

Seasonal Thermal Energy Storage Program

AQUIFER THERMAL ENERGY STORAGE REFERENCE MANUAL



Prepared for the U.S. Department of Energy
Office of Advanced Conservation Technologies
under Contact DE-AC06-76 RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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STORAGE REFERENCE MANUAL**

L.S. Prater

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

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CONTRIBUTORS

Contributions for the Aquifer Thermal Energy Storage (ATES) Reference Manual have been prepared by the staff of the Seasonal Thermal Energy Storage (STES) Program. The following individuals have coordinated input and prepared contributions for sections of the ATES Reference Manual:

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These individuals will continue to coordinate input for sections of the manual and will prepare section revisions as needed.

ACKNOWLEDGMENT

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1.0 INTRODUCTION

1.0 INTRODUCTION

This is the reference manual of the Seasonal Thermal Energy Storage (STES) Program, which is managed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE).

The Aquifer Thermal Energy Storage (ATES) Reference Manual is the primary document for the transfer of technical information of the STES Program. It has been issued in preliminary form and will be updated periodically to include more technical data and results of research. As the program progresses and new technical data become available, sections of the manual will be revised to incorporate these data. The revised sections will be distributed to all individuals holding a copy of the manual.

1.1 THE SEASONAL THERMAL ENERGY STORAGE PROGRAM

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The STES Program is managed by PNL for the U.S. Department of Energy. The STES Program will demonstrate the storage and retrieval of energy on a seasonal basis, using surplus heat or cold that is available from waste or other sources. Seasonal thermal energy storage can reduce both peak-period demand for electricity and load problems of electric utilities. It can increase the feasibility of district heating and cooling systems. Aquifers, ponds, earth and lakes have potential for seasonal storage. Initially, the STES Program is investigating the storage of energy in ground-water systems (aquifers). Other methods of seasonal storage will be evaluated by studying existing literature and by following current work in other countries. New program directions may result from these studies.

The STES Program is divided into the ATES Demonstration Program and the Technical Support Program. The ATES Demonstration Program will show the commercial potential of storing thermal energy in aquifers. The Technical Support Program will seek ways to reduce technological and other barriers to the development of energy storage systems prior to significant investment in demonstration or commercial facilities.

Storage of thermal energy is expected to contribute to achieving the goals of the National Energy Plan. The U.S. Department of Energy predicts that, by the year 2000, seasonal aquifer storage could replace or conserve up to 350 million barrels of oil per year. Storage of thermal energy will encourage a shift from the use of oil and natural gas to more abundant or more available energy sources such as coal, solar, and nuclear power. Thermal energy storage, when incorporated into energy supply and conservation systems, permits efficient and economical use of intermittent energy like solar energy or off-peak electrical power. Thermal storage also may allow use of waste heat from industries and utilities.

Most geologists and ground-water hydrologists agree that heated and chilled water can be injected, stored, and recovered from aquifers. Storing thermal energy in aquifers could solve a number of problems and yield a number of benefits, including: a) collecting and storing solar heat in the summer for use in the winter, b) cooling buildings more economically in the summer, and c) using waste heat that is generated in electric plants and industrial plants. Geologic materials are good thermal insulators and potentially suitable aquifers are distributed throughout the United States. Recent studies and small-scale field experiments have shown energy recovery rates above 70% for seasonal storage. However, successful demonstration of large-scale aquifer thermal energy storage has not yet been attempted and the concept's economic feasibility and institutional acceptability have yet to be established.

Energy for use in an aquifer thermal energy storage system could come from solar heat, power plant cogeneration, winter chill, and sources of industrial waste heat such as aluminum plants, paper and pulp mills, food processing plants, garbage incineration units, cement plants, and iron and steel mills. For heating, energy ranging from 50°C to over 150°C is available. Potential uses include space heating on an individual or district scale, heating for industrial or institutional plants, and heat for processing/manufacturing.

2.0 AQUIFER THERMAL ENERGY
STORAGE DEMONSTRATION PROGRAM

2.0 AQUIFER THERMAL ENERGY STORAGE DEMONSTRATION PROGRAM

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The objective of the Aquifer Thermal Energy Storage (ATES) Demonstration Program is to demonstrate the commercial potential of the technology for aquifer thermal energy storage. This program will stimulate the interest of industry by demonstrating the feasibility of using an aquifer for thermal energy storage, thereby reducing fossil fuel consumption, minimizing thermal pollution, and significantly reducing utility capital investments required to account for peak power requirements.

The ATES Demonstration Program consists of two parts:

Phase I - Conceptual Design. The purpose of this work is to develop site-specific conceptual designs for aquifer thermal energy storage demonstration systems. Phase I will include aquifer characterization.

Phase II - Final Design, Construction and Operation. The purpose of this work is to implement ATES Demonstration projects selected from Phase I conceptual designs.

In response to a Request for Proposal (RFP), prospective contractors submitted proposals for Phase I work. These proposals have been evaluated and contracts have been awarded to three firms: TRW, Incorporated; Dames & Moore; and the University of Minnesota. These contractors will develop conceptual designs for integrated systems containing the following elements: an energy source, thermal transport, aquifer storage, and a practical application. Aquifers will be characterized by geologic exploration and analysis of existing data. Functional design criteria will be developed for each subsystem and for the integrated systems. From the functional design criteria and the aquifer characterization reports, conceptual designs will be developed and proposals submitted for continued work in Phase II. During Phase II, ATES Demonstration Projects will be designed, constructed, and operated.

2.1 TRW, INCORPORATED DEMONSTRATION

2.1 TRW, INCORPORATED DEMONSTRATION PROJECT - BETHEL, ALASKA

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The site of the TRW demonstration will be Bethel, Alaska. The energy source to be used for the demonstration is waste heat from the power plant that is owned and operated by the Bethel Utility Corporation. TRW will investigate the possibility of storing this waste heat in an aquifer beneath the permafrost at a depth of approximately 400 ft. When the hot water (less than 100°C) is recovered from storage, it will be used for space heating of several public buildings, including the Bethel hospital.

Bethel is in southwestern Alaska on the Kuskokwim River. It is the regional center for trade, transportation, administration, health care, and education. Bethel is well suited for demonstrating ATEs because it is typical of many small communities in northern areas.

Bethel, like many isolated communities in Alaska, uses diesel generators for power. The energy from cooling water and exhaust gas is usually wasted. This waste heat can be used as an energy source when hot water generated by the cooling system is combined with hot water generated in heat exchangers installed in the exhaust stacks. The injection temperature of the heated water will be in the low temperature (about 100°C) range.

2.2 DAMES & MOORE
DEMONSTRATION PROJECT

2.2 DAMES & MOORE DEMONSTRATION PROJECT - STONY BROOK, NEW YORK

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The site of the Dames & Moore Demonstration Project will be the Stony Brook campus of the State University of New York. Dames & Moore will investigate the possibility of using a portion of the Magothy aquifer as a storage medium for chilled water. The conceptual design will use an existing cooling tower for localized chilling of aquifer water in the winter and an existing chilled water distribution system for cooling several campus buildings in the summer.

The Stony Brook facility serves about 16,000 students on an 1100-acre campus. Approximately 3,500,000 ft² of office, classroom, laboratory, dormitory and service buildings are heated and cooled by a central system. Cooling consumes approximately one third of the 8.5 million gallons of No. 6 fuel oil used each year. It would probably take less than five years to recover the costs of an aquifer thermal energy storage facility at Stony Brook.

If successful, the demonstration could prove the feasibility of using an aquifer thermal energy storage system to reduce the summer power peaks required to air condition building complexes such as universities, apartment buildings, industrial parks, and large industrial sites.

Other major participants in this contract are the State University of New York at Stony Brook, the New York State Energy Research and Development Agency (NYSERDA), and the Engineering Consulting Firm of Ambrosino and DePinto. NYSERDA is a supporting sponsor and Ambrosino and DePinto will perform the above-ground engineering services. Phase I of this program is scheduled to be completed in FY-1982.

**2.3 UNIVERSITY OF MINNESOTA
DEMONSTRATION PROJECT**

2.3 UNIVERSITY OF MINNESOTA DEMONSTRATION PROJECT - MINNEAPOLIS-ST. PAUL,
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The University of Minnesota demonstration will use cogeneration steam from the university heating plant as an energy source. High-temperature (150°C) water will be stored in the Franconia-Ironton-Galesville aquifer which underlies the St. Paul campus. After its recovery, the stored energy will be used for district heating on the St. Paul campus.

The aquifer system that underlies the entire Twin-Cities area (Minneapolis and St. Paul) shows good potential for aquifer thermal energy storage. It consists of a sequence of four aquifers with intervening confining layers. One of the aquifers, called the Franconia-Ironton-Galesville (FIG), is little used, is 200- to 300-ft thick and has a low natural flow rate. It also has a good yield and a fairly low gradient. The FIG aquifer is the proposed storage medium.

The stored energy will be used to supply the St. Paul Campus with space and water heating. The campus is currently heated by coal-fired boilers.

The university's heating system is in the process of being cross-connected so that the south-east plant (currently being retrofitted for cogeneration), the Minneapolis heating plant and the St. Paul heating plant can supply each other. The aquifer demonstration will thus be an add-on to an on-going project to increase the efficiency and flexibility of the heating system. Phase I of the program is scheduled to be completed in FY-1982.

3.0 TECHNICAL SUPPORT PROGRAM

3.0 TECHNICAL SUPPORT PROGRAM

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The Technical Support Program will conduct studies that are needed to provide a sound technical base for the demonstration of STES concepts. The program is intended to reduce technological barriers to the development of energy storage systems prior to the significant investment in demonstration or commercial facilities. It will not only provide technological information on energy storage systems, but will also assist in identifying systems that are economically sound, environmentally acceptable and within existing legal and institutional constraints. It will support the ATES Demonstration Program and evaluate alternate methods of seasonal storage. Through research and testing of novel storage concepts, aquifer characteristics, system designs and system operating criteria, task personnel can assist developers in obtaining a successful energy storage facility.

Activities of the Technical Support Program include the following: a) performing analytical, laboratory and field research activities; b) developing field test facilities to obtain advanced data; c) establishing a center of knowledge and information for STES; and d) transferring of STES technology to promote its commercial use.

The Technical Support Program has been broken down into eight tasks. The Technical Support tasks are listed below. Each task is followed by the name of the task leader.

Legal/Institutional Assessment	Paul L. Hendrickson
Economic Assessment	Ray W. Reilly
Environmental Assessment	George E. Wukelic
Field Test Facilities	David A. Myers

Compendia of Existing Information
Laboratory Analysis
Numerical Simulation
Non-Aquifer STES Concepts

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3.1 LEGAL/INSTITUTIONAL ASSESSMENT

3.1 LEGAL/INSTITUTIONAL ASSESSMENT

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This task will examine the legal and institutional issues that are likely to affect Aquifer Thermal Energy Storage (ATES) development. Any laws or regulations that may affect ATES development will be identified and analyzed. A secondary objective of the task is to monitor the compliance of all demonstration contractors with legal and permit requirements.

The social impact of Seasonal Thermal Energy Storage (STES) technology development comes primarily from the inherent commitment of the local environment for energy storage; i.e., the commitment of a local ground-water aquifer for storage of the heated or chilled water. This use of the aquifer can cause changes in water quality that could affect the future uses of the resource.

The Legal/Institutional Assessment Task will assure that STES activities comply with the various state and Federal statutes and regulations regarding water resource appropriation and resource protection. The task will also support the demonstration and test programs by identifying requirements and monitoring compliance.

Internal Activities - FY-1980

Work began in FY-1980 on analysis of legal and institutional issues associated with ATES. Issues under consideration include ownership and protection of the stored-heat resource, methods of acquiring storage rights, and requirements for well drilling and injection. The status of these issues will be updated in FY-1982 and FY-1985.

Monitoring and evaluating regulatory developments and requirements (both Federal and state) likely to affect ATES projects began in FY-1980 and will continue through FY-1985. The principal regulatory vehicle will be the Underground Injection Control (UIC) Program which will be implemented under

the Federal Safe Drinking Water Act (PL 93-523). Regulations applicable to ATES under this program will be promulgated by FY-1982. Work will involve contributing to regulation development, monitoring developments and assessing effects.

Future Activities

Monitoring the compliance of the contractors of the ATES Demonstration Program with applicable local, state and Federal regulatory requirements will begin in FY-1981 and continue through FY-1985. There are concerns about compliance both from legal and public-relations viewpoints, as noncompliance could compromise the demonstration projects and jeopardize the entire STES Program.

The task will begin to analyze regulatory/institutional issues associated with end use of stored energy in FY-1981. The analysis will continue through FY-1982. The legal/institutional issues involving end uses of stored thermal energy are likely to be more complex than the storage issues. The task will investigate end-use issues, with special attention given to issues relating to district heating. Issues to be investigated include the following: coordinating entities, financing heat delivery and space-heating retrofit, the pricing of delivered heat, and mandatory/optional use requirements.

Analysis of regulatory/institutional issues associated with various non-aquifer thermal energy storage technologies will begin in FY-1981 and be completed by the end of FY-1981.

Preparation of a compendium of state and Federal requirements for STES development will begin in FY-1982 and be completed by the end of FY-1983. The compendium will be updated in FY-1985.

Preliminary Findings of the Legal/Institutional Assessment Task

The Legal/Institutional Task has examined a number of legal and regulatory issues that could potentially affect implementation of the Aquifer Thermal Energy Storage (ATES) concept. The ATES concept involves the storage of thermal energy in an underground aquifer until a later date when it can be effectively used. Either heat energy or chill can be stored. The stored energy may be used for district space heating and cooling, for industrial processes, and in agriculture or aquaculture.

A central concern of the ATES operator will be to make sure that the thermal energy can be stored, protected and recaptured when desired. These activities must be conducted without incurring liability. At a minimum, the ATES operator will need to purchase or, when necessary, condemn (assuming statutory authority) sufficient surface property rights to provide site access, drill needed wells and provide adequate spacing from nearby land-use activities. Acquisition of a subsurface energy storage easement may be needed if significant liability is foreseen or if intentional interference with the ATES operation by a surface owner/user is considered possible. Both of these contingencies are more likely if a relatively shallow aquifer is used for storage, although the likelihood of each can be rendered very small by careful aquifer selection. Liability from ATES operations is most likely to occur from interference with existing users of an aquifer as a potable water source. Interference would most likely be claimed for increased water temperature, although it is also possible that an ATES operation could lead to some chemical contamination of ground water. Other existing ground-water users, potential ground-water users in states recognizing overlying ground-water rights, and mineral rights holders (if ATES operation interferes with mineral interests) might also claim interference. The possibility that someone could drill with impunity into the energy storage bubble with the purpose of capturing stored energy and/or interfering with an ATES operation is remote, even if the ATES operator has not acquired any property interests. An ATES operator can probably assure the right to store, protect, and recapture the energy and to adequately limit the possibility of future liability. It is also likely that this assurance can be provided at a reasonable cost, especially in relation to total ATES costs.

An ATES operator will have to acquire certain permits. Most states have requirements related to well drilling, construction and abandonment. In addition, a permit from a state agency or the U.S. Environmental Protection Agency under the Underground Injection Control (UIC) Program established by the Safe Drinking Water Act of 1974 will eventually be required. Final UIC requirements for the well classification that is likely to include ATES wells will probably not be issued for several years. An ATES operator may also need to write an environmental impact statement.

A variety of legal, institutional and regulatory issues will occur at the stage of heat or chill delivery. It may be difficult to find an investor-owned entity that has sufficient economic incentive to construct and operate an ATES delivery system. Consequently, the responsibility may fall to a public body. A variety of other issues related to financing, rate setting, service areas, taxation, and other areas will require resolution. These issues are likely to be most complex for a residential district heating system.

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3.2 ECONOMIC ASSESSMENT

3.2 ECONOMIC ASSESSMENT

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Economic analysis is a major objective of the overall Seasonal Thermal Energy Storage (STES) Program. Studies will be conducted to assess the economic feasibility of high temperature, low temperature (heat), chill, and non-aquifer STES. The Economic Assessment Task will gather data needed for accurate assessments and will develop a methodology for economic analysis of the ATES Demonstration Projects.

Internal Activities - FY-1980

Economic Methodologies

The objective of this subtask is to develop methodologies for economic analysis of STES designs and concepts. Subtask activities include selecting and defining criteria and figures of merit. A computer code to simulate/evaluate the economics of district heating and/or cooling systems will be developed. Methodologies may also be developed to evaluate alternate technologies.

AQUASTOR is a computer code that was developed during FY-1979 and 1980 to provide an in-house capability for extensive economic analyses of ATES systems. Completion of the code will probably extend through FY-1981.

Economic Support/Evaluation

This subtask supports the STES Program Office in the following areas: economics of high temperature STES, economics of low temperature (heat) STES, economics of chill STES, and economics of non-aquifer STES. Support will generally take the form of:

- evaluation of specific concepts and/or designs for STES
- evaluation of alternative technologies
- review of articles, reports, and other documents for the STES Program Office
- development of general marketing documents
- technical monitoring of external contracts
- economics support to the ATES Demonstration Program, including definition of methodologies and criteria for proposal evaluation.

A Descriptive Analysis of Aquifer Thermal Energy Storage Systems was written in response to a request from the Department of Energy to provide a brief description of ATES technology for the layman.

External Activities - FY-1980

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A report entitled Guidelines for Conceptual Design and Evaluation of ATES is being prepared by GE TEMPO. It will enable potential users of ATES to determine whether or not ATES is suitable for providing their energy. It will also give them information on how to initiate ATES design. Completion date is September 30, 1980.

Future Activities

In years subsequent to FY-1980, the Economic Assessment Task will collect economic data from each of the ATES demonstration projects. These data will be used to assess the economic performance of each ATES demonstration installation. Task activities will also include the development of a standardized analytical methodology and/or a standard cost accounts system.

The Economic Assessment Task will keep in close communication with the demonstration projects and will develop a data base of costs for each of the construction activities and for each of the purchases of capital equipment.

This task will also analyze the demonstration projects to determine the economic performance of each. A final report will be written on the cost-effectiveness of the demonstration projects.

The AQUASTOR model will be further developed to enable rigorous analyses of a wide range of potential ATES applications. Modifications will include an improved time-varying simulation of aquifer efficiency, a better method for matching supply and demand, and the capability to input inflation and

escalation rates in order to facilitate the computation of life cycle costs. AQUASTOR will subsequently be used to define, describe, and evaluate representative systems for the major STES applications.

Using data collected through the ATES Demonstration Program, sensitivity analyses will be performed on each of the applications to develop an envelope of economically reasonable conditions for each application. The Economic Assessment Task will investigate the effects of:

- aquifer characteristics and the resultant efficiency
- financing modes
- government subsidies.

In addition, the task will investigate the economic benefits that would accrue from improvements in technology in various subsystems of ATES systems.

The Economic Assessment Task will also estimate the potential for ATES implementation. A linear programming model will be developed to provide market penetration estimates for ATES based upon economics and input from technical components of the STES Program.

The most promising alternate seasonal thermal energy storage techniques will be analyzed. The Economic Analysis Task will recommend alternatives that merit further research and/or development. The task will also estimate the commercial potential of alternate technologies.

Preliminary Findings of the Economic Analysis Task

Excerpts from: The Economics of Aquifer Storage of Chilled Water for Air Conditioning by R. W. Reilly, D. R. Brown, and H. D. Huber, presented at the 15th Intersociety Energy Conversion Engineering Conference, August 18-22, 1980, Seattle, Washington.

Introduction

Air conditioning of residential and commercial buildings consumes 3.5% of the nation's total energy budget, about 2.7 quads/year. This cooling is generally supplied by compression-cycle air conditioners or absorption chilling devices. The former impose expensive peak-load capacity requirements upon electric utilities, whereas the latter consume fossil fuels. One alternative to these conventional technologies is cooling by chilled water delivered to the demand site in pipelines. Winter-chilled water can be injected into aquifers and recovered during the summer for air conditioning by fan-coil cooling systems. Furthermore, such cooling systems can be used for industrial process chilling operations at temperatures around 45⁰F, and for pre-chilling of materials for processes occurring below this temperature. Direct consumption of fossil fuels is eliminated, and the consumption of electricity during times of peak demand is considerably less than would be experienced with electric compression devices. Widespread use of such a cooling technology could have a significant impact upon the nation's demand for scarce energy resources.

Assuming that the technology of such an aquifer storage cycle is well in-hand (and there appear to be no major technical difficulties), then the most important factor affecting its commercial use is economics. We have developed cost estimates for chill energy delivered to a point demand under a range of economic and technical conditions. By investigating a point demand as the load, two purposes are accomplished:

- Emphasis is placed upon the effects of various energy collection and storage parameters upon the cost of cooling, rather than upon the potentially overwhelming cost effect of a large distribution system.

- Costs can be estimated for potential point-demand users, that is, large commercial and industrial users with existing distribution systems such as airports, major office complexes, and factories.

This work was performed in support of the Seasonal Thermal Energy Storage (STES) Program at the Pacific Northwest Laboratory (PNL), the Department of Energy's lead laboratory for seasonal thermal energy storage. Funding was provided by the Office of Advanced Conservation Technologies, U.S. Department of Energy.

Methodology

AQUASTOR, a computer code developed at PNL, is used to evaluate the economics of cooling and/or heating using energy supplied by an ATES installation.

The code was adapted from GEOCITY, a code for economic evaluation of geothermal district heating systems. It has two major parts. The supply submodel simulates the exploration, development, and operation of an ATES system and the transmission of this energy to a distribution center. It also calculates the unit cost of energy. The distribution submodel simulates the development and operation of district and/or point demand cooling (heating) systems and calculates the unit cost of delivered energy. This investigation focuses upon the energy supply submodel, because with a single point demand the contribution of distribution cost to total cost is very small.

AQUASTOR can simulate nearly any financial and tax structure by varying the rates of return on equity and debt, the debt-equity ratio, tax rates, investment credits, and depreciation schedules. Both municipal utility and private ownership can be simulated. The reservoir submodel and the distribution submodel may have the same or different financial structures and costs of capital. In this investigation, we assumed municipal ownership for all cases.

The code calculates the cost of cooling by actually designing thermal collection and delivery systems, developing cost estimates for these systems, and simulating cash flows over the lifetime of the system. Piping, insulation, pumps, and other capital items are optimized in the design, based upon capital, operation, and maintenance costs. During the winter, cold river water

is pumped through a heat exchanger to chill aquifer water withdrawn from the "supply" well field. (Winter air, snowfall, ocean water, or other naturally cold media could also serve as the chill sources.) The aquifer water is immediately reinjected into the aquifer through the "storage" well field and stored until it is required for cooling. At that time it is withdrawn from the aquifer and either used as a cooling fluid directly, or circulated through a second heat exchanger to chill a cooling fluid in the distribution system. After the aquifer water has transferred its chill energy, it is returned to the aquifer through the supply well field.

AQUASTOR does not 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
- in situ aquifer temperature.

The fluid recovery factor is simply the ratio of the water recovered from the storage well-field to the previously injected water. It can vary from a fractional value 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 the air conditioning system's response to temperature degradation of the cooling fluid. (Some users may shut down when the temperature of the water starts to degrade. Others may be able to continue operation by increasing the flow rates or by employing supplemental energy sources.) The thermal efficiency factor is similarly the ratio of chill energy recovered to chill energy injected, both defined by the temperature of the in situ aquifer water. Defining storage efficiency in this manner isolates aquifer storage efficiency from the characteristics of the above-ground equipment.

The aquifer simulation subroutine can be simply described. The annual storage volume of water is input into the aquifer at the temperature calculated by the heat exchanger and piping heat loss subroutines. Assumptions are made about the amount of water that can be withdrawn before the temperature of the aquifer becomes too high for use in the above-ground air conditioning equipment (fluid recovery fraction) and about the overall thermal efficiency

of the aquifer. Then, through an enthalpy balance, an average temperature is calculated for all the water that is withdrawn during the following cooling season.

The code operates on average-year performance. 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, and it is expected to approximate a steady state afterwards. In the present configuration of AQUASTOR only the steady state situation is modeled.

AQUASTOR calculates the unit cost of energy based upon the required revenue principle: the present worth of the revenues over the economic life of the system must be equal to the present worth of the expenses, including return on investment, over that same economic life. All costs in this investigation are presented as life-cycle costs in 1979 price levels.

Summary

The cost of air conditioning using chill energy supplied by an Aquifer Thermal Energy Storage system is extremely dependent upon site-specific conditions. Under favorable demand, supply, and geologic conditions, ATES cooling can be competitive with both electric compression and absorption-chiller devices. Under less favorable conditions, its cost of cooling could be an order of magnitude too high.

A few implications can be drawn for all ATES cooling systems. It will be uneconomical to pump chilled water for very long distances due to the low-energy density of the fluid. Hence an ATES system will typically be located on or near a suitable aquifer with the energy supplied by a nearby chill source (such as winter air collected at the site). In this investigation, schedule 10 piping in steel casing was employed. By using less expensive, non-cased, uninsulated pipe, the cost of piping can probably be reduced by about 30%. But even allowing for this cost reduction, it appears that the transmission range will be severely limited. Combination of ATES air conditioning with ATES heating, however, would greatly increase the load factor of the transmission

pipeline, thus extending the economically feasible transport distance. Generally, this combination would require the added expense of a 3-pipe or 4-pipe system.

The temperature gain of the cooling water at the load site must be optimized. A few degrees variance in the delivery water temperature can markedly affect the cost of cooling. This temperature differential (between the cooling water supplied to the load and the reject temperature) is bounded on two sides: on the low side by the temperature of the chill source, or the freezing point, and on the upper side by the target temperature of the air conditioning system. Between these two bounds the actual temperature differential is controlled by the approach temperatures of the heat exchangers at both the chill source and the load, pipe insulation, and aquifer thermal efficiency. Selection of these system components must be optimized based upon cost/performance tradeoffs.

3.3 ENVIRONMENTAL ASSESSMENT

3.3 ENVIRONMENTAL ASSESSMENT

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The Environmental Assessment Task will ascertain and meet programmatic and site-specific environmental requirements for the ATES Program. The task will acquire and evaluate environmental data, provide environmental advisory assistance, develop requirements for subcontractors, and monitor subcontractors.

Internal Activities - FY-1980

Environmental Documentation Support

Environmental documentation is the primary support area of the Environmental Assessment Task. The objective of this activity is to help determine and meet environmental documentation requirements at both the Federal and state levels so that no National Environmental Policy Act (NEPA)-related program delays or disruptions occur. Specifically, this task must anticipate and fulfill the requirements of NEPA, must help identify the significant environmentally related problem areas and information voids, and must assist in defining technical research and development activities required to fulfill environmental documentation compliance.

The task is preparing a comprehensive programmatic Environmental Assessment (EA). The draft of the EA will have been completed and reviewed by all appropriate PNL and Department of Energy (DOE) offices during FY-1980. The final EA will be published as a DOE report in early FY-1981. Early publication of this document is important because it is intended to serve as a tiering document for the site-specific environmental reports, assessments or impact statements required to support the ATES Demonstration Projects initiated in

FY-1980. Although preparation of the comprehensive environmental impact reports for the demonstration sites is the responsibility of the contractor, the Environmental Assessment Task of the STES Program will be responsible for preparing the official DOE Environmental Assessment for each selected Phase II ATES Demonstration.

During FY-1980 the staff on this subtask drafted the ATES Environmental Assessment. The Oak Ridge National Laboratory (ORNL) provided primary technical support for development of the EA.

Environmental Data Acquisition and Evaluation

Acquisition of environmental data is an important activity of the Environmental Assessment task. The technical and engineering activities of ATES technology development and the environmental concerns and environmental regulatory requirements must be integrated. The objective is to ensure that meaningful environmental data are acquired and fully evaluated during the feasibility testing and demonstration phases to support eventual commercial use. This activity will support the test facility activities, the demonstration projects, and the other technical support tasks. The information generated in this support area will be used in the NEPA environmental documents and will address anticipated concerns of the general public.

Environmental Advisory Assistance

The Environmental Assessment Task will provide environmental advisory assistance to the STES Program. The staff will answer internal and external queries concerning environmental matters, assist STES personnel in evaluating demonstration proposals for environmental considerations, evaluate contractor environmental documents, and assist in preparing of program-level reports and publications.

With the exception of the increased FY-1980 and 1981 assistance to contractors on demonstration projects, this support effort should be fairly uniform throughout the program's lifetime.

In FY-1981 environmental activities will be directed toward fulfilling the environmental requirements of the Phase I demonstration projects. This effort will include guiding, assisting, and approving contractors' environmental plans, activities, and reports.

External Activities - FY-1980

Oak Ridge National Laboratory (ORNL)

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During FY-1980, all required external support for environmental assessment was provided by ORNL. The Oak Ridge National Laboratory began preparation of an Environmental Assessment for ATES during FY-1979. This effort was continued in FY-1980, when ORNL received a contract to revise and finalize a draft EA.

Future Activities

Initial (FY-1980) efforts involved identifying environmental concerns associated with ATES technology. In FY-1981, effort will be directed toward ensuring that PNL and the STES subcontractors acquire appropriate environmental data. In FY-1982 and FY-1983, the Environmental Assessment Task will participate in the design of environmental observation/monitoring plans. Longer term efforts during FY-1983-1985 will be directed toward preparing reports. These reports will be used to support the environmental documentation required by NEPA.

DOE Personnel Involved with Preparation of NEPA Environmental Documentation

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Recommended References

Council on Environmental Quality (CEQ) Regulations for Implementing the Procedural Provisions of the National Environmental Policy Act, 40 CFR Parts 1500-1508.

DOE Environmental Contracts Seasonal Thermal Energy Storage Projects:
Don Silawsky, Office of Environment, NEPA Affairs, 252-4610; Marty Rogowski, Office of General Counsel, 252-6947; and Herb Myers, Office of Conservation and Solar Energy, 252-9345.

DOE Guidelines for Compliance with the National Environmental Policy Act as Required by the CEQ Regulations, 45 F.R. 20694.

The National Environmental Policy Act of 1969, as Amended, P.L. 91-190, 42 USC 4321-4347, January 1, 1970, as amended by P.L. 94-52 July 3, 1975, and P.L. 94-83, August 9, 1975.

U.S. DOE, "Environmental Development Plans," Energy Storage Systems, EDP-0040, September 1979.

U.S. DOE, "Energy Storage System Program Summary Documented, FY-1981," January 1980.

3.4 FIELD TEST FACILITIES

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A major task under the Technical Support Program is to develop one or more Field Test Facilities (FTF). The FTFs will be used to test heating and/or chilling technologies for energy storage in aquifers. The FTF is the forerunner of demonstration projects for aquifer thermal energy storage. As a forerunner, the facility will assist in the development of energy storage technology through research and development activities.

Internal Activities

The Field Test Facility Task will manage contracts for field experiments. The task has been developing a test requirements plan to serve as a basis for evaluating FTF experiments.

Using the test requirements plan, an FTF experiment was designed to use the Pasco Gravels aquifer underlying the area near Richland, Washington. Drilling specifications were developed and potential drill sites were evaluated under the constraints of current land use and ownership. Seven exploratory drill sites were selected. The shallow, unconfined nature of the Pasco Gravels aquifer minimized the need to obtain highly specialized drilling contractors. The drilling contract was awarded to a local driller of domestic and irrigation wells. Seven wells were drilled to depths of 70 ft. The aquifer was highly variable in water bearing characteristics over very short distances. Well yields ranged from about 5 gpm (gallons per minute) with excessive drawdown to over 200 gpm with drawdowns of only 0.15 ft. This variability in aquifer characteristics limits the usefulness of the Richland FTF site for thermal injection and storage. Future plans for the site are limited to isothermal experiments involving gradient control and injectivity in shallow unconfined systems.

External Activities

Auburn University Field Test Facility

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Auburn University has conducted FTF activities at a site near Mobile, Alabama, for the past several years. Two injection/storage/recovery cycles have been completed. These cycles used an aquifer lying 130 to 200 ft below the surface. Injection temperatures were maintained as close to 55⁰C as possible. Each of the cycles involved the injection of 57,000 m³ (15 x 10⁶ gal) of water. Recovery of injected energy was 66% on the first cycle and 76% on the second.

Injection pressures increased with time and necessitated backflushing of the system to remove particulates from the vicinity of the injection well. Sediment analysis of the injection stream indicate that as much as 6000 lb of clay size material may have been injected. Regular periodic backflushing served to maintain injection well capacity.

Future work at the Mobile, Alabama FTF includes upgrading the experiment to a full and true doublet configuration, in which supply and injection wells are completed in the same aquifer. A determination of the vertical permeability is planned through anisotropy experiments. Thermal gradients within the upper and lower confining beds will be measured. Three additional cycles of injection/storage/recovery are planned. These cycles will be run at 55⁰C, 90⁰C and 125⁰C. These elevated temperature experiments will test the hypothesis of buoyancy tilting of the heated water front. Recovery efficiencies are expected to be lower for the 90⁰C and 125⁰C experiments. If the efficiency is significantly less, then the experiment will center around increasing the recovery through the use of partially penetrating wells or related technology.

Texas A&M Field Test Facility

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An experimental FTF for the storage of chilled water was carried out by Texas A&M University. The source of chilled water was a winter-operated spray pond. Water temperatures were reduced from an ambient temperature of 70⁰F (21⁰C) to less than 50⁰F (10⁰C) before injection. The water was injected into a shallow semi-confined aquifer lying approximately 50 ft below the surface. High ground-water velocities coupled with above normal rainfall during the experiment caused unreasonable losses of the stored energy. Despite the energy loss, the storage experiment did have some positive effects. Ambient dissolved iron concentrations in the ground water were about 7-9 mg/l; following aeration and filtration these levels were significantly reduced. Injection of aerated (oxygenated) water into the aquifer resulted in the reduction of dissolved iron to less than 0.3 mg/l upon recovery.

High Temperature Field Test Facility

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Pacific Northwest Laboratory is attempting to locate a suitable site for a high (150⁰C) temperature FTF. These efforts are being directed toward the Midwest, where aquifers with appropriate characteristics are known to exist.

3.5 COMPENDIA OF EXISTING INFORMATION

3.5 COMPENDIA OF EXISTING INFORMATION

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The objective of the Compendia Task is to collect, summarize, and transmit STES-related information. Compendia Task efforts will assist the future development of STES technology and will provide technical information for test facilities and demonstration projects.

Internal Activities - FY-1980

Library Establishment, Maintenance, and Development

This subtask will develop and maintain a useful library of STES-related information.

As a result of work done during FY-1979 and FY-1980, Compendia Task staff members have assembled a useful STES library. The library contains approximately 1400 articles with a wide range of key references on topics related to thermal energy storage. Although the library contains articles pertaining to many types of seasonal thermal energy storage, the main emphasis is on the storage of thermal energy in ground-water aquifers.

During FY-1979 and FY-1980, efforts were made to identify and procure STES-related articles. Customized searches were run on computerized data bases (including DIALOG and RECON), reference lists were obtained from the Compressed Air Energy Storage and the Geothermal Program libraries at PNL, and several national laboratories, including Lawrence Berkeley Laboratory (LBL) and Oak Ridge National Laboratory (ORNL), provided reference lists. These reference lists and data base searches were used to procure STES-related articles. Staff members working on the STES Program also helped identify articles for the library.

Library articles have been indexed according to author, title, and subject. A card file was established for each index and the card files are kept in the library. Periodically, the author index and subject index are printed for distribution.

Lawrence Livermore Laboratory is assisting PNL in the development of a STES data base. Bibliographic information from the library will be included in this data base. Each library article will be represented by an abstract, key words, and bibliographic information. Customized literature searches will be possible.

Future maintenance and development of the STES library will be subcontracted. The library will still be physically located at PNL, but library activities will be conducted by an external organization.

Literature Reviews and Summary Papers

The objective of this subtask is to summarize and reference important work on selected topics. This subtask will produce various papers covering topics pertinent to STES. These papers are intended to support other STES Program efforts by providing information on topics that are of concern to the program.

A preliminary list of topic areas has been compiled, and relative priorities have been assigned to these topic areas (Table 3.5.1).

Some of the topics listed in Table 3.5.1 will be selected for study by PNL staff members, and some of the topics will be studied under subcontracts. Three topics have been selected for study by PNL during FY-1980. These three topics are as follows: ATES site-characterization methods, regional aquifer assessments, and thermal fatigue of reservoir materials.

More topics will be selected for study during future fiscal years. Topic selection will reflect programmatic needs.

TABLE 3.5.1. Preliminary List of Topic Areas

<u>Topic Area</u>	<u>Relative Priority</u>
1. Site selection and regional assessments	High
2. Energy sources and uses	High
3. Fluid flow and energy transport in reservoirs	High
4. Environmental considerations	High
5. Legal and institutional considerations	Medium
6. Economic feasibility	High
7. STES-related experiments	Medium
8. STES-related mathematical and computer modeling	High
9. STES-related demonstrations	Medium
10. Nonaquifer storage methods	Medium
11. Well drilling and maintenance	Low
12. Well casing and screening materials	Low
13. Reservoir characterization methods	Medium
14. Reservoir pretreatment and rehabilitation	Medium
15. Well field design and operating criteria	High
16. Reservoir consolidation and subsidence	Low
17. Corrosion, scaling, and encrustation	Low
18. Thermal fatigue of reservoir and well materials	High
19. Wellbore and piping heat losses	Medium
20. Heat transfer equipment	Medium
21. Water treatment and filtering techniques	Low
22. Reservoir plugging mechanisms	High
23. Water quality	High
24. Reinjection	High

External Activities - FY-1980

Publication of the ATES Newsletter

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The objective of this subtask is to publish a quarterly newsletter containing brief reports about ATES projects around the world. The ATES Newsletter is now being published quarterly and has an international distribution list. The ATES Newsletter is a valuable means for disseminating current information about ATES projects.

Survey of Ground-Water Source Heat Pump Operations in the Portland Area

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This study will assess the use of ground-water source heat pumps for large-scale heating and cooling operations in the Portland area. It is scheduled to be completed in early FY-1981. Basically, the survey of ground-water source heat pump operations consists of the following tasks: 1) identification of sites, 2) documentation of system design, operational procedures, operational problems and overall system performance of each site, and 3) analysis of the heat pump operations. All of this information will be contained in a report that Oregon State University (OSU) will submit to PNL.

Oregon State University will also assess the potential benefit of using aquifer thermal energy storage in conjunction with ground-water source heat pumps. As part of this effort, OSU will study potential heat pump designs that can efficiently use ground water in a wide temperature range. The information from this effort will also be summarized in a report.

Survey of Ground-Water ReInjection Experience in Air Conditioning Applications

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The objective is to conduct a nation-wide survey of ground-water reInjection experience in air conditioning applications. Midwest Research Institute (MRI) has conducted a survey of air conditioning operations that use ground-water reInjection. Basically, the work consisted of three tasks: site identification, documentation of selected sites, and analysis of site data. The site identification task involved identifying sites across the United States where ground water is used for air conditioning operations and then is reInjected. Selection of sites was based on availability of information and geographic location. The sites chosen for documentation were representative of reInjection sites in different geographic locations and hydrogeologic environments. The second task involved documentation of the sites. Documentation of each site consisted of three parts: well system design, operational performance history, and an analysis of the reInjection experience. The third task, data analysis, involved the identification of real and potential problems with the reInjection operations of each site.

The results of the study will be contained in MRI's final report, which will be submitted to PNL in September 1980.

Regional Aquifer Assessment Study

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The objective of this study is to quantitatively describe the ATES potential of major aquifers throughout the United States. Century West Engineering has collected existing hydrogeological information for major aquifers throughout the United States. This information has been used to characterize each

aquifer. On the basis of its characteristics, each aquifer has been evaluated for its ATEs potential. This project should be completed during September 1980. Century West Engineering will submit to PNL a report containing evaluations of major United States aquifers.

Establishment of a STES Data Base on the Technology Information System

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The objective of this subtask is to establish a STES data base on the Technology Information System (TIS). The data base will provide easy access to bibliographic information from the library and to data files generated by the STES Technical Support Program and the ATEs Demonstration Program. Scientists at Lawrence Livermore Laboratory (LLL) have developed a data base system for DOE's Office of Advanced Conservation Technologies. This system, called the Technology Information System (TIS), will provide standardized information for research and development in energy storage systems. The TIS is a computer-based hierarchy of technical, econometric, and other data bases and models. These include physical and chemical properties of energy storage materials, characterization data for energy storage components and systems, and modeling programs for energy storage applications. Bibliographic information and numeric test data are also included. The TIS has been established for the use of program managers and project personnel under contract to DOE's Office of Advanced Conservation Technologies. Authorized users can achieve access to TIS from remote computer terminals by telephone dial-up.

A STES data base is being established on the TIS. Under an Interlaboratory Work Agreement, Lawrence Livermore Laboratory (LLL) is assisting PNL in this endeavor. STES staff members and subcontractors have access to the STES data base. The data base will contain bibliographic and numeric data files. It may also eventually contain some interactive models.

Study of Coupled Energy and Mass Transport in Geologic Media

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This study will examine the physical principles of energy and mass transport in geologic media. This project is intended to strengthen existing theoretical knowledge and to provide information on engineering design and site evaluation for ATEs systems. Research will focus primarily on energy transport mechanisms in the unsaturated zone of the unconfined aquifer system. The overall objective of this project is to identify soil and environmental conditions or parameters influencing aquifer thermal energy storage efficiency. Definition of these important parameters will provide needed technical support to the STES Program. The scope of research includes a thorough literature review, laboratory work, and limited computer modeling. The research is divided into two phases. The first phase consists of a literature review and a parametric analysis of important transport mechanisms pertinent to mass and energy transport in unconsolidated unsaturated porous media. In the second phase the research will further characterize transport mechanisms through laboratory experimentation.

An annotated bibliography and a preliminary interpretive report on the main facets of energy and mass transport will be submitted to PNL.

3.6 LABORATORY ANALYSIS

3.6 LABORATORY ANALYSIS

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The Laboratory Analysis Task will provide information required for development of ATES facility design, operation, and maintenance guidelines. Characterization of the mineralogy, ground-water chemistry, thermal diffusivity, fluid-flow properties (permeability, porosity), and thermomechanical properties (compressibility, friability) is essential for ATES site evaluation, selection, and operation. Such data are also required for numerical simulation.

Laboratory analyses can be of assistance in assessing operational problems like reservoir clogging and environmental problems like ground-water quality changes. Example studies include: particulate plugging, clay swelling and dispersion, rock-fluid incompatibilities, fluid-fluid incompatibilities, temperature-dependent mineral dissolution and precipitation, creep compaction, oxidation reactions, and gas exsolution.

The following laboratory support work was conducted in FY-1980:

- Design and construction of the STES Laboratory Flow Facility were begun.
- Generic investigation of temperature-induced permeability alterations and creep compaction was begun.
- Design was completed and construction began on the Mobile Injectivity Test apparatus.

The STES Laboratory Flow Facility will provide for testing of generic and site-specific aquifer/aquiclude media under simulated field conditions including time varying stresses, temperature, flow directions, flow rate, and brine chemistries. Measurables include sample strain (deformation), permeability, porosity, viscosity, pH, and dissolved and suspended constituent chemistry.

Investigations of temperature-induced permeability alterations and creep compaction will provide information for ATES design, operation, and maintenance guidelines. Work in FY-1980 involved compiling and reviewing of literature on temperature- and stress-induced changes in physical and chemical properties of porous materials, developing of a comprehensive laboratory experimental strategy, and beginning laboratory experiments on Ottawa sand and Massillon sandstone (measurement of permeability, compressibility and water quality under elevated temperature and stress conditions).

The injectivity test apparatus is a mobile field unit designed to permit pre-operational studies on well injectivity impairment. Membrane filtration tests, reservoir core flood tests, and laser particle counting comprise the major components of the test stand. Fluid samples upstream and downstream of the main heat exchangers are analyzed and a quantitative estimate of injection well longevity is made. Subsequently, recommendations are given concerning well backflush programs, filtration and/or chemical additive measures.

Activities for FY-1981 will be to:

- Complete the STES Laboratory Flow Facility construction and installation
- Continue generic investigations of aquifer stability at temperature and pressure
- Begin laboratory studies for Field Test Facilities (FTF) and demonstration projects.
- Complete the mobile well injectivity test apparatus and test at FTF site(s).

Laboratory experiments in support of Field Test Facilities and demonstration programs will be carried out at PNL and under subcontract. (The laboratory-based flow facility and the mobile injectivity test apparatus are being designed and constructed by Terra Tek, Inc.) Testing of the injectivity apparatus will be done at the high temperature Field Test Facility.

Activities for FY-1982 through FY-1985 are as follows:

- Complete generic investigation of porous media aquifer stability
- Evaluate aquifer stability for FTF and demonstration project sites
- Define mechanism(s) for STES induced changes in permeability, compressibility, and water quality
- Identify applicable procedures for aquifer preconditioning, maintenance and rehabilitation to prevent permeability degradation or adverse water quality changes.

Studies carried out under the Laboratory Analysis Task will provide for characterization of the mechanisms that could potentially cause injection/recovery impairment and water quality alterations under ATES operating conditions. Understanding of the mechanisms will allow development and application of preventive and/or remedial procedures.

Technical Progress and Preliminary Results of the Laboratory Analysis Task

Subtask 1 - Physical and Chemical Stability of Aquifer Materials

Efforts to date have centered on reviewing the available literature, new theoretical developments, experimental strategy, and identification and fabrication of test facilities. A topical report has been drafted covering the apparent degradation of permeability with moderate increases in fluid temperature. Researchers have observed a decrease of more than 50% in sandstone permeability to liquid water when the temperature is increased from 25⁰C to less than 175⁰C (Figure 3.6.1). Similar changes are not observed when dry nitrogen, mineral oil, or dry alcohol is used as the working fluid. Unfortunately, sample deformation and fluid viscosity changes at temperature have not been monitored in previous studies. Equipment is currently being constructed to permit simultaneous measurement of fluid temperatures, pressures, viscosities, and chemistry as well as the stress and deformation of the porous material.

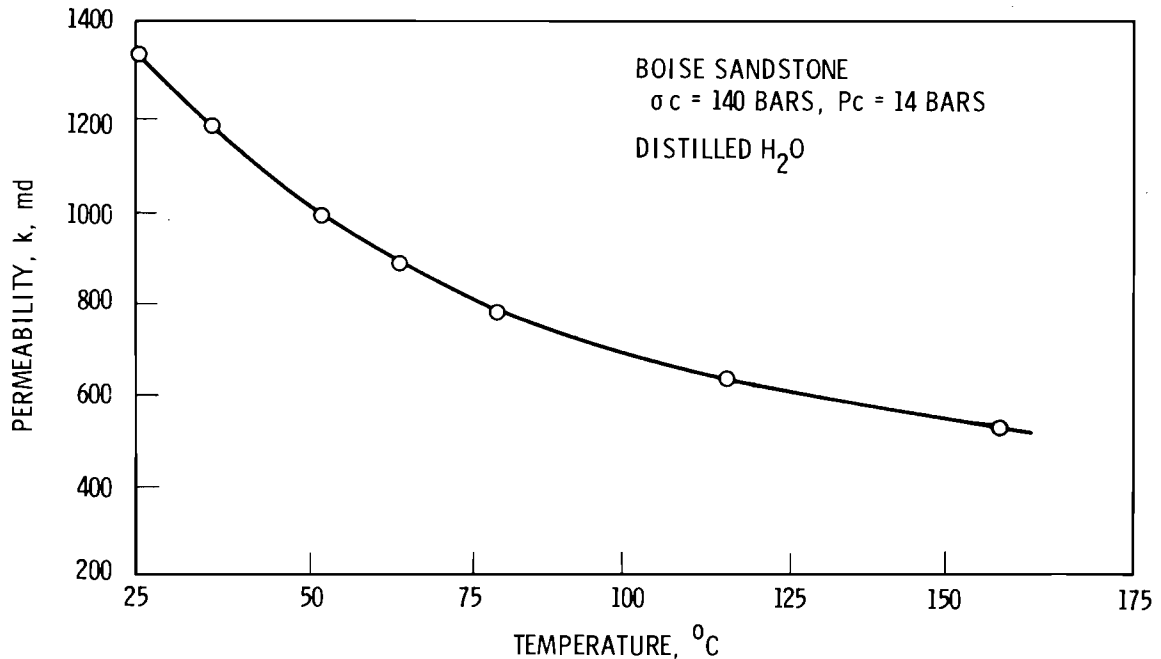


FIGURE 3.6.1. Example Permeability Versus Temperature Curve (Weinbrandt 1975)

Four potential causes for the observed permeability changes are being systematically explored: 1) sample consolidation or densification, 2) particulate plugging, 3) anomalous fluid viscosities, and 4) silica complexing with iron or nickel leached from the test apparatus. A schematic of the experimental apparatus is shown in Figure 3.6.2.

Information is being acquired on chemical equilibrium constants and reaction rates at temperature for some primary constituents in ground water. For example, Figure 3.6.3 contains data for quartz, calcite, and hematite at various temperatures. Figure 3.6.4 shows the time required to achieve 90% silica saturation in a quartz-water system. Ground-water constituents are shown in Table 3.6.1. Data are also being collected on thermal conductivity, thermal expansion, and specific heat capacities.

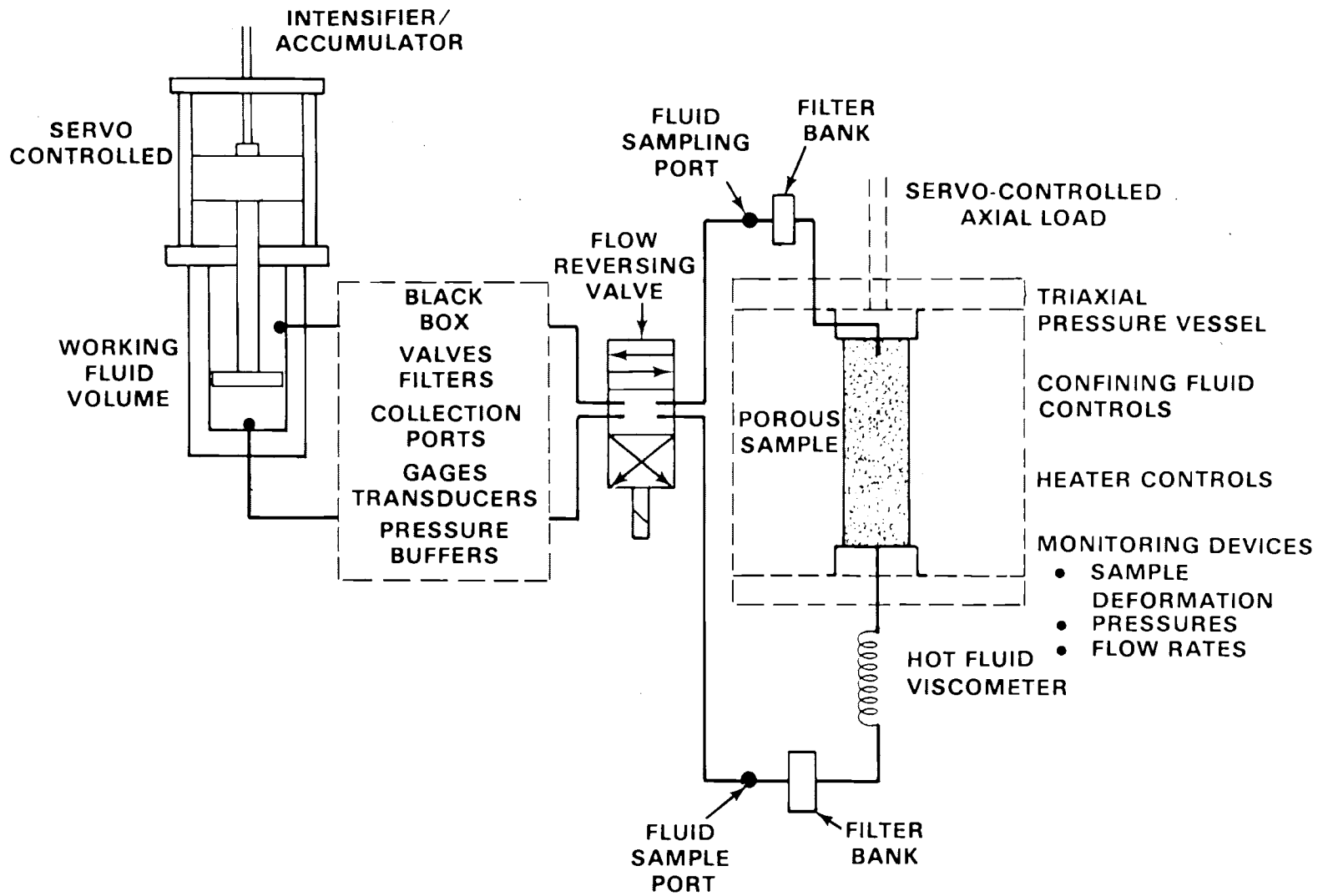


FIGURE 3.6.2. Simplified Schematic of the Experimental Stress-Strain and Fluid Flow Measurement Equipment

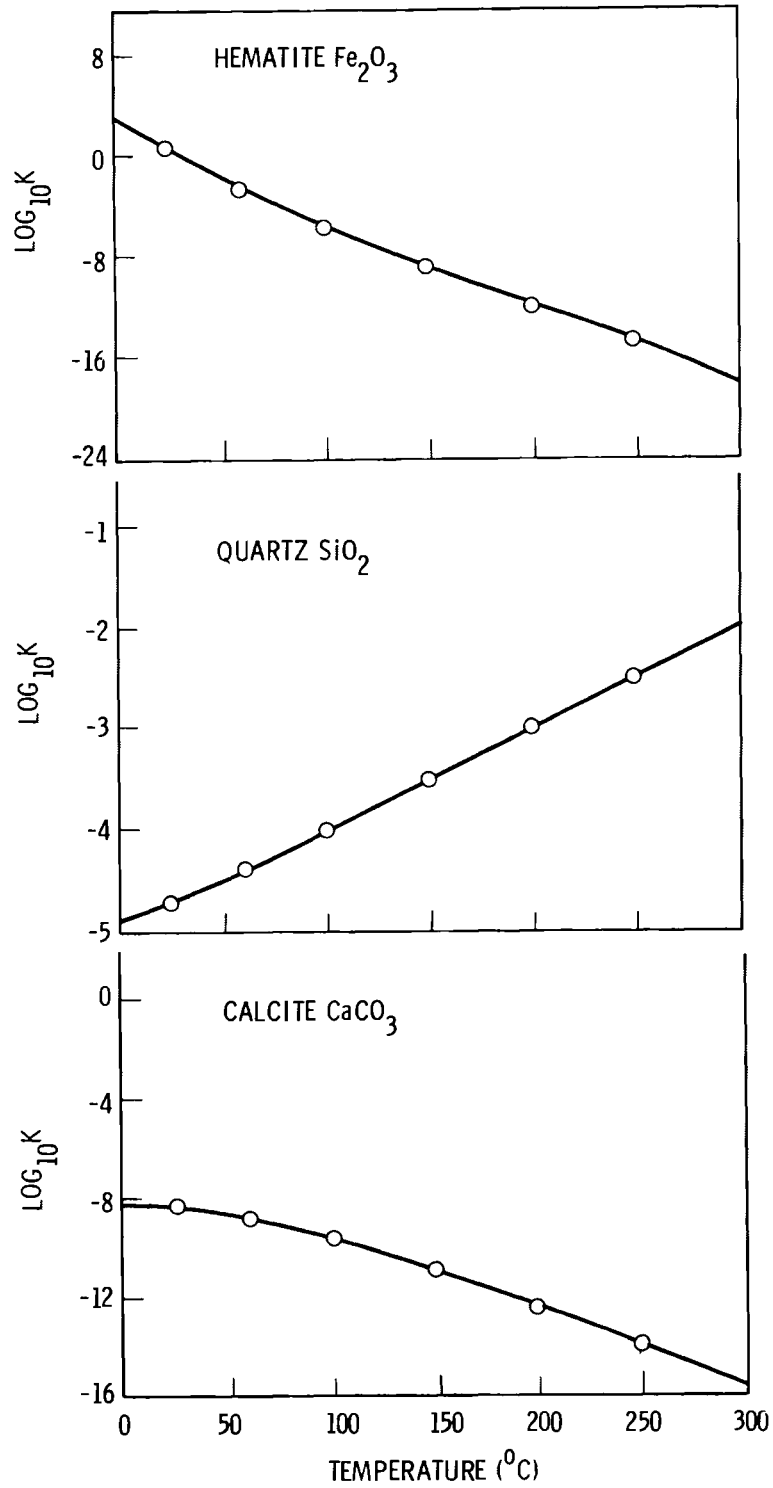


FIGURE 3.6.3. Example Equilibrium Solubilities

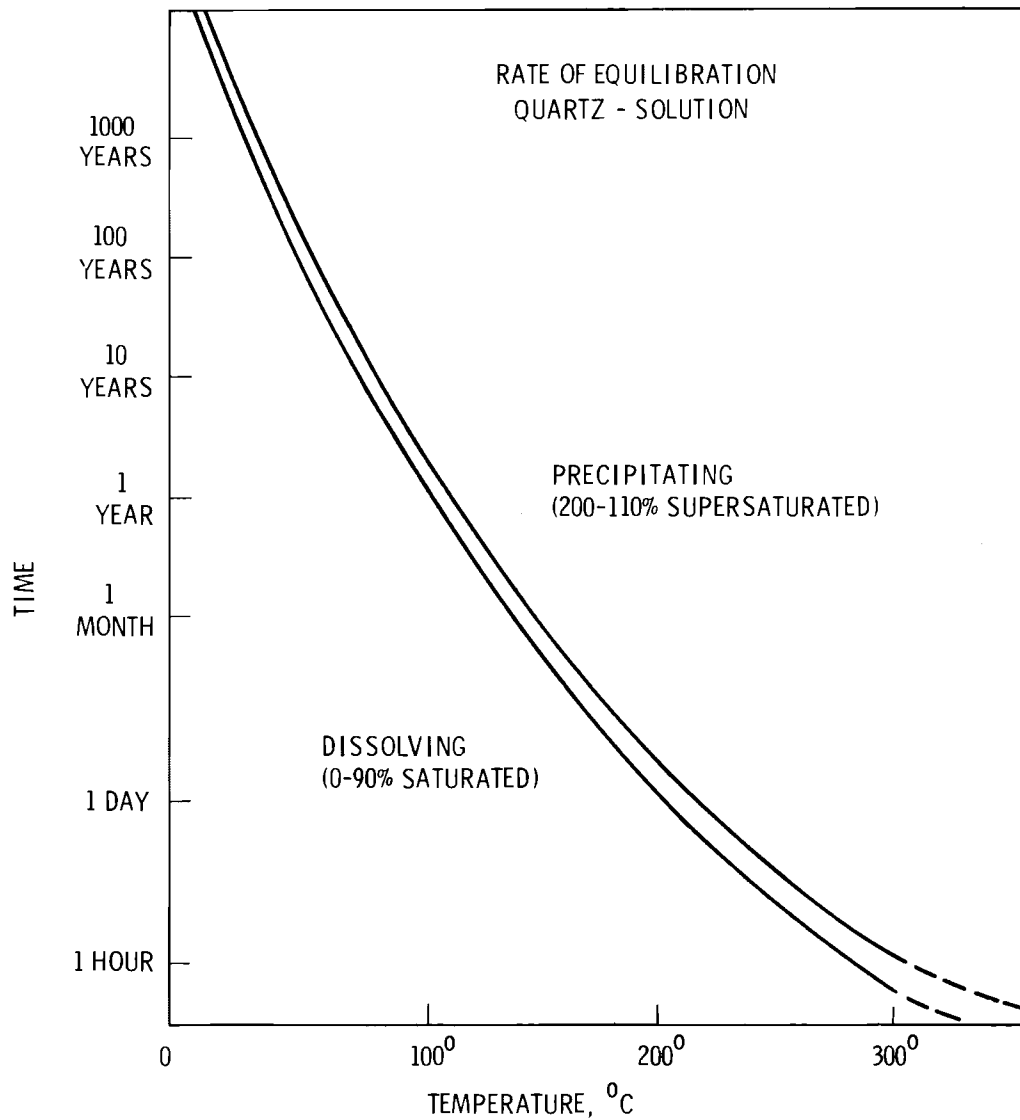


FIGURE 3.6.4. Time Required to Achieve 90% Silica Saturation in a Quartz-Water System (Rimstidt 1977)

TABLE 3.6.1. Chemical Constituents of Primary Importance

<u>Element</u>	<u>Required Detection Limit (mg l⁻¹)</u>
Ca ²⁺	0.1
Mg ²⁺	0.1
Sr ²⁺	0.1
Na ⁺	0.5
K ⁺	0.05
Li ⁺	0.1
NH ₄ ⁺	0.1
Cl ⁻	0.5
SO ₄ ²⁻	0.2
HCO ₃ ⁻ } CO ₃ ²⁻ }	0.1
S ²⁻	0.01
Fe ^{tot}	0.05
Al	0.02
Si	0.1
O ₂	0.1
PO ₄	0.1
Mn ^{tot}	0.1
Organic Carbon	0.1

Subtask 2 - Site Specific Field Support

Progress to date has been limited to preliminary development of field acquisition and handling procedures for sediment cores and ground-water specimens, and to identification of a suite of laboratory tests recommended for any given field site. The tests include, but are not limited to, the following:

- mineralogy and ground-water chemistry
- particle and pore size distributions
- clay swelling and particle dispersion potential
- particulate plugging and mineral scaling potential (injectivity impairment)
- simultaneous stress-strain/permeability tests
- water quality alterations
- well casing and pipe corrosion
- thermal diffusivity of caprocks.

Subtask 3 - Laboratory Support Capabilities Development

The primary support facilities include the aforementioned brine flow loop capable of elevated and cyclical temperature pressures, flow rates and directions, and the mobile injectivity test stand.

Additional facilities are currently available to measure thermophysical properties, clay swelling and dispersion potentials, casing corrosion, particle and pore size distribution, sediment mineralogy, and ground-water chemistry.

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3.7 NUMERICAL SIMULATION

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Activities of the Numerical Simulation Task include:

- developing a technology capable of predicting the transport and retrieval of a thermal energy resource within the ground-water environment
- conducting analytical analyses (exact or asymptotic) to demonstrate the sound mathematical/numerical character of the technology
- demonstrating the model's simulative ability through the simulation of experiments conducted by Auburn University.

Internal Activities - FY-1980

A previously developed model of ground-water flow for multidimensional systems has been employed as the core of the much broader model required for the technical support of STES. Energy- and solute-transport mechanisms have been added to the fluid (mass) transport model. The three partial differential equations are then solved in a cyclical, uncoupled solution scheme that employs the most current estimates of the dependent variable values in the evaluation of nonlinear contributions and forcing functions. Both density and viscosity are functions of the local pressure, temperature, and/or solute concentration. For efficient simulation of field problems with complex geometry, the model has been structured to execute in stages. The staged structure gives a user the opportunity to thoroughly check the geometric structure of the domain, the physical parameters of the problem, and aspects of the solution sequence prior to making the commitment of a complete run. An acronym has been adopted for this model. The acronym is CFEST, and it stands for coupled fluid, energy, and solute transport.

Exact or asymptotic analyses that will lend credence to the algorithm selected and developed have been identified from the literature. Specifically,

reports by Intercomp Resource Development and Engineering, Inc. (1976) and Tsang et al. (1978) include those analyses desired. Aside from standard solutions to line source/sink problems, these reports also identify approximate or asymptotic solutions by Avdonin (1964), Gringarten and Sauty (1975), Coats and Smith (1964) and Hoopes and Harlemen (1967).

The Numerical Simulation Task has completed the initial development of an interactive automatic mesh generation capability. As a first step toward a general two- and three-dimensional methodology, a two-dimensional areal field has been discretized. The mesh generator presently assumes a doublet axis collinear with the ambient ground-water movement. This assumption allows the discretization of a symmetric half plane. Extension of this mesh generation capability to include an arbitrary ambient flow will involve including the mirror image of the present half plane result. Further development to include the vertical dimension will employ a well-log technique. Single well applications or those having non-interfering doublets may make use of an axisymmetric analysis giving rise to a vertical plane. Automatic discretization of this domain is currently under development.

The Numerical Simulation Task has acquired data from the Lawrence Berkeley Laboratory. These data are sufficient for the calibration and verification of the model. Calibration and verification through the use of these Auburn University (Mobile, Alabama test site) data will not only provide a check with in situ measurements but will also provide an excellent comparison with predictions made by competitive models that are currently available.

External Activities - FY-1980

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The overall objective of the external activities of the Numerical Simulation Task is to produce a version of the INTERCOMP (1976) model that can

be run on a machine having a restricted word size. In particular, the program is being adapted to an IBM machine.

The adaption of INTERCOMP (1976) to the IBM facility will be documented through comparative analyses. The first segment of this work will involve analytical solutions, while the latter will entail the simulation of previous, current, and proposed Auburn University experiments at their Mobile, Alabama test site.

A copy of the INTERCOMP (1976) model has been put up on the IBM system and errors symptomatic of truncation processes have been identified. Current efforts are concentrated upon identifying and developing analytical solutions that will enable the isolation of cause-effect in the truncation processes. Most significant errors have been found in the mass and energy conservation check algorithms. The use of double precision for specific arrays and algorithms is being investigated.

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Simulation of Texas A&M Chill Experiment. A study paralleling that done for the Auburn University experiment shall be completed for the Texas A&M chill experiment. The rationale used to select simulation parameters will be defined and documented. An evaluation of the quality and completeness of the data shall be made. Simulation of the experiment shall follow the justification of any assumptions or simplifications made in experiment's numerical analogue.

Formal agreements are being put in place in order to complete the reporting phase of the Texas A&M experiment. As a result, the data have not yet been made available to the Earth Sciences Division of Lawrence Berkeley Laboratory (LBL). Current action at LBL is focused upon a revision of the convection, conduction, and compaction (CCC) code. This revision will incorporate a more economical direct solution processor.

Generic and Parameter Studies. Using models developed for the numerical simulation of confined aquifer STES installations, LBL personnel shall seek to identify key dimensionless parameter groups that characterize the hydrothermal processes and recovery efficiency of typical STES facilities. The basic objective is the development of a general approximate graphical or semi-analytic technique that will predict energy recovery factors for a given aquifer and operational design.

The CCC code is presently being employed to examine parameters involving: 1) vertical heat loss to confining layers, 2) radial heat loss due to smearing and tilting of the thermal front, and 3) the characteristic tilting time of the thermal front due to buoyancy flow. These parameter groups are expressed in terms of thermal and hydraulic properties of the STES system. Calculations tentatively indicate the uniqueness of these dimensionless groups for temperatures ranging from 35⁰ to 90⁰C. In addition to the above work, the linear flow model developed by Lund University, Sweden, is being employed in an investigation of recovery efficiency. An optimal aspect ratio (thermal front radius/aquifer thickness) has been identified. Beyond a certain point, increasing injection volume does not substantially improve the recovery factor.

(In addition to C. F. Tsang, Tom Buscheck and Christine Doughty of the Earth Sciences Division of LBL are involved in this work (415-486-6071).)

Evaluation of Auburn University's Field Test Facility Design. Using the numerical simulation abilities of the CCC code, investigators will evaluate and suggest improvements to the experimental design of Auburn University's Field Test Facility (FTF). Numerical simulations suggesting the recovery efficiency and implied impacts of both the 55⁰ and 90⁰C full cycles shall be provided for the facility and operational designs that are finally adopted.

This work is divided into two phases. The first phase involves the evaluation of the proposed design and the second phase tests the predictive ability of the CCC code. Evaluation of the proposed design was completed in June of 1980. Construction of the Mobile, Alabama facility will soon be initiated.

Unconfined Aquifer Model

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Personnel from LBL will evaluate the concept of an unconfined aquifer model for simulating fluid and energy flow. A numerical simulation capability (perhaps modeled after the confined aquifer CCC code) shall be provided for the coupled, unsaturated-saturated unconfined aquifer. Such a model will include the coupled mechanisms of fluid and energy transport.

This objective has only recently been identified and initiated. A report on the feasibility of this technology is due at the conclusion of the fiscal year.

Future Activities

In fiscal year 1981, the emphasis in numerical simulations will shift from the analysis of confined aquifers to that of unconfined aquifers. It is currently proposed to examine the saturated-unsaturated interfaces's transport phenomena through the use of a sand box model. Such a physical model may also be used to generate data with which to verify numerical simulations. To assure the timely development of unconfined aquifer predictive ability, PNL and LBL will coordinate a joint effort in the area of numerical simulation.

A compendium of state-of-the-art thermal modeling will be prepared during the coming year. This document will provide participants in the ATES Demonstration Program with a reference for analysis of specific problems.

Also in FY-1981, the Numerical Simulation Task will seek techniques for the solution of simplified flow fields. These analyses will address environmental questions concerning the long-term effects of ATES facilities on down-gradient users of the aquifer system.

Fiscal years 1982 through 1985 will see a continuation of earlier efforts as well as the development of a more general and comprehensive numerical

simulation ability. Site-specific modeling of demonstration projects by independent professionals (PNL, LBL) will assure the selection of optimum Phase II candidates within the demonstration program. Results from the flow facility will allow for numerical simulation of the effects of thermomechanical and thermochemical alteration of permeabilities. The impact of regional flow control upon design and economics may have to be included in our analyses. Well system designs that could be used instead of the doublet well system must also be analyzed. Operational theory for the optimum management of nonisothermal aquifers will be an important topic of study during this period of demonstration project start-up.

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3.8 NON-AQUIFER STES CONCEPTS

3.8 NON-AQUIFER STES CONCEPTS

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The objectives of this task are to select promising non-aquifer thermal energy storage concepts for seasonal applications and to perform further research that can lead to their use.

While the current thrust of the STES Program is in aquifer storage, this task will assess other storage systems such as large pond storage, earth storage, chemical storage, ice storage and other more advanced concepts. These systems, in combination with aquifer storage as a hybrid system, may ultimately prove to be most economical.

The general approach used to accomplish the task objective is as follows:

- Survey proposed non-aquifer STES systems to evaluate the following:
 - operating characteristics
 - possible applications
 - potential thermal effectiveness
 - potential cost effectiveness.
- Select promising concepts for more detailed evaluation of potential energy savings and thermal and cost effectiveness.
- If warranted, develop a program to fully evaluate particularly promising systems.
- Establish and maintain a library of information on non-aquifer concepts.

Internal Activities - FY-1980

Internal activities during FY-1980 included: establishing and maintaining a library and performing a preliminary evaluation of concepts.

Future Activities

Future activities of this task will include the following: maintaining and further developing a library of information on non-aquifer concepts, keeping current with developments of new concepts, investigating and evaluating the gamut of non-aquifer thermal energy storage concepts for use on a seasonal basis, selecting the most promising STES concepts for further study, performing detailed studies and experiments to verify the technical and economic viability of the best concepts, and assisting in the commercial implementation of the practical concepts.

Preliminary Findings of the Non-Aquifer STES Concepts Task

A large amount of literature was scanned to review non-aquifer thermal energy storage methods that might be used on a seasonal basis. The literature review included publications as recent as July 1979. Since the oil embargo in 1973, many paper studies and much laboratory work has been done to research Thermal Energy Storage (TES). Most of the research has been done in support of solar energy and the use of industrial waste heat. The research applies primarily to hourly and daily storage, rather than seasonal.

The most developed TES methods are also for the hourly and daily category. The only applied development on a large-scale for seasonal TES has been using aquifers at Auburn and Texas A&M Universities. Non-aquifer STES applied development has been limited to small-scale solar ponds.

Sensible TES

Sensible TES is the most advanced technology because of its simplicity and low cost. It will be the first TES method to be implemented on a large-scale. In Europe, daily storage with off-peak electrically powered MgO, Al₂O₃ and cast iron TES furnaces is a well-developed concept. The concept will also be used in the U.S. when utilities and regulating agencies incorporate the practice. Use of off-peak power for STES applications may also receive some attention. Hot water heater tank TES is an old and well-developed method that only applies to daily or weekly storage.

Hourly and daily storage with high temperature pressurized water (more than 100°C) is also well developed. But due to the high cost of pressure vessels, longer duration storage is unlikely. This concept is used mainly to supply peaking steam and to heat boiler feedwater.

Daily and weekly storage systems using water and or rocks are used extensively in solar home heating applications. Masonry walls are used for solar passive heating. Earth and wet earth (mud) storage have been used in agriculture applications by private developers.

Large insulated pond TES with water appears to be one of the most promising STES methods. Large volumes of low temperature heat (more than 90°C) can

be stored at a low cost. This would be attractive for district water heating and agricultural uses. Coupled with heat pumps in buildings, this method can be used for both heating and cooling when two ponds are used. This method provides a viable option to aquifer TES where aquifer storage is not practical. Ponds can also be covered with solar heat collectors to provide a source of heat for the pond.

Wet earth TES also has potential for STES systems and should be studied further.

Other concepts which may be used for STES include natural lakes and ponds, solar ponds, mine open pits, caverns and rock TES. Use of these concepts are very site specific.

Large, insulated tanks are worthy of consideration because they may be used in a wide variety of places and their relatively high cost may be offset by good storage efficiency.

Latent TES

Overall, the use of latent heat for TES is not a well developed method. It is usually more complex and costly than sensible heat concepts.

Use of latent heat in STES applications will probably be limited to building and refrigeration ice cooling in the near term. Compacted winter snow and ice can be harvested and placed in a insulated reservoir for summer cooling of buildings or refrigeration of crops. Sites for use of this method are limited, however, and ice harvesting economics must be studied.

Glaubers salt and paraffin are being experimented with for daily low temperature TES. Salts and eutectics are being developed for daily TES high temperature applications like power generation, boiler feedwater pre-heating and industrial process heating.

Due to high cost of materials, heat exchangers and containment, latent heat TES will be limited to hourly, daily, and perhaps weekly applications. Use of a hybrid concept of water and encapsulated phase change material (PCM) may be used to provide daily fixed temperature buffer storage for a STES system.

Thermochemical TES

Thermochemical TES is even less developed and more complex than latent TES. The development work in this area has been limited to paper studies and laboratory scale tests. The only concept advanced far enough to be considered for seasonal use in the next five years is the sulfuric acid/water heat pump being developed by Rocket Research.

There are conflicting reports about thermochemical TES having potential for STES applications. Engineering and full scale tests will have to be performed before the potential of thermochemical TES can be determined.

Recommendations

Based upon this preliminary evaluation it appears that the most promising non-aquifer STES concepts for more detailed evaluation are:

Sensible STES Heating^(a)

- Large (more than 100,000,000 gallons) engineered insulated pond TES with 95°C water
- Wet earth TES with less than 95°C water
- Natural lakes and ponds, solar ponds, mines, caverns, rocks, and large tanks.

Latent STES Cooling

- Ice and compacted snow TES.

Thermochemical STES Heating and Cooling

- Sulfuric acid/water heat pump at 66° to 200°C.

Use of these concepts with conventional and high temperature heat pumps should also be evaluated further.

These recommendations are based upon a rapid review and assessment of the literature. Further study may reveal some promising concepts that are not

(a) Cooling with heat pumps.

included. Also, current research and development studies may improve the potential of other concepts that are presently unfeasible.

Large thermal energy inventories and low inventory turnover rates are needed for STES. Many of the more expensive storage concepts now under development can only be justified on a daily or weekly basis due to their higher inventory turnover rates.

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