support of the Underground Energy Storage Program at the Pacific Northwest Laboratory (PNL), under the sponsorship of the Office of Energy Systems Research, U.S. Department of Energy.

Costs were estimated for point demand and residential development ATES systems using the computer code AQUASTOR. AQUASTOR was developed at PNL specifically for the economic analysis of ATES systems. In this analysis the cost effect of varying a wide range of technical and economic parameters was examined. Those parameters exhibiting a substantial influence on the costs of ATES delivered chill were:

- system size
- well flow rate
- transmission distance
- source temperature
- well depth
- cost of capital.

The primary constraint of ATES chill systems is the extremely low energy density of the storage fluid. The energy available for chilling in a pound of 35°F water is approximately 20 Btu, depending on the specific design characteristics of the system. By comparison, the energy available for heating in a pound of 325°F water is approximately 100 Btu, again depending on design conditions. Because of this much lower energy density, equipment for handling the chilled water must be substantially larger to deliver the same amount of energy. This relationship puts a premium on factors affecting wellfield and transmission system design. The cost effects of the parameters identified above are summarized below.

Significant economies-of-scale are available for ATES systems. In fact, fairly large systems are required to approach cost-effectiveness. Costs are fairly constant for peak demands (at 25% load factor) 8 to 10 MW

and larger. Costs rise quickly for systems with peak demands less than 3 to 5 MW. These trends appear to hold regardless of source temperature or system type (point demand or residential district).

Well flow rate has a substantial impact on ATES chill costs. Due to the low energy density of cold water, voluminous amounts of water must be stored in the aquifer. Wellfields can be a substantial portion of ATES chill system capital costs. An increase in well productivity (flow rate) reduces the number of wells and pumps required. Fewer wells mean less interconnecting well manifolding and less pumping energy within the manifolding.

Lengthy transmission distances can quickly result in prohibitive costs, especially for smaller (less than 10 MW) ATES systems. Extensive transmission systems can become a major portion of system capital cost as well as increasing the thermal loss to surroundings. Larger ATES systems are somewhat shielded from these cost effects due to economies-of-scale available in piping systems and a decrease in thermal loss to the surroundings per pound of water transported.

The source temperature deliverable to an ATES system is an important determinant of system economics. A lower source temperature ultimately allows a lower deliverable temperature to the user, with more usable energy per pound of water. This higher energy density allows lower system fluid flow and directly reduces the amount of piping, pumping, and well drilling required. The load reject temperature influences costs in a similar manner. An increase in load reject temperature essentially increases the amount of delivered energy at no increase in cost. The important overall factor, then, is the difference between the maximum usable (reject) temperature and the source temperature.

Well depth can be an important factor in ATES chill system costs. Increasing well depth increases the capital cost of the well and its pump. Electrical energy required to pump water to the surface is also increased. Because the low energy density of chilled water necessitates the transportation and storage of large quantities of water, the cost effect of

well depth is more pronounced than for hot water storage systems. Electrical pumping energy is a significant part of the delivered cost of chill and well pumping is a major portion of the electrical consumption.

Aquifer thermal energy storage systems are generally capital-intensive projects. Thus, the cost of financing is important in determining a system's cost-effectiveness. Municipalities offer financing possibilities at substantially lower interest than is available for private entities. For this reason a municipality can consider a broader range of other system parameters as part of a potentially cost-effective ATES system.

The availability of a suitable aquifer is obviously of prime concern when considering an ATES installation. Potential site-specific availability of aquifers is not addressed here. This analysis assumes a (more or less) suitable aquifer exists and examines the cost effect of a range of possible thermal efficiencies. Aquifer thermal efficiency is an important ATES cost parameter, but no more so than the other parameters noted above.

The cost of ATES-delivered chill for a 5-MW system with a 35°F source temperature was estimated to be \$22.80/MBtu. The comparable cost of chilled water from a compressive chiller device would be \$8.96/MBtu. Both levelized energy costs were calculated based on an electrical energy cost of 5¢/kWh with 1% real escalation per year. As compared to ATES-delivered heat, ATES-delivered chill suffers from two major disadvantages when competing with conventional energy systems. First, the low energy density of the cold water requires an expensive investment to deliver a relatively small amount of energy. Second, the competing technology, electrically driven compressive chillers, is highly efficient. Therefore, cost-effective ATES chill systems will be limited to special situations with design conditions more advantageous than those considered here.

Of the cost components for a 5-MW point demand system with a 35°F source temperature, capital costs dominate. However, O&M and electricity charges are significant portions of the total levelized energy cost. Electricity charges are more important for ATES chill systems than for ATES

heat systems due to the absence of purchased thermal energy costs and the pumping of large quantities of water. As system size increases, the proportion of levelized energy cost attributable to electricity increases because capital equipment shows economies-of-scale, while pumping energy is directly proportional to water flow rate (system size).

ACKNOWLEDGMENTS

The author gratefully acknowledges the considerable contributions of H. D. Huber and R. W. Reilly toward the development of AQUASTOR and its application in the analysis of ATEs systems.

CONTENTS

FOREWORD.	iii
PREFACE	v
SUMMARY	vii
ACKNOWLEDGMENTS	xi
FIGURES	xv
TABLES.	xvi
1.0 INTRODUCTION	1.1
2.0 THE AQUIFER THERMAL ENERGY STORAGE CONCEPT	2.1
2.1 THE TECHNOLOGY.	2.1
2.2 COMPARISON WITH OTHER STORAGE TECHNOLOGIES.	2.3
2.3 POTENTIAL ENERGY SOURCES.	2.4
2.4 POTENTIAL USERS	2.5
2.5 AQUIFER AVAILABILITY.	2.6
2.6 TECHNOLOGY STATUS	2.6
3.0 TECHNICAL APPROACH	3.1
3.1 ECONOMIC METHODOLOGY.	3.1
3.2 THE AQUASTOR CODE	3.2
3.2.1 The Aquifer Storage Submodel	3.3
3.2.2 The Distribution Submodel.	3.4
3.3 TECHNICAL AND ECONOMIC ASSUMPTIONS.	3.5
4.0 POINT DEMAND COST ESTIMATES.	4.1
4.1 BASE CASE RESULTS	4.1
4.2 COMPONENT COST BREAKDOWN.	4.2
4.3 THE COST OF CONVENTIONAL HEAT DELIVERY.	4.4

4.4	PARAMETRIC ANALYSES	4.4
4.4.1	Source Availability.	4.6
4.4.2	Well Parameters.	4.7
4.4.3	Aquifer Parameters	4.10
4.4.4	Demand Parameters.	4.14
4.4.5	Economic Parameters.	4.18
4.5	DISCUSSION.	4.21
5.0	RESIDENTIAL DEVELOPMENT COST ESTIMATES	5.1
5.1	BASE CASE RESULTS	5.2
5.2	DISCUSSION.	5.3
	REFERENCES.	R.1
	APPENDIX - POINT DEMAND ATEs COST ESTIMATES FOR 35°F, 40°F, AND 45°F SOURCES	A.1

FIGURES

2.1	Aquifer Thermal Energy Storage	2.2
4.1	System Modeled by Base Case.	4.1
4.2	Energy Cost as a Function of System Size	4.2
4.3	Component Cost Breakdown for the 35°F, 5-MW System	4.3
4.4	Energy Cost as a Function of Source Availability	4.7
4.5	Energy Cost as a Function of Well Productivity	4.8
4.6	Energy Cost as a Function of Well Cost	4.9
4.7	Energy Cost as a Function of Well Life	4.10
4.8	Energy Cost as a Function of Aquifer Depth, Pumping Charges Excluded	4.11
4.9	Energy Cost as a Function of Aquifer Depth, Pumping Charges Included	4.11
4.10	Energy Cost as a Function of Well Spacing.	4.12
4.11	Energy Cost as a Function of Aquifer Performance	4.15
4.12	Energy Cost as a Function of Demand Load Factor.	4.16
4.13	Energy Cost as a Function of Transmission Distance	4.17
4.14	Energy Cost for a System with No User Heat Exchanger	4.18
4.15	Energy Cost as a Function of Load Reject Temperature	4.19
4.16	Energy Cost as a Function of Cost of Electricity	4.20
4.17	Energy Cost as a Function of Cost of Capital	4.20
5.1	Energy Costs for Minneapolis Residential Developments.	5.2
5.2	Energy Costs for Kansas City Residential Developments.	5.2
5.3	Energy Costs for Fort Worth Residential Developments	5.3
A.1	Energy Cost as a Function of Source Availability	A.1
A.2	Energy Cost as a Function of Well Productivity	A.2

A.3	Energy Cost as a Function of Well Cost	A.3
A.4	Energy Cost as a Function of Well Life	A.4
A.5	Energy Cost as a Function of Aquifer Depth	A.5
A.6	Energy Cost as a Function of Well Spacing.	A.6
A.7	Energy Cost as a Function of Aquifer Performance	A.7
A.8	Energy Cost as a Function of Demand Load Factor.	A.8
A.9	Energy Cost as a Function of Transmission Distance	A.9
A.10	Energy Cost as a Function of Electricity Cost.	A.10
A.11	Energy Cost as a Function of Cost of Capital	A.11
A.12	Energy Cost as a Function of Load Reject Temperature	A.12

TABLES

3.1	Modeling Assumptions for Estimating Aquifer Chill Storage Costs.	3.6
3.2	Cost Ranges for Selected Elements of ATES Systems.	3.7
4.1	Modeling Assumptions for Low Cost ATES Chill System.	4.5

AQUIFER THERMAL ENERGY STORAGE COSTS WITH A SEASONAL CHILL SOURCE

1.0 INTRODUCTION

Seasonal storage of thermal energy in aquifers has the potential to make a significant contribution toward national energy conservation and fuel substitution goals. Aquifer thermal energy storage (ATES) can increase the overall thermodynamic efficiency of energy generation, while enabling waste heat and energies of opportunity to be substituted for scarce, costly fuels such as oil and natural gas.

The work described in this report was performed in support of the Underground Energy Storage Program at the Pacific Northwest Laboratory (PNL), the U.S. Department of Energy (DOE) lead laboratory for underground energy storage research and development. Funding was provided by DOE's Office of Energy Systems Research.

This report provides cost estimates for thermal energy delivered by aquifer thermal energy storage (ATES) systems coupled to a seasonal chill source. This work parallels a previous investigation (Reilly, Brown, and Huber 1981) in which the cost of ATES-delivered heat was estimated. No critical differences exist between the ATES concept applied with chill and the ATES concept applied with heat.

This report focuses solely upon economic assessment. Technical feasibility and institutional issues are not included here, but are treated in other publications issued by the Underground Energy Storage Program.

Section 2 provides background information on the ATES concept from the general perspective of either heat or chill storage. The ATES technology is described and compared with other storage technologies. Potential energy sources and end users are discussed. Readers already familiar with the concept may wish to proceed immediately to Section 3, which specifically addresses the technical approach used to analyze chill storage in aquifers. Here, the economic methodology, computer code, and technical and economic assumptions employed to estimate the costs are documented.

The resulting point demand cost estimates are presented in Section 4. The cost estimates for the residential developments studied are discussed in Section 5. The Appendix graphically documents all point demand cost estimates for all the source temperatures analyzed in this investigation.

2.0 THE AQUIFER THERMAL ENERGY STORAGE CONCEPT

This section presents a generalized description of the ATES concept. The technology is described and compared with other seasonal storage technologies. Potential energy sources and users are discussed, as is the current status of ATES development.

2.1 THE TECHNOLOGY

An ATES installation in its simplest form is composed of a pair of ordinary water wells drilled into an aquifer (Figure 2.1). During operation, the ground water is withdrawn from the supply well, heated (or chilled) in a heat exchanger, and then returned to the same aquifer through the storage well. (The two wells are horizontally separated to ensure that the storage bubble is unaffected by operations at the supply well.) Thermal energy is stored in the aquifer until needed. At recovery the storage well is pumped and the hot (or chilled) water is circulated through a heat exchanger to recapture the stored energy and then returned to the aquifer through the supply well. The thermal energy can then be employed for space or process heating (cooling), thus reducing the need to generate primary energy. The concept is simple and relatively efficient.

As with other energy storage technologies, ATES is characterized by a net energy loss. Depending upon system design and aquifer characteristics, only approximately 50% to 90% of the input energy can be recovered for beneficial use. The remainder is dissipated to the surroundings.

The key to ATES effectiveness is that the recovered energy is energy that would have been wasted or unavailable without seasonal storage, generally because no demand existed for it at the time of availability. This mismatch of energy supply and demand over time is the pervasive condition that makes ATES attractive.

SEASONAL THERMAL ENERGY STORAGE

FIGURE 2.1. Aquifer Thermal Energy Storage

2.2 COMPARISON WITH OTHER STORAGE TECHNOLOGIES

Aquifer thermal energy storage is only one of many seasonal storage concepts under investigation. Under certain conditions ATES appears to be competitive with, and probably superior to, other modes of long-term thermal storage. The merits of ATES are identified below.

- Storage costs are not directly related to the total amount of energy stored because use of the aquifer is essentially free. Rather, storage costs are proportional to the rate of energy storage or retrieval. The rate of water injection and withdrawal determines the number of wells, and well-related costs constitute the largest portion of the capital cost for a typical ATES installation.
- Energy is stored as heat or chill. Most waste energy and energies of opportunity exist in this same form of thermal energy, and many of the ultimate uses for the stored energy are in the form of heat or chill. Avoiding a transformation between energy forms (such as from thermal to electrical and back to thermal) eliminates the losses inherent in such transformations.
- Water is an inexpensive, widely available storage medium with a very high heat capacity. It is safe, and the technologies for its control are well developed.
- The water is not consumed by the storage process, but instead is available for continuous cycling (or for other uses).
- Aquifers provide natural thermal insulation.
- Aquifers provide safe containment for high-temperature, pressurized water.
- Aquifers are readily available throughout most of the U.S.
- Short-term storage cycles may readily be superposed over the seasonal cycle. This characteristic makes ATES very flexible and suitable for a wide range of applications.

2.3 POTENTIAL ENERGY SOURCES

Aquifer thermal energy storage, like any storage technology, can be effective only if a relatively inexpensive source of energy is available. In general, three major sources of thermal energy will be available for storage: cogenerated heat, climate-related energy, and industrial waste heat.

Cogeneration is the simultaneous production of electricity and heat in the same facility, generally in constant proportions. It is a desirable mode of energy production because of its high efficiency: approximately 85% of the fuel's energy content is made available as electricity and hot water, as compared to an overall generation efficiency of roughly 33% in conventional electric plants. Despite this gain in efficiency, cogeneration is not widely practiced because the heat is generated according to electrical demand (electricity is usually the primary product), which seldom coincides with the demand for heat. Hence, there is the continuous problem of too little or too much heat to meet the demand, making the technology impractical for many applications. The availability of an efficient form of long-term storage for large amounts of heat (such as ATEs) can make cogeneration attractive for many uses. Even if a storage efficiency of only 60% is available, the overall efficiency of the cogeneration/storage installation would be approximately 60%, a considerable improvement over conventional modes of power generation (Meyer, Housz, Ayres, and Ingram 1977).

The second class of mismatched supply and demand is the use of climate energies of opportunity for heating and cooling buildings. Winter chill is readily available in the form of snow, cold air, or cold surface water. Seasonal storage can make this energy available for summer air conditioning. Likewise, summer heat can be captured for winter heating. In higher latitudes, where winter daylight is limited in duration and intensity, seasonal storage provides the only means of employing solar energy for significant amounts of space heating. In lower latitudes it may

facilitate the cost-effective use of solar energy by reducing or eliminating backup systems normally required for solar installations.

Industrial waste heat is the third class of energy that is available for seasonal storage utilization. Seasonal storage of this year-round supply would extend its possible applications, and simultaneously reduce the need for expensive heat dissipation equipment at the plant site.

2.4 POTENTIAL USERS

The market for thermal energy withdrawn from ATES systems is extensive, limited only by the economics of application. The market falls naturally into two segments: space heating and cooling and industrial process heat. Total national energy consumption in 1981 was 73.9 quads. Space heating and cooling of residential and commercial sectors (including hot water for sanitary purposes) accounted for approximately 25% of total consumption, or 18.5 quads. Process steam and direct heat in the industrial sector represents roughly 20% of the total, or 14.8 quads.

Various investigations estimate that up to 55% of the nation's space heating and cooling demand could be economically provided by conventional hot water district heating/cooling systems (Karkheck, Powell, and Beardsworth 1977). It is unclear how many existing installations could benefit from the added reliability and reduced system cost offered by ATES systems, but it is likely that this number is significant. It is estimated that up to 10% of the nation's total energy consumption could be provided by ATES process heat systems, based on technical evaluations (Intertechnology Corporation 1977). Finally, agriculture and aquaculture appear to hold unlimited potential for the utilization of waste heat, at least from a technical viewpoint. Numerous pilot operations have demonstrated the ability of properly applied waste heat to increase the yield of existing crops and to enable cultivation of crops in areas previously too cold for those particular crops. A cost-effective operation for agriculture using seasonally-stored energy remains to be demonstrated.

2.5 AQUIFER AVAILABILITY

One factor governing market penetration for ATES will be the availability of a suitable aquifer. In general, this will not seriously constrain ATES on a national basis, because roughly two-thirds of the U.S. is underlain by aquifers (Meyer 1977). However, not all aquifers are compatible with ATES technology; each potential installation will need to demonstrate the existence of a suitable geologic formation.

2.6 TECHNOLOGY STATUS

The U.S. Department of Energy, Office of Energy Systems Research, under the Thermal and Mechanical Energy Storage Program, maintains an ambitious research program to facilitate the development of the ATES concept. The Pacific Northwest Laboratory, operated for DOE by Battelle Memorial Institute, is the lead laboratory for ATES research. At PNL, the Underground Energy Storage (UES) Program has undertaken a wide range of investigations aimed at developing the ATES concept. These activities include field test facilities to investigate the response of aquifer systems to hot water injection, mathematical modeling of aquifer storage systems, environmental and institutional assessment of the ATES technologies, and economic assessment. Additionally, a number of ancillary activities have been undertaken to support the technology, including development of an extensive library on ATES and related technologies.

3.0 TECHNICAL APPROACH

The purpose of this report is to provide cost estimates for thermal energy delivered by aquifer thermal energy storage systems coupled to a seasonal chill source. The most important factors contributing to the cost of ATEs were identified and the effect of these parameters on cost was then assessed through a systematic sensitivity analysis. Two types of loads were investigated: point demands and residential developments. The point demand investigation estimated the cost of ATEs-supplied process chill for an industrial user, or space conditioning chill for an entity with an existing chilled water distribution system, such as an airport or university. The residential systems investigated were homogeneous developments of either single-family homes or garden apartment buildings, evaluated under three climatic conditions: 1) a Minneapolis, Minnesota climate with 35°F water available for 120 days per year, 2) a Kansas City, Missouri climate with 40°F water available for 90 days per year, and 3) a Fort Worth, Texas climate with 45°F water available for 60 days per year.

3.1 ECONOMIC METHODOLOGY

The figure of merit for this cost analysis is the unit cost of delivered energy, expressed in dollars per million British thermal units (\$/MBtu). This cost is the price that must be charged to the end user to recover all costs of production, including capital investment, operating expenses, and taxes, as well as a specified rate of return on investment. This unit cost can be directly compared to a per-unit cost of chill delivery from more conventional sources such as electrically driven compressive chillers.

The unit cost of energy developed is a levelized cost, expressed in constant 1980 price levels. It was calculated in a discounted cash flow analysis, using the basic equation presented below. The complete life cycle of the ATEs system was considered in the analysis, including aquifer exploration, storage and transmission systems installation, and a 30-year operating life.

$$\$/\text{MBtu} = \frac{\sum_{n=1,ny} [(Pw_n)(C_n + E_n + T_n)]}{\sum_{n=1,ny} [(Pw_n)(Btu_n)]}$$

where $\$/\text{MBtu}$ = levelized unit cost of energy

ny = operating life

Pw_n = present worth factor for year n

C_n = capital expenditures in year n

E_n = expenses in year n

T_n = taxes paid in year n

Btu_n = energy sold in year n .

System design, cost estimation, cash flow analysis, and calculation of the levelized cost of energy delivery were all performed through use of a technoeconomic computer code called AQUASTOR.

3.2 THE AQUASTOR CODE

AQUASTOR is a computer model for systematic investigation of the cost of energy from an aquifer thermal energy storage (ATES) system. AQUASTOR is extremely flexible, and can simulate heating systems (using stored hot water) or cooling systems (with stored chilled water). The code also contains the provision for cooling systems that employ stored hot water and absorption chillers. AQUASTOR combines system design functions with a detailed cash flow simulation routine to estimate the cost of ATES energy delivery. The code provides the flexibility to individually or collectively evaluate the impact of varying economic and technical assumptions and uncertainties on the cost of energy delivery. A full description of the model is given in Huber, Brown, and Reilly (1982).

The model consists of two parts: an aquifer storage submodel and a distribution submodel. The storage submodel calculates the life-cycle cost of energy production by simulating the exploration, development, and

operation of an ATES storage system and the construction and operation of a transmission pipeline for delivering the energy to a distribution center. The distribution submodel calculates the life-cycle cost of energy delivery by simulating cash flows for construction and operation of a distribution system. Each of the submodel systems is considered to be its own operating entity with a tailored financial configuration, including its own tax rates and incentives, capital structure, and depreciation schedule. The code can simulate a two-entity system (e.g., a private company selling stored energy to a municipal distribution system) or a single entity (by using the same financial structure for both sets of inputs).

3.2.1 The Aquifer Storage Submodel

The storage submodel employs energy source characteristics, aquifer efficiency characteristics and peak/annual flow requirements to design the storage and transmission systems. It uses a triple set of nested iterations to design heat exchangers, pipelines, and wellfields, while balancing mass and thermal flows between the supply and demand portions of the system. These iterations take into account water and heat losses (gains) in both aquifer systems and in all pipelines.

The storage submodel assumes that thermal energy is purchased from an external source on a \$/MBtu basis, and that the heat is delivered through a liquid medium (water). The code designs a shell and tube heat exchanger for extracting the energy, and calculates the pump size and pumping power required to operate both sides of the heat exchanger.

AQUASTOR does not attempt to simulate fluid or thermal flow within the aquifer. Rather, it captures the relevant aquifer characteristics in three input parameters: fluid recovery fraction, thermal storage efficiency, and discovery aquifer temperature. The fluid recovery fraction is simply the ratio of the water volume recovered from the storage wellfield to the previously injected volume. It can vary from a fraction to greater than one, depending upon the nature of the aquifer being simulated, the temperature differential between the injected water and the in-situ water,

and heating (cooling) system response to temperature degradation.^(a) The thermal storage efficiency is similarly the ratio of energy recovered to energy injected, both defined with respect to the discovery (natural) water temperature of the aquifer. Defining storage efficiency in this manner isolates aquifer storage efficiency from the characteristics of the above-ground equipment. The storage and supply wellfields may have different thermal efficiency factors (because of different injection temperatures and water recovery ratios); they will usually have different fluid recovery factors, the one being the reciprocal of the other.

The code employs a simple enthalpy balance to determine the average temperature of water recovered from the storage aquifer, once the injection temperature, natural aquifer temperature, and fluid and thermal recovery parameters have been specified. The wellfield and transmission pipeline systems are designed based upon this average temperature.

The storage submodel operates on an average-year performance basis. In an actual ATES development, aquifer efficiency is expected to rise dramatically over the first several years of operation as the aquifer is conditioned to the temperature of storage by lost thermal energy; it is expected to approach a steady state thereafter. The current AQUASTOR configuration models only the steady-state situation.

The aquifer submodel estimates the cost of developing and operating energy collection and storage systems, and develops the life-cycle cost of energy storage. The end result of this subprogram is a levelized unit cost of energy storage on a \$/MBtu basis. This stored energy is then "sold" to the distribution entity for input into the distribution system.

3.2.2 The Distribution Submodel

The distribution submodel develops a design for a hot (chilled) water distribution system and calculates annual capital, operating and maintenance costs for the system. Climate parameters are used to determine

^(a)Some users may shut down when the temperature of the recovered water starts to degrade; others may be able to continue operation by increasing flow rates, or by employing supplemental energy sources.

peak and average heat (chill) demands, load factors, and any supplemental heat (chill) requirements. The peak demand is then employed to design the fluid transmission lines: the pipe size and insulation thickness is automatically optimized to a lowest total cost based upon the mix of capital cost, thermal losses, and required pumping energy.

The input data consist of demand characteristics for a point demand or district heating (cooling) system. Materials and design options for piping, insulation, and casing are also input. If district heating (cooling) is being modeled, the input data include city layout, characteristics of districts that constitute the city, and various options and adjustment factors.

The city is defined by its distance from the aquifer, climatic characteristics, and the number and type of districts within the city. Each district is a contiguous area consisting of buildings of similar heat (chill) demand and uniform density. Five district types, representing typical residential areas, are defined; others can be added as necessary.

3.3 TECHNICAL AND ECONOMIC ASSUMPTIONS

The cost of aquifer chill storage was estimated using the technical and economic assumptions listed in Table 3.1. These assumptions are intended to reflect costs and conditions likely to exist in many parts of the nation. Additional cost information concerning specific ATES elements is given in Table 3.2.

Nine base case configurations were generated to cover a range of potential conditions. These consisted of three source temperatures (35°F, 40°F, and 45°F), applied to each of three system sizes (2 Mwt, 5 Mwt, and 20 Mwt peak demand). These configurations were subsequently used as the base for parametric analysis to determine the importance of various economic and technical assumptions.

TABLE 3.1. Modeling Assumptions for Estimating Aquifer Chill Storage Costs

<u>Economic Assumptions</u>	
Start of construction	January 1987
System startup	January 1990
Operating life	30 years
Base year for cost estimates	January 1980
Cost Information	
Electricity	\$0.05/kWh
Well drilling and casing	\$100/foot
Price Escalation Information	
General inflation	6%/year
Electricity	7%/year
Capital equipment	6%/year
O&M expense	6%/year
Financing Information	
Mode	municipal financing (no taxes)
Interest rate	10%/year
<u>Technical Assumptions</u>	
Energy Source	
Availability	90 days/year
Supply temperature	35°F
	40°F
	45°F
Return temperature	55°F
Load Description	
Peak demand	2, 5, and 20 MW
Load factor	25%
Reject temperature	60°F
Wellfield Description	
Well depth	400 feet
Well spacing	25 acres
Maximum well productivity	150,000 lb/hr (300 gpm)
Supply Aquifer	
Thermal efficiency	95%
Fluid recovery factor	100%
Storage Aquifer	
Thermal efficiency	90%
Fluid recovery factor	100%
Transmission Systems	
Pipe	carbon steel
Insulation	calcium silicate
Storage system construction	above ground
Distribution system construction	buried
Source-to-user separation	3000 meters, one way

TABLE 3.2. Cost Ranges for Selected Elements of ATES Systems

Element	Description	Cost 1980 Dollars
Carbon steel pipe (material only)	4-in. sch 40	\$ 4.20/ft
	12-in. sch 40	\$12.50/ft
	24-in. sch 40	\$60.00/ft
Calcium silicate insulation (material + installation)	2-in. insul., 6-in. pipe	\$ 8.50/ft
	3-in. insul., 12-in. pipe	\$18.00/ft
	4-in. insul., 18-in. pipe	\$33.00/ft
Polyurethane insulation (material + installation)	2-in. insul., 6-in. pipe	\$ 8.00/ft
	3-in. insul., 12-in. pipe	\$25.00/ft
	4-in. insul., 18-in. pipe	\$50.00/ft
PVC casing (material only)	6-in. casing	\$ 5.10/ft
	12-in. casing	\$11.00/ft
	18-in. casing	\$24.00/ft
Steel casing (material only)	12-in. casing	\$10.00/ft
	24-in. casing	\$24.00/ft
	36-in. casing	\$50.00/ft
Valves (equipment + installation)	4-in.	\$520 each
	12-in.	\$2350 each
	24-in.	\$13,450 each
Downhole pumps (equipment + installation)	300 gpm, 200-ft head	\$10,600 each
	300 gpm, 400-ft head	\$13,000 each
	1000 gpm, 400-ft head	\$32,600 each
Shell and tube heat exchanger	1000 ft ² HTA	\$27,200
	5000 ft ² HTA	\$95,600
	25,000 ft ² HTA	\$335,400

4.0 POINT DEMAND COST ESTIMATES

In this section, cost estimates are developed for energy delivered from an ATEs installation to a point demand.

4.1 BASE CASE RESULT

The system modeled is depicted in Figure 4.1. The ATEs installation consists of a pair of wellfields (in the same aquifer), two heat

FIGURE 4.1. System Modeled by Base Case

exchangers, and the transmission piping connecting these four major elements. All piping is assumed to be composed of carbon steel pipe, with calcium silicate insulation and aluminum casing, constructed above ground. All of the energy available from the chill source is assumed to be stored in the aquifer during a 90-day period. This energy is then recovered from the aquifer during the remaining portion of the year at a 25% load factor (annual average-to-peak flow ratio). No distribution or end-use costs are included in the estimates.

The results of this analysis are presented in Figure 4.2, which shows how the cost of ATES varies with system size at three source temperatures. Aquifer thermal energy storage is highly dependent upon economies-of-scale for cost-effective implementation: the cost curve is fairly flat beyond 8 MW, and tends to rise steeply for system sizes below 5 MW. As a figure of comparison, a 5-MW system demand is approximately equal to the peak system demand of 730 single-family houses in the Kansas City climate.

FIGURE 4.2. Energy Cost as a Function of System Size

4.2 COMPONENT COST BREAKDOWN

The cost of ATES energy is broken down by components for the 5-MW, 35°F base case configuration in Figure 4.3. The unit energy cost is

FIGURE 4.3. Component Cost Breakdown for the 35°F, 5-MW System

\$22.80/MBtu in January 1980 dollars. The electrical (pumping energy) component of this levelized cost is \$4.33, or 19% of the total cost. Pumping energy is a much more important cost component for ATES chill systems than for ATES heat systems for two major reasons. First, ATES chill systems pay no money for acquiring the cold water source. However, purchased thermal energy charges were typically the dominating cost component for ATES heat systems, often accounting for nearly half of the levelized energy cost. Without any purchased thermal energy charges, the fractions of total cost attributable to capital, O&M, and electricity components naturally increase. The second major reason for the significance of pumping energy in ATES chill systems is the low energy density of the stored fluid. Four to five times as much water must be stored in an ATES chill system to deliver the same number of Btus as an ATES heat system. The extremely large quantities of water that must be transported and stored require substantial pumping energy. Although the large quantities of water also require bigger pipe and more wells,

economies-of-scale in capital equipment reduce the relative importance of capital as system size increases. As an example, for the 2-MW base case at 35°F, electrical pumping charges constitute only 14% of the levelized energy cost. However, for the 20-MW base case at 35°F, electrical pumping charges account for 24% of the levelized energy cost.

4.3 THE COST OF CONVENTIONAL HEAT DELIVERY

To place the cost of ATES-delivered chill in perspective, comparable cost estimates were made for chilled water generated from conventional technology. If chilled water were to be supplied by an electrically driven compressive chiller device (at 5¢/kWh and 1% real escalation), then the levelized cost of energy would be \$8.96/MBtu. This is substantially lower than for the ATES base case configurations, which ranged from \$30.44/MBtu for the 2-MW system to \$17.95/MBtu for the 20-MW system. As compared to ATES-delivered heat, ATES-delivered chill suffers from two major disadvantages when competing with conventional energy systems. The low energy density of the cold water requires an expensive investment to deliver a relatively small amount of energy and the competing technology, electrically driven compressive chillers, is highly efficient. However, under certain conditions an ATES system would be able to provide chilled water at a substantially lower cost than conventional systems. The levelized energy cost of an ATES system built under the design and financial conditions shown in Table 4.1 would be \$4.46/MBtu. Admittedly, the assumptions in Table 4.1 represent a rather fortuitous situation, but none of the parameters taken individually is unrealistic.

4.4 PARAMETRIC ANALYSES

Parametric analyses were conducted to investigate the effects of varying technical and economic assumptions upon the cost of ATES development and operation. These results are presented in graphs similar to that of Figure 4.2, with the levelized unit cost of energy presented on the ordinate, and the independent variable being investigated on the abscissa. The levelized unit cost of energy includes capital (including

TABLE 4.1. Modeling Assumptions for Low Cost ATEs Chill System

Economic Assumptions

Start of construction	January 1987
System startup	January 1990
Operating life	30 years
Base year for cost estimates	January 1980
Cost Information	
Electricity	\$0.05/kWh
Well drilling and casing	\$20/foot
Price Escalation Information	
General inflation	6%/year
Electricity	7%/year
Capital equipment	6%/year
O&M expense	6%/year
Financing Information	
Mode	municipal financing (no taxes)
Interest rate	8%/year

Technical Assumptions

Energy Source	
Availability	120 days/year
Supply temperature	35°F
Return temperature	60°F
Load Description	
Peak demand	20 MW
Load factor	25%
Reject temperature	65°F
Wellfield Description	
Well depth	200 feet
Well spacing	5 acres
Maximum well productivity	500,000 lb/hr
Supply Aquifer	
Thermal efficiency	95%
Fluid recovery factor	100%
Storage Aquifer	
Thermal efficiency	90%
Fluid recovery factor	100%
Transmission Systems	
Pipe	carbon steel
Insulation	calcium silicate
Storage system construction	above ground
Distribution system construction	buried
Source-to-user separation	1000 meters, one way

owner's expense), pumping energy, and operation and maintenance. Each graph presents the results for three system sizes: 2-MW, 5-MW, and 20-MW peak demand. Only the results for the 35°F source are presented in the body of the report. Results for the 40°F and 45°F sources are included in the appendix. In general, the curves for these higher temperatures are identical to those for the 35°F source, but shifted higher on the vertical (cost) axis.

4.4.1 Source Availability

One of the major capital components of an ATES system is the cost of well drilling and development. Because all ATES wells serve as both injection and withdrawal wells, the total number of wells required is determined by the peak system flow, either into or out of the aquifer. Peak flow into the aquifer is determined by the need to store enough energy during the available storage period to satisfy total annual demand. Peak flow out of the aquifer is determined by the peak demand of the users. The number of wells required is determined by the maximum of these two rates.^(a)

Figure 4.4 presents the relationship of source availability and levelized cost. In the base case, the energy was assumed to be available continuously (24 hours per day) over a 90-day period. The variability in levelized energy cost stems from the effect source availability has on the number of wells. For the 2-MW system, an increase in source availability from 60 to 75 days results in only a small decrease in levelized energy costs, because the number of wells does not change between these two points. The small drop in cost reflects a decrease in source heat exchanger and transmission pipe sizes. As source availability rises to 90 days for the 2-MW system, levelized energy cost drops more quickly because the number of wells is reduced by one in each of the wellfields. Further

(a) The injection capacity of a well can differ markedly from its withdrawal capacity, thereby changing the ratio of input-to-withdrawal wells, and ultimately affecting the total number of system wells required. In this investigation, however, we have assumed equal withdrawal and injection capacities.

FIGURE 4.4. Energy Cost as a Function of Source Availability

increases in source availability do not dramatically lower the levelized energy cost because the number of wells becomes controlled by demand parameters. Levelized energy costs for 5- and 20-MW systems react similarly to changes in source availability. Each system size reaches a point at which an increase in source availability will not further decrease the number of wells. This point varies from 78 to 89 days for systems with peak demands between 2 and 20 MW.

4.4.2 Well Parameters

Three well parameters--productivity, cost, and lifetime--affect the costs of ATES chill systems to varying degrees.

4.4.2.1 Well Productivity

Well productivity or well flow rate has a dramatic effect on the costs of ATES chill systems. Because the energy density of chilled water is so low, large quantities of water must be transported and stored to meet the load requirements of the end user. The supply and storage wellfields dominate the capital cost of ATES chill systems. This puts a premium on the effective use of the wells. An additional well adds not only drilling cost, but also the expenses of an additional pump and the pipeline

necessary to connect the well to the existing manifold system. The results of varying well productivity are presented in Figure 4.5. In the base case, a maximum well production of 150,000 lb/hr (about 300 gpm) was assumed. This is not highly productive for water or geothermal wells,^(a) but it is probably reasonable for the aquifer transmissivities that will be required for economic thermal efficiencies.

FIGURE 4.5. Energy Cost as a Function of Well Productivity

4.4.2.2 Well Cost

The effect of well cost on the levelized cost of energy delivery is depicted in Figure 4.6. Well cost includes drilling, casing, and well development, but not the cost of the downhole pump. In the base case, wells were assumed to cost \$100/foot. Well drillers in many parts of the nation regularly drill suitable wells for under \$20/foot. In other regions, notably Alaska, well drilling costs can exceed \$200/foot.

(a)Some geothermal wells are rated at over 1,000,000 lb/hr.

FIGURE 4.6. Energy Cost as a Function of Well Cost

In addition to the capital cost of the well, other significant costs are associated with the wellfield. Hence, well cost does not have as much impact on levelized energy cost as does well flow rate (productivity). Of course, well cost and productivity are interdependent parameters, and are controllable by the developer to some extent. Economic tradeoffs exist that depend upon drilling and aquifer parameters. These need to be optimized in the design of the wellfield.

4.4.2.3 Well Life

The effect of well life on levelized cost is similar to that of well cost because, as the average well life decreases, the total cost of wells increases. As indicated by Figure 4.7, there is not much effect on the levelized cost of energy until the average system well life falls below 5 years. Because most water-well experience indicates an economic life of greater than 10 years, well life will probably not be a major cost concern for ATEs systems.

FIGURE 4.7. Energy Cost as a Function of Well Life

4.4.3 Aquifer Parameters

Characteristics of the aquifer that influence ATES chill system costs include aquifer depth, well spacing, and aquifer thermal efficiency.

4.4.3.1 Aquifer Depth

Increased aquifer depth can increase the cost of delivered energy in two ways. First, it increases the capital cost of well drilling and casing. Second, it may increase the size (capital cost) of the pump required, as well as the work (electricity) required to pump water to the surface heat exchanger. Pumping head is determined by the static water level in the well and well drawdown, factors that may not directly relate to well depth. Depending on site-specific aquifer characteristics, the actual pumping head could be as little as none (i.e., an artesian well) or as much as the entire well depth. The cost of ATES-delivered chill was calculated under these two limiting conditions. The difference in levelized cost amounted to \$0.80/MBtu at a 200-foot well depth and \$6.00/MBtu at a well depth of 1500 feet for systems with a 35°F source temperature. The effect of well depth on chill costs without the expense

of well pumping is shown in Figure 4.8. In Figure 4.9, the same relationship is shown with pumping charges associated with the full depth of the well included. The cost of chill at a specific site would fall somewhere between these two extremes.

FIGURE 4.8. Energy Cost as a Function of Aquifer Depth, Pumping Charges Excluded

FIGURE 4.9. Energy Cost as a Function of Aquifer Depth, Pumping Charges Included

Because the low energy density of chilled water necessitates the transportation and storage of large quantities of water, the cost effect of well depth is more pronounced than for hot water storage systems. Electrical pumping energy is a significant part of the delivered cost of chill and well pumping can be a major portion of the electrical consumption.

4.4.3.2 Well Spacing

The appropriate well spacing for supply and storage wellfields is determined by a number of aquifer-related factors ultimately affecting well productivity and energy recovery. Well spacing can be important in that it controls the amount of manifolding connecting the wells of both the supply and storage wellfields. Aquifer thermal energy storage chill systems employ a large number of wells as compared to ATES heat systems, increasing the importance of well spacing as a parameter. The cost curves in Figure 4.10 show the relationship of delivered chill costs to well spacing.

FIGURE 4.10. Energy Cost as a Function of Well Spacing

4.4.3.3 Aquifer Thermal Efficiency

Aquifer thermal efficiency (the ratio of energy recovered from the aquifer to the initial input energy) is dependent upon a large number of geologic and operational parameters, many of which are not fully understood at this time. In general, the most efficient ATES systems will have the following characteristics:

- Large amounts of water will be stored. Thermal energy is lost at the bubble surface, which grows as the square of the radius. The volume stored grows as the cube of the radius. Because the fraction of chill loss is a function of the ratio of the surface area to volume, the larger the scale of injection, the smaller will be this ratio and, hence, the more efficient will be the ATES system.
- The aquifer will be confined, bounded below and above by impervious layers (aquitards) that minimize chill and fluid transfer to the neighboring formations. The overlying aquitard will also prevent dilution of the thermal energy by infiltration of warmer water from an overlying aquifer or from a surface source.
- The regional flow rate within the aquifer will be negligible. A substantial natural flow would sweep the injected water "downstream" before the chill could be withdrawn in the recovery cycle.
- The aquifer will be thick enough to permit a compact storage geometry. A thin aquifer, for example, would result in a long, flat bubble with a high surface-to-volume ratio, and a correspondingly lower efficiency.
- The end-user will have flexible flow and temperature requirements. Toward the latter part of the withdrawal operation, the water temperature will tend to rise, slowly at first, and then more quickly as the mixed water at the edge of the storage bubble is recovered. If the system design (end-user) is flexible enough to use this higher temperature water (e.g., a chilling system with oversized heat

transfer surface), then the total amount of energy recovered will be greater than if the system must cease operation immediately when the water temperature rises a few degrees.

Fairly high thermal efficiencies should be attainable for ATES chill systems due to the low temperature differential between storage and in-situ water. Thermal transfer at the boundary of the stored water will be minimized by the low temperature differential. In addition, recovery problems caused by the difference in density between injected and natural ground water should be eliminated, for all practical purposes.

In this investigation, only the steady-state condition was modeled, and aquifer thermal efficiency was assumed constant over time. The model used two input parameters to simulate aquifer efficiency: aquifer thermal storage efficiency (ratio of annual energy recovery to annual energy injection - both with respect to the aquifer discovery temperature), and aquifer fluid recovery fraction (ratio of annual water volume recovery to annual volume injected). For the base case, we have assumed that 100% of the injected water was recovered before the water became too warm to use, and that 90% of the injected chill was recovered in this water volume. (The thermal and fluid recovery fractions were assumed not to vary with source temperature under base case conditions.)

In Figure 4.11 the relationship of energy cost to overall aquifer efficiency is illustrated. Both fluid recovery fraction (top) and aquifer thermal efficiency (bottom) were varied continuously so as to deliver the same average temperature water during the recovery cycle. At the left side of the curves, a very poor aquifer is modeled. The fluid recovery factor is 70% and the thermal efficiency is only 63%: thus, only 70% of the injected water is recovered, containing only 63% of the total input energy. The right edge of the curves is the base case, representing a good aquifer.

4.4.4 Demand Parameters

Four demand parameters affect the cost of an ATES chill system. These are load factor, transmission distance, presence or absence of a heat exchanger, and the load reject temperature.

FIGURE 4.11. Energy Cost as a Function of Aquifer Performance

4.4.4.1 Load Factor

The load factor is defined as the ratio of average annual hourly demand to peak hourly demand, and is one of the most important parameters affecting the unit cost of energy. The fixed portions of the unit energy cost are inversely proportional to the load factor, and fixed costs are predominant for an ATES system. The variable portions of the unit cost of energy do not vary with changes in load factor.

In this analysis (summarized in Figure 4.12), a greater load factor is equivalent to a larger annual rate of energy storage, because peak demand is maintained constant as load factor is increased. The base case load factor is 25%, which is higher than expected for a cooling system for a residential development, but not at all unusual for process chill users.

Unfortunately, the ATES developer can do little to increase the load factor for a particular application, because load factor is a property of the user's needs. One approach often taken with district heating systems is to undersize system components. This increases the load factor, but it

FIGURE 4.12. Energy Cost as a Function of Demand Load Factor

also results in a unserved peak demand that must be filled through a supplemental source. As another approach, the developer can increase the system load factor by combining noncoincident users on a single system.

4.4.4.2 Transmission Distance

The cost of ATES-delivered energy is dependent upon the total distance over which the fluid must be transmitted. In the base case, each of the four legs is modeled at 1500 meters, giving a source-to-user separation of 3000 meters (about 2 miles) and a total pumping distance (excluding the wellfield manifold) of 6000 meters. The analysis of source-user separation distance summarized in Figure 4.13 indicates that the relationship between transmission distance and the energy cost is essentially linear. Economic transmission distance is strongly a function of system size. For the 20-MW systems, delivered chill costs rise relatively slowly as transportation distance increases. For the 2-MW systems, the cost of energy quickly becomes prohibitive with increasing transmission distance.

FIGURE 4.13. Energy Cost as a Function of Transmission Distance

Transmission cost is highly dependent on fluid temperature (see Appendix) because the chilling capacity of each pound of fluid decreases with temperature. Pipe size, casing size, and insulation volume can all be reduced with decreased temperature. Economic transmission distance is also highly dependent upon load factor. Greater utilization of capital equipment lowers the overall cost per unit of delivered energy.

4.4.4.3 No User Heat Exchanger Operation

The water stored in the aquifer must generally be isolated from the chilled water distribution system by a heat exchanger, both to protect the aquifer from environmental damage, and to protect the expensive distribution systems from corrosion. This requirement imposes severe penalties upon the cost of ATES-delivered energy in the form of added capital and operating costs of a heat exchanger, and increased temperature of the fluid delivered to the distribution system. In some situations (e.g., when using a nonpotable, but noncorrosive, aquifer water) the heat exchanger may no longer be required for protecting the aquifer and distribution system. Figure 4.14 provides cost estimates for an ATES system with no user heat exchanger for comparison with the base case ATES configuration.

FIGURE 4.14. Energy Cost for a System with No User Heat Exchanger

4.4.4.4 Load Reject Temperature

The load reject temperature influences costs in a manner similar to the source temperature. The difference between the load reject and source temperatures represents the maximum amount of useful energy that could be delivered to the end user. The actual amount delivered to the end user is less due to thermal losses in the aquifer and piping system, and losses associated with the approach temperatures at both system heat exchangers. Increasing the load reject temperature (see Figure 4.15) effectively increases the amount of delivered energy at no increase in cost. As one might expect, the importance of load reject temperature increases as the source temperature approaches the load reject temperature.

4.4.5 Economic Parameters

The costs of electricity and capital are the primary economic parameters affecting ATES chill system overall costs.

4.4.5.1 Cost of Electricity

Electricity charges for pumping energy constitute 19% of the levelized energy cost for the 35°F source, 5-MW base case. As compared to heat

FIGURE 4.15. Energy Cost as a Function of Load Reject Temperature

systems, electricity charges are more important for ATES chill systems for two reasons. Purchased thermal energy was a major cost component for ATES heat systems. With purchased thermal energy eliminated, the proportion of total costs attributed to electricity naturally rises. The second reason is the low energy density of chilled water. The need to transport and store very large quantities of chilled water to meet the end user's peak and annual cooling requirements causes increases in both capital and operating (pumping) charges. Electricity use increases in relative importance because pumping energy is directly proportional to flow while piping systems show economies-of-scale with flow rate. The effect of the cost of electricity on the cost of ATES-delivered chill is shown in Figure 4.16.

4.4.5.2 Cost of Capital

The effect of financing mode is depicted in Figure 4.17. Both municipal (100% tax-free bonds) and private (after-tax rate, 50% bond/50% equity) financing were investigated. For the private financing cases, a 10% investment tax credit was assumed, and double-declining depreciation was used. The financing arrangement can often make the difference between

FIGURE 4.16. Energy Cost as a Function of Cost of Electricity

FIGURE 4.17. Energy Cost as a Function of Cost of Capital

economic success or failure. The availability of tax credits, accelerated depreciation, and sources of capital can change with the whims of legislative action. Any site-specific analysis of a potential ATES installation should include a detailed assessment of financing possibilities and the prevailing tax laws.

4.5 DISCUSSION

It is apparent from the analyses just presented that the economic performance of an ATES system is dependent upon a large number of system and economic parameters. System size is very important, as cost-effective use of ATES technology is heavily dependent upon economies-of-scale. Wellfield parameters, especially well flow rate, substantially influence ATES chill system costs because of the large quantities of water being stored. Other important parameters include source temperature, load factor, transmission distance, and aquifer thermal efficiency.

5.0 RESIDENTIAL DEVELOPMENT COST ESTIMATES

The estimated cost of supplying ATEs energy to residential developments for space cooling is reported in this section. As was documented in Section 4, three source temperatures were investigated: 35°F, 40°F, and 45°F. These three source temperatures are associated with the climates of Minneapolis, Minnesota, Kansas City, Missouri, and Fort Worth, Texas, respectively. Unfortunately, those climates with an abundance of winter chill typically have a small air conditioning load and vice-versa. The best locations for aquifer thermal storage of chill will have continental climates where both a large chill source and a large cooling need exist on an annual basis.

Two types of residential developments were investigated for each climate: single-family houses and garden apartment buildings. The single-family houses have 1620 square feet on one level, with an assumed building density of four houses per acre. The apartment houses are two-story buildings with an assumed building density of 2.18 acres per building. There are 60 units per building, with each unit having 990 square feet.

The residential cost estimates employed the same system design and base-case assumptions as in the point-demand analysis, with one major difference. Residential costs include the cost of constructing and operating a distribution system to transport the hot water from the user heat exchanger to the end user. As in the point-demand analysis, the cost of end-use equipment is not included in the cost estimates. The distribution systems modeled are assumed to be buried in a retrofit operation, with cost allowances made for trenching, pipelaying, backfilling, and repaving. The pipes themselves are schedule 40 carbon steel, with calcium silicate insulation in a steel casing.

In these residential cost analyses, the system peak is assumed to be less than the sum of the individual peaks, because the peak load for all units within the system will not occur simultaneously. A diversity factor of 72% was assumed, allowing for the downsizing of distribution system laterals and mains (Huber, McDonald, Bloomster, and Schulte 1978).

5.1 BASE CASE RESULTS

The levelized costs of ATEs-delivered chill for single-family houses and apartment houses in Minneapolis, Kansas City, and Fort Worth climates are presented in Figures 5.1, 5.2, and 5.3, respectively.

FIGURE 5.1. Energy Costs for Minneapolis Residential Developments

FIGURE 5.2. Energy Costs for Kansas City Residential Developments

FIGURE 5.3. Energy Costs for Fort Worth Residential Developments

5.2 DISCUSSION

The most striking feature of these cost curves is the exorbitant cost of delivering chill under all of the residential cases considered. These costs completely overshadow the otherwise interesting effects of climate and economies-of-scale, as well as the differences between apartments and houses. One would expect residential costs for ATES chill to rise over the point demand situation due to the addition of an expensive distribution system, and this is certainly a prime reason for the higher costs. More important than this, however, is the load factor associated with each of the climates investigated. The system load factor in Minneapolis is only 3.6%, with Kansas City and Fort Worth only 8.9% and 14.5%, respectively. The load factor for the base case configuration of the point demand systems was 25%. The low residential load factors represent an underutilization of a capital-intensive system, a situation that can only lead to high cost per unit of output.

In summary, it does not appear that ATES-delivered chill will be competitive for residential cooling applications. The otherwise marginal attractiveness of ATES chill systems vanishes under the extremely low load factors characteristic of residential cooling systems.

REFERENCES

- 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, Vols. I and II. PNL-4236, Pacific Northwest Laboratory, Richland, Washington.
- Huber, H. D., C. L. McDonald, C. H. Bloomster, and S. C. Schulte. 1978. User Manual for GEOCITY: A Computer Model for Geothermal District Heating Cost Analysis. PNL-2742, Pacific Northwest Laboratory, Richland, Washington.
- Intertechnology Corporation. 1977. Analysis of the Economic Potential of Solar Thermal Energy to Provide Industrial Process Heat, Volume I. Warrentown, Virginia.
- Karkheck, J., E. Powell, and E. Beardsworth. 1977. "Prospects for District Heating in the United States." Science. 195:948-955.
- Meyer, C. F. 1977. "Heat Storage Wells: Key to Large-Scale Cogeneration." Public Power. July-August:28-30.
- Meyer, C. F., W. Housz, B. L. Ayres, and H. M. Ingram. 1977. Role of the Heat Storage Well in Future U.S. Energy Systems. GE76TMP-27A, GE Tempo, Santa Barbara, California.
- Reilly, R. W., D. R. Brown, and H. D. Huber. 1981. Aquifer Thermal Energy Storage Costs with a Seasonal Heat Source. PNL-4135, Pacific Northwest Laboratory, Richland, Washington.

APPENDIX

POINT DEMAND AQUIFER THERMAL ENERGY STORAGE ESTIMATES FOR 35°F, 40°F, and 45°F SOURCES

FIGURE A.1. Energy Cost as a Function of Source Availability

FIGURE A.2. Energy Cost as a Function of Well Productivity

FIGURE A.3. Energy Cost as a Function of Well Cost

FIGURE A.4. Energy Cost as a Function of Well Life

FIGURE A.5. Energy Cost as a Function of Aquifer Depth

FIGURE A.6. Energy Cost as a Function of Well Spacing

FIGURE A.7. Energy Cost as a Function of Aquifer Performance

FIGURE A.8. Energy Cost as a Function of Demand Load Factor

FIGURE A.9. Energy Cost as a Function of Transmission Distance

FIGURE A.10. Energy Cost as a Function of Electricity Cost

FIGURE A.11. Energy Cost as a Function of Cost of Capital

FIGURE A.12. Energy Cost as a Function of Load Reject Temperature

DISTRIBUTION

No of
Copies

No of
Copies

OFFSITE

	US Department of Energy Attn: J. Brogan Office of Energy Systems Res. Forrestal Bldg., CE-141 5E-052 Washington, DC 20585	Auburn University Attn: F. J. Molz School of Engineering Auburn, AL 36830
	US Department of Energy Attn: I. Gyuk Office of Energy Systems Res. Forrestal Bld, CE-141 5E-052 Washington, DC 20585	Walter Hausz 4520 Via Vistosa Santa Barbara, CA 93110
5	US Department of Energy Attn: R. Shivers Office of Energy Systems Res. Forrestal Bld, CE-141 5E-052 Washington, DC 20585	Lawrence Berkeley Laboratory Attn: C. F. Tsang University of California Bldg. 90, Room 1012-H 1 Cyclotron Road Berkeley, CA 94720
	US Department of Energy Attn: J. H. Swisher Office of Energy Systems Res. Forrestal Bld, CE-141 5E-052 Washington, DC 20585	Lawrence Livermore Laboratory Attn: Tech. Info. Dept, L-3 University of California PO Box 808 Livermore, CA 94550
	US Department of Energy Attn: Director, Policy and Planning Office of Conservation and Solar Applications Washington, DC 20545	Charles F. Meyer 1141 Cima Linda Lane Santa Barbara, CA 93108
27	DOE Technical Information Center	Minnesota Geological Survey Attn: M. Walton 319 15th Avenue S.E. Minneapolis, MN 55455
	Argonne National Laboratory Attn: A. Michaels Building 362 9700 S. Cass Avenue Argonne, IL 60439	National Aeronautic and Space Administration Asst. Adm. for Energy Programs Washington, DC 20546
		New York State Energy Research & Development Agency Attn: Director Rockefeller Plaza Albany, NY 12223

No of
Copies

Oak Ridge National Laboratory
Attn: J. F. Martin
PO Box Y
Oak Ridge, TN 37830

Office of Congressman
Sid Morrison
Attn: Kevin Billings,
Legislative Asst.
1330 Longworth Bldg.
Washington, DC 20515

Rocket Research Company
Attn: D. D. Huxtable
Director Energy R&D
York Center
Redmond, WA 98052

Sandia Laboratories
Attn: L. Radosevich
PO Box 969
Livermore, CA 94550

Sandia Laboratories
Technical Library Div. 3141
Albuquerque, NM 87185

Sandia Laboratories
Attn: William G. Wilson
PO Box 969
Organization 8453
Livermore, CA 94550

Solar Energy Research Inst.
Attn: Director
1536 Cole Blvd.
Golden, CO 80401

Terra Tek, Inc.
Attn: C. Cooley
University Research Park
400 Wakara Way
Salt Lake City, UT 84108

No of
Copies

Union Carbide Corporation
Nuclear Division
Attn: Library
Y-12 Plant
PO Box Y
Oak Ridge, TN 37830

University of Minnesota
Attn: W. E. Soderberg
Program Director, ATES
Physical Plant Operations
200 Shops Bldg.
319 15th Avenue S.E.
Minneapolis, MN 55455

US Army Corps of Engineers
Attn: Library
PO Box 59
Louisville, KY 40202

US Department of Interior
Attn: Natural Resources
Library
Serials Branch (G/E)
Washington, DC 20240

ONSITE

DOE Richland Operations Office

H. E. Ransom/D. R. Segna

39 Pacific Northwest Laboratory

D. E. Blahnik
C. H. Bloomster
D. R. Brown (10)
H. D. Huber
L. D. Kannberg
C. T. Kincaid
J. R. Raymond (15)
R. W. Reilly
L. D. Williams
Technical Information (5)
Publishing Coordination (2)