Thermal Energy Storage in Aquifers - Preliminary Information

R. D. Allen

December 1979

**Prepared for the U.S. Department of Energy
under Contract EY-76-C-06-1830**

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

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or 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.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract EY-76-C-06-1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy \$ ____*; Microfiche \$3.00

*Pages	NTIS Selling Price
001-025	\$4.00
026-050	\$4.50
051-075	\$5.25
076-100	\$6.00
101-125	\$6.50
126-150	\$7.25
151-175	\$8.00
176-200	\$9.00
201-225	\$9.25
226-250	\$9.50
251-275	\$10.75
276-300	\$11.00

3 3679 00053 1469

THERMAL ENERGY STORAGE IN AQUIFERS -
PRELIMINARY INFORMATION

R. D. Allen

December 1979

Prepared for
the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

Aquifer storage of chilled and heated water is drawing international attention because of the growing need to conserve and store energy. Aquifers are underground formations of water-saturated permeable rock or unconsolidated sediments. Most aquifers are flat lying or gently inclined, ranging in depth from several meters to several kilometers. Unconfined aquifers are below the vadose zone and may accept downward percolating groundwater whereas confined aquifers are bounded above by low permeability rock members which retard vertical migration of water. Confined aquifers receive water through unconfined "windows" or fracture systems, horizontally removed from the zone of confinement. The concept of aquifer storage arose because permeable formations are widespread in geologic occurrence, offer very large volumes of thermally insulated containment, and can be economically utilized with existing hydraulic technology. In general, manufactured storage devices, such as insulated tankage, are not economically competitive with these naturally available media.

An Aquifer Thermal Energy Storage (ATES) system injects water at low ($T < 90^{\circ}\text{C}$), medium ($90^{\circ}\text{C} < T < 150^{\circ}\text{C}$) or high temperature ($T > 150^{\circ}\text{C}$) into an aquifer through one or more wells. The low temperature category includes both chilled and warm water. A confined aquifer is generally preferred for low temperature storage and is required for medium and high temperature storage. The operating cycle consists of the injection, storage, and withdrawal periods. A practical withdrawal and injection system requires two or more wells. In the two-well arrangement, ground water is pumped from Well No. 1, heated or cooled to the desired temperature, then injected into Well No. 2. During utilization the fluid is pumped from Well No. 2, passed through a heat exchange cycle, and reinjected into Well No. 1. The temperature of the reinjected "spent" water is not greatly different from the ambient temperature of the ground water. Practical moderate-to-large systems will require design and development of multiple well fields.

The dual or multiple well arrangement maintains most of the water within the aquifer throughout the operational and storage periods because water withdrawn is reinjected immediately after passage through the heat exchanger. Computer models and experimental field data indicate that thermal recovery efficiencies may exceed 70% for confined aquifers from which water is pumped at reasonable flow velocity. Efficiencies for shallow unconfined aquifers may be lower unless an unsaturated zone of reasonable thickness prevents dilution by surface waters and thermal losses to the atmosphere.

Temperature conditioning of the water may be accomplished by outdoor winter evaporative chilling, by heat exchange with rivers or lakes, by commercial or industrial waste heat exchange, by cogeneration or heat exchange at an electric generating plant, or by solar heating. Potential applications include air conditioning, space heating, domestic and process water heating, and electrical power generation.

Although the economic feasibility of chilled water systems has not yet been demonstrated, feasibility is believed to be adequate for low temperature warm water storage. Evaluation of medium temperature water storage must await field testing. Superheated water for use in electrical power generation may require storage below 1677 m within a confined aquifer. Downhole pumps with large capacity would be needed to inject and retrieve the working fluid. In addition, silica scale deposition in high temperature, high pressure steam turbines could impact the cost of operation. Reinjection of water in a closed system might alleviate this anticipated problem.

CONTENTS

	<u>Page</u>
SUMMARY	iii
FIGURES	vii
TABLES.	ix
1.0 INTRODUCTION	1
2.0 CONCLUSIONS.	7
3.0 CONCEPTUAL DESIGNS	9
3.1 J.F. KENNEDY INTERNATIONAL AIRPORT.	9
3.2 NEGEV, ISRAEL	11
3.3 SWITZERLAND	12
3.4 GERMANY	14
3.5 DENMARK	15
4.0 NUMERICAL MODELING	17
4.1 LAWRENCE BERKELEY LABORATORY.	17
4.2 U.S. GEOLOGICAL SURVEY.	27
4.3 SWEDEN.	28
4.4 OTHER MODELS.	31
5.0 FIELD EXPERIMENTS.	33
5.1 TEXAS A & M UNIVERSITY.	33
5.2 AUBURN UNIVERSITY	37
5.3 KREFELD, GERMANY.	45
5.4 CAMPUGET, FRANCE.	45
5.5 JAPAN	47
5.6 PEOPLES REPUBLIC OF CHINA	49
6.0 RELEVANT TECHNICAL INFORMATION	51
6.1 COGENERATION OF ELECTRICITY AND HEAT.	51
6.2 HIGH TEMPERATURE STORAGE.	52
6.3 AQUIFER SIMULATION.	55
6.4 PETROLEUM EXPERIENCE IN WATER INJECTION	55
7.0 FEASIBILITY STUDIES.	59
7.1 BELLINGHAM, WASHINGTON.	59

	<u>Page</u>
7.2 TVA PROJECT	60
7.3 TWIN CITIES, MINNESOTA.	61
8.0 PRELIMINARY AQUIFER SELECTION CONSIDERATIONS	65
9.0 PRELIMINARY DESIGN AND OPERATING CONSIDERATIONS.	67
REFERENCES.	71
APPENDIX. NUMERICAL SUMMARY.	A-1

FIGURES

	<u>Page</u>
1. Conceptual Well Doublet System Installed in Confined Aquifer.	3
2. Calculated Isotherms in Aquifers with Partial Penetration	19
3. Calculated Isotherms for a Two-Well System with Full Penetration.	20
4. Energy Recovered as a Percentage of Energy Injected Versus Cycle Number	21
5. Calculated Production Temperatures from Chilled Water Storage	22
6. Calculated Isotherms in an Aquifer with a Clay Lens	23
7. Calculated Isotherms in Aquifers with Simulated Inhomogeneities	24
8. Calculated Energy Recoveries from Aquifer Storage	25
9. Well Site Log and Construction Details for Both Injection and Pumped Wells.	34
10. Schematic Diagram Showing the Details of the Project Site near Mobile, Alabama	38
11. Fence Diagram of the Well Field Penetrating the Storage Formation	39
12. Schematic of Second Aquifer Experiment at Auburn University.	41
13. Cogeneration Plant and Hot-Water Transmission Pipelines for Minneapolis District Heating System	62
14. Schematic Diagram of Heat Storage Well Doublet Operation	63

TABLES

	<u>Page</u>
1. Operating Characteristics for Conceptual System at Negev, Israel.	12
2. Characteristics of Conceptual Swiss Aquifer Heat Accumulator	13
3. Geometrical and Operating Characteristics for Two Spherical Heat Accumulators	13
4. Characteristics of a Danish Aquifer Warm Water Storage Plant	15
5. Energy Input/Output Data for Five Cycles.	26
6. Energy Input/Output from an Aquifer Model over 6 Years	29
7. Energy Input/Output from Storage Cyclinders Over 5 Years	30
8. Characteristics of Prototype System at Texas A & M University.	35
9. Physical Characteristics of the Auburn University Aquifer	39
10. Characteristics of the Aquifer Storage System at Campuget.	45

THERMAL ENERGY STORAGE IN AQUIFERS - PRELIMINARY INFORMATION

1.0 INTRODUCTION

The basic function of an energy storage system is to accept, store and discharge energy in accordance with availability and demand. Thus, a thermal energy storage system provides a buffer between time-dependent energy inputs and thermal and/or electrical power loads. Energy may be supplied to storage as water heated by a working fluid from a solar collection system, by an industrial or utility waste heat source or by a cogeneration power plant. Conversely, chilled water may be stored for future use in air conditioning.

Aquifers are units of permeable rock or unconsolidated sediments which contain and may conduct water. Most aquifers are of sedimentary origin and are either flat-lying or gently dipping within a particular locale. Aquifers range in depth from as little as 2 m to several kilometers below ground surface. Confined aquifers are bounded above and below by strata with very low permeabilities which prevent vertical transport of water out of the aquifer; these aquifers are saturated with water at pressures determined by the vertical distances to their associated water tables. Because of their large volumes of available containment, aquifers have been used to store natural gas and liquid wastes. Their potential use to store water at high, medium or low energy levels is a relatively new concept inspired by the need to manage energy efficiently.

The features of confined aquifers which coincide with design requirements include: 1) large volumes, e.g., on the order of 10^7 m³; 2) low thermal conductivities of overlying and underlying strata; 3) discovery water pressures sufficient to store thermally conditioned water; 4) sufficiently high transmissivity to accept high input and supply high output rates; 5) fluid migration rates sufficiently low to

maximize thermal containment and recovery; 6) environmental acceptability; and 7) geographic proximity to energy supply and consumption points. For unconfined aquifers, those without a sealing caprock, Condition 3) does not apply. Relatively near-surface aquifers of this type may be economically utilized over modest temperature ranges because of lower drilling and pumping costs.

Aquifer thermal energy storage (ATES) systems operate in three modes: 1) fluid withdrawal/energy conditioning/injection; 2) fluid storage; and 3) fluid withdrawal/utilization/reinjection. At least two wells are needed to conserve the large volume of water necessary to repeatedly deliver and accept thermal energy. A conceptual well doublet system which utilizes a confined aquifer is shown in Figure 1.

To determine the feasibility and effectiveness of an aquifer storage system, the behavior must be evaluated during injection, storage, and withdrawal portions of the first and subsequent cycles. Factors important to aquifer utilization include: 1) adequate input/output energy rates during successive cycles; 2) negligible degradation of permeability due to physical, chemical or biological processes; 3) structural compatibility of the aquifer system with fluctuations in the temperature and pressure of the working fluid; and 4) maintenance of water quality.

This paper summarizes pertinent developments in aquifer energy storage technology, and includes theoretical and experimental data reported in the literature. This information is designed to assist in the selection of suitable aquifers and design of storage facilities. The material is presented according to the type of study involved because particular investigations do not address a single level of thermal storage.

ATES conceptual designs discussed in Section 3 include: 1) winter chilling of water at JFK Airport with storage for use in summer air conditioning; 2) storage of waste heat from an electrical power plant in Israel to irrigate winter crops; 3) storage of industrial waste hot water to supply space and domestic water heating for a small Swiss city; 4) an artificial aquifer design used in Germany; and 5) aquifer storage of hot water for district heating in Denmark.

- 1 - CONFINED AQUIFER
- 2 - AQUITARD (IMPERVIOUS LAYER)
- 3 - IMPERVIOUS UNDERLYING FORMATION
- 4 - UNCONFINED AQUIFER
- 5 - WATER TABLE
- 6 - VADOSE ZONE
- 7 - HOT WATER INJECTION REGION
- 8 - WATER SOURCE / REINJECTION REGION
- 9 - WELL CASING
- 10 - WELL SCREEN / PUMP
- 11 - EDUCTOR / INJECTOR PIPE
- 12 - GROUND SURFACE
- 13 - HEAT EXCHANGER
- 14 - HEAT STORAGE FLOW DIRECTIONS
- 15 - HEAT UTILIZATION FLOW DIRECTIONS

FIGURE 1. Conceptual Well Doublet System Installed in Confined Aquifer

Numerical models of aquifer liquid thermal storage system behavior, described in Section 4, include those developed at the Lawrence Berkeley Laboratory, U.S. Geological Survey, in Sweden, and in Japan. Modeling efforts are also reported in Denmark, France and Switzerland. An hydraulic model developed at Pacific Northwest Laboratory has been modified to include energy and solute transport in porous media.

Field experiments are described in Section 5. Experiments at Auburn University are providing valuable experience in ATEs system operations.

Section 6 addresses cogeneration of electricity and heat, high temperature storage, aquifer simulation, and petroleum experience in water injection. In cogeneration a small increment of heat is added to the plant cooling water.

Feasibility studies for proposed demonstrations, described in Section 7, are under way at Bellingham, Washington, TVA Project, Tennessee, and Twin Cities, Minnesota. Separately managed Bellingham Projects could use waste heat from the Intalco Aluminum Company smelting plant and waste heat from a garbage burning plant, respectively. The Twin Cities Project is based upon cogeneration of power and heat. The TVA Project consists of identifying potential sources of thermal energy, aquifer storage criteria and sites, and potential energy consumers.

Preliminary aquifer selection considerations have been defined relative to qualitative hydrological, geological, thermal, mechanical, mineralogical and geographic characteristics (Section 8). Preliminary design and operating considerations have been developed (Section 9) which include the following: 1) impact of operation on permeability and geologic containment; 2) monitoring requirements; 3) volume and efficiency requirements; 4) water migration due to hydraulic and thermal gradients; 5) water chemistry including suspended solids; 6) system design, e.g., well diameter and depth; 7) system size, e.g., number of wells; 8) aquifer improvement measures; 9) environmental impact; 10) geostatic pressure requirement for superheated water; and 11) economic

factors. Some of these qualitative considerations will be subject to quantification, modification, or rejection as the results of the Seasonal Thermal Energy Storage program become available.

The appendix cites quantitative properties of aquifers and characteristics associated with aquifer storage technology.

•
•
•

•

•

•

2.0 CONCLUSIONS

The conclusions itemized in this section are based primarily upon explicit statements and implicit findings expressed by the authors of articles cited in this document. An attempt has been made to avoid conjectural or questionable deductions. It must be realized that thermal energy storage in aquifers is likely to evolve substantially in the years ahead. As a consequence, some of these conclusions are likely to be modified or fortified by future experiments and demonstrations.

1. Existing technology is adequate to develop low temperature water storage in aquifers at the experimental level. However, chilled water storage and utilization may not be economically practical.
2. Space heating and domestic/process water heating are the most likely near-term applications.
3. Storage of superheated water for power generation may require a depth of 1677 m or more and resolution of pumping and geochemical problems which could impact storage efficiency and equipment reliability/ maintainability.
4. Energy recovery efficiencies from confined aquifers may exceed 70% after two or more cycles.
5. Numerical models describing the liquid injection/storage/withdrawal cycle now include most known important parameters of heat and mass transfer. However, models are limited by the properties and dimensions assumed. Particular refinements may be developed by comparisons with field test data.
6. Unconfined, near-surface aquifers may be useful, despite probable lower recovery efficiency, because of lower capital and operating costs, and greater availability than confined aquifers.
7. Aquifer storage systems must not deleteriously impact the hydro-sphere by solute contamination or thermal pollution. Although not anticipated as a problem, uplift and subsidence, if either occurs, must be minimized.

8. Preliminary economic analysis, based on cogeneration of electricity and hot water, shows total potential thermal energy recovery 30% to 50% higher than the additional energy input because much of the heat previously lost through cooling water and stack exhaust would be retrieved.
9. The required reservoir volume and system cycling characteristics are determined by thermal supply and demand as functions of time.

3.0 CONCEPTUAL DESIGNS

Conceptual designs of aquifer thermal energy storage systems include the broad features of energy supply, reservoir location and configuration, and energy utilization. Detailed hardware design and assembly are not addressed. Several projects have contributed novel design ideas.

3.1 J.F. KENNEDY INTERNATIONAL AIRPORT

Storing winter cold for air conditioning is being studied for technical and economic feasibility under a joint U.S. Department of Energy and New York State Energy Research and Development Administration grant at JFK Airport (Hibshman 1978; Singer 1978). Cold water would be stored in an extensive confined aquifer. The concept involves withdrawal of ground water in winter during electrical off-peak hours, cooling it with winter air, and storing it in the aquifer at 2.2°C (36°F) to 3.3°C (38°F). During the air conditioning season, the cool water would be withdrawn to supply chilled water for air conditioning at 7.2°C (45°F). The warmed water would then be recharged into the ground at another location or discharged into Jamaica Bay.

It is planned that the study result in a demonstration system designed for broad application both within New York State and nationwide. The JFK site offers the opportunity to study a large installation in an urban setting. The project will address a peak air conditioning capacity load of 24,000 tons. As with typical commercial sites, the air conditioning load is large relative to the heating load. This is due to the concentration of people, machinery, lighting and working hours between 7 a.m. and 7 p.m. System design will minimize peak load operation and maximize off-peak pumping utilization. The system will employ hybrid operating modes to optimize utilization of stored cool water from the aquifer and minimize on-peak pumping requirements. For example, ice may be produced during off-peak hours to meet peak midday energy requirements.

The program is a four-phase investigation and demonstration of technical and economic feasibility. Phase I, a preliminary engineering and economic evaluation, was completed in September 1978. Phase I considered alternative methods of cooling the aquifer water (air versus Jamaica Bay water), use of the cooling towers and sensible heat exchangers; developed preliminary cost estimates; and addressed the technical feasibilities of below- and aboveground systems. This study suggested a potential installed system payback of 3.5 to 8 years.

Phase Ia and b are now in progress (Singer 1978). Phase Ia consists of an exploratory drilling program whereas Phase Ib is a review of the engineering, economic and technical conclusions from Phases I and Ia. It also includes an environmental impact analysis, and an analysis of the aboveground system. Drilling of four, 10.16-cm (4-in) diameter test borings and observation wells was completed in November 1978.

The purpose of drilling was to refine the cost estimates of the well system, to determine the water quality of the aquifer, and to determine surface subsidence potential with time. The four wells range in depth from 130.8 to 152.4 m (429 to 500 ft). Of particular interest were the thickness and compressibility of the confining stratum, the Gardiners Clay unit; and the thickness, permeability and transmissivity of the Jameco and Magothy aquifers. The four drilling sites were chosen to identify the extents of the aquifers.

The holes were geophysically logged for resistivity, spontaneous potential, gamma, and caliper. Samples were inspected for lithology and laboratory tested for moisture density, hydrometer measurements, consolidation, permeability, and particle size distribution.

The thickness of the Gardiners Clay formation ranges among 28.4 m (93 ft) in the farthest east boring (well #3), 26.2 m (86 ft) in the south (well #2), 16.2 m (53 ft) in the west (well #1), and 13.4 m (44 ft) in the north (well #4). The dip of the formation is approximately southeast. The Jameco and Magothy aquifers, on the other hand, dip southwest. The total thickness ranges from 54 m (177 ft) in the farthest west boring to 26.5 m (87 ft) in the east, and from 48.5 m (159 ft) in

the south to 45.1 m (148 ft) in the north. Of particular interest was the highly permeable Jameco (estimated permeability from 8,759 to 81,475 l/m^2 day (215 to 2,000 gpd/ft²) with thickness 9.1 to 12.2 m (30 to 40 ft) in well #1, 15.2 to 18.3 m (50 to 60 ft) in the most southerly point, 21.3 to 24.4 m (70 to 80 ft) in well #3, and 27.4 to 30.5 m (90 to 100 ft) in well #4.

The permeability data indicate an adequate confined aquifer, having a thick consolidated confining aquitard. Subsidence should not be a major problem. Additional study will be required to confirm this conclusion for the specific site location.

Future studies (Singer 1978) will develop the economics, technical feasibility, institutional relations and potential environmental effects of the program. These phases will consist of:

Phase II - Implementation of pilot well system to examine technical feasibility, environmental effects and institutional aspects of adding heat or cold to JFK aquifer. Demonstration pumping of the well system to determine optimum removal and recharge flow rates.

Phase III - Implementation of project to provide 25% of JFK air conditioning requirements.

Phase IV - Implementation of project to provide 100% of JFK air conditioning requirements.

3.2 NEGEV, ISRAEL

A conceptual system for utilizing waste heat from a power station for winter agriculture in Negev, Israel has been described by Nir and Schwarz (1978). During the warm season, which lasts 8 months, the power station would draw cold water from an aquifer for plant cooling. The warmed water would be returned to another region of the same aquifer, thus maintaining a closed liquid cycle. During the cold period, warm water would be drawn from the aquifer and delivered to the air and soil of a greenhouse. The operating parameters assumed are listed in Table 1.

TABLE 1. Operating Characteristics for Conceptual
System at Negev, Israel

Power plant electrical capacity	800 MW (e)
Power production efficiency	0.33 ^(a)
Plant operation power factor	0.8
Cooling water temperature rise	35°C
Rejected heat	312 Mcal/s
Condenser temperature	58°C
Cooling cycle water flow	770x10 ³ m ³ /day
Heat losses in storage	10%
Heat losses in transport	20%
Heat delivered to user	225 Mcal/s = 6.75x10 ⁹ Mcal/yr
Aquifer water storage capacity	400x10 ⁶ m ³

(a) Corrected for increased condenser temperature

3.3 SWITZERLAND

Mathey and Menjoz (1978) have computed the characteristics of an underground "heat accumulator" with a capacity of 10 Tcal. This is a vertical coaxial system rather than a horizontally displaced doublet. The storage volume is designed to use industrial warm waste water injected at 70°C and withdrawn at 35 to 60°C. Water is injected at the bottom and withdrawn at the top. Heat may be recuperated with a heat pump. The system is to function as a closed circuit to avoid reduction in permeability. Other data are shown in Table 2.

These authors have also computed the characteristics of heat accumulators for space heating and domestic water heating for a city of 20,000 people at latitude 47°. The accumulators are assumed to be spherical, and the injection temperature is assumed to be 100°C. Calculated characteristics for constant and intermittent input are compared in Table 3.

TABLE 2. Characteristics of Conceptual Swiss Aquifer
Heat Accumulator

Ground volume	$6 \times 10^5 \text{ m}^3$
Height	40 m
Horizontal drains	6 upper and 6 lower, radiating from the well, and 35 to 40 m long
Well diameter	2.2 m
Geology	uncemented gravel and sand
Permeability	$K \text{ (Darcy)} > 10^{-5} \text{ m/s}$
Depth of aquifer	2 to 10 m
Maximum flow (injection or discharge)	50 l/s
Accumulated energy	10 Tcal
Storage Temperature	70°C
Withdrawal temperature	35 to 60°C
Estimated cost	3×10^6 francs (Swiss)

TABLE 3. Geometrical and Operating Characteristics for Two
Spherical Heat Accumulators

	<u>Constant Production</u>	<u>Solar Production</u>
Radius	73 m	88 m
Volume	$1.6 \times 10^6 \text{ m}^3$	$2.8 \times 10^6 \text{ m}^3$
Stored heat	350 TJ	600 TJ
Loss of heat	575 kw	750 kw
Loss per m^2	8 W	7.2 W
Loss in 6 mo.	2.2%	1.7%
Temperature decrease per 100 days	1.3%	1.0%

3.4 GERMANY

Jank (1978) partially describes an artificial aquifer design philosophy followed in Germany at present. Two narrow vertical walls are constructed to confine an aquifer width of 5 m. Inexpensive fabrication methods are used. The walls separate warm water within the artificial aquifer from colder groundwater outside. The gravel between the walls is said to provide good thermal insulation. (Presumably this minimizes end losses which are not described in this brief article.) A layer of earth 2 m thick is excavated from the surface. Wells and pipes for charging and discharging are installed. A vapor barrier is introduced and the 2-m-deep excavation is filled with gravel. The surface is then covered with gravel and humus.

The aquifer has horizontal temperature layers. The heat capacity of the isolated aquifer, if used as seasonal storage, is said to be on the order of 50 Tcal. Assuming injection temperatures below 80°C and an average heat capacity of 600 kcal/m³°K, this is said to require an aquifer surface of about 300 x 300 m. (This calculation is not obvious. If the heat capacity is 600 kcal/m³°K, it would require approximately $8.33 \times 10^7 \text{ m}^3$ to store 50 Tcal.)

3.5 DENMARK

Qvale (1978) has reported some characteristics of an aquifer warm water storage plant to be established at a site in Horsholm, Denmark. Site and plant characteristics are shown in Table 4.

J. Leth^(a) of Riso National Laboratory recently described the Danish Seasonal Thermal Energy Storage Program to staff members of the Pacific Northwest Laboratory. Funding to 1982 of about \$1,300,000 will support mathematical modeling, geological surveying and the demonstration plant at Horsholm. Finite element analysis has been applied to developing two-dimensional models for horizontal and vertical layers. The models

(a) Presentation by Joergen Leth of Riso National Laboratory, Denmark, at Pacific Northwest Laboratory, Richland, Washington, on August 15, 1979.

TABLE 4. Characteristics of a Danish Aquifer Warm
Water Storage Plant

Size of reservoir	ca. 10^5 m^3
Depth	ca. 50 m
Ground water temperature	ca. 7°C
Storage temperature	ca. 80°C
District heating return temperature	ca. 50°C
Pumping capacity	ca. $70 \text{ m}^3/\text{hr}$
Design & construction period	ca. 18 mos
Estimated cost	\$50,000

show high instability of the temperature front. Laboratory experiments show good agreement with the models. A three dimensional code has been started.

Geological investigation is using existing water well data. The principal aquifer is a sedimentary section overlying chalk beds. Ground waters in the aquifer and in the chalk are essentially isolated from each other by clay layers beneath the aquifer. High variations in permeability occur. One candidate site with permeability of 200 darcies was abandoned due to lack of hot water vertical containment.

The Danish demonstration plant conceptual design uses four outer production wells equidistant from a central injection (storage) well. Water pumped from the production wells is to be heated by a garbage burner and then injected into the central well. Hot water extracted from the storage well will be passed through three stainless steel or titanium plate heat exchangers to supply a district heating system 20 km distant and then reinjected into the production wells. Well depths will be about 50 m.

A garbage burner north of Copenhagen supplies heat 5 days per week and an oil burner supplies heat on weekends. Aquifer storage during the 5-day interval will reduce weekend oil consumption. The garbage burner

will heat ground water at 7°C to 103 to 105°C before injection. Return ground water from the heat exchangers will be at 68 to 70°C. These temperatures apply to summer operation; they will be about 5°C higher in winter to reduce oil consumption. The district heating water will vary in temperature between 104 and 69°C. The water injection and energy storage rates are to be 70 m³/hr and 2 kcal/hr, respectively. An efficiency of 68% is projected for this demonstration after several years of operation. Equilibrium is likely to be established after five 1-year cycles.

The aquifer reservoir volume is 10⁵ m³. Four outlying wells (beyond the production wells) may be required to stabilize the water table. Temperatures will be measured at nine well levels as well as in heat exchangers using a combination of resistance thermometers, thermistors, thermocouples, and temperature transducers. A computerized monitoring system will record flow rates and temperatures and will regulate valves accordingly. Water pump motors may be positioned above water level to avoid the need for special high temperature design. Part of the rationale for four production wells supplying only one injection well is based on the sharp decrease in water viscosity with increase in temperature. In addition to the weekly interval for storage and extraction, various longer intervals (up to several months) will be tested.

4.0 NUMERICAL MODELING

Numerical models of aquifer liquid thermal storage system behavior have been developed at the Lawrence Berkeley Laboratory, the U.S. Geological Survey, in Sweden, and in Japan. Model efforts are also reported in Denmark, France and Switzerland. At the Pacific Northwest Laboratory an existing hydraulic model has been modified to include effects of energy and solute transport.

4.1 LAWRENCE BERKELEY LABORATORY

Sophisticated computer models have been developed to predict the behavior of aquifer thermal storage systems (Tsang 1977 and 1978; Tsang et al 1978). A numerical model, developed at the Lawrence Berkeley Laboratory to examine hot and chilled water storage, is called "CCC" which stands for "Conduction, Convection and Compaction". The model uses the so called Integrated Finite Difference Method. Heat and mass flow are computed through three-dimensional, water-saturated porous systems. Concurrently, vertical deformation is calculated with Terzaghi's one-dimensional consolidation theory. The numerical model has been partially validated by comparison with analytical and semi-analytical solutions due to Theis (1935), Avdonin (1964), and Gringarten and Sauty (1975).

The following physical effects are evaluated simultaneously by the model:

- flow of hot and cold water with large viscosity and density differences
- effects of temperature on fluid heat capacity, viscosity, and density
- heat convection and conduction in the aquifer
- influence of gravity on fluid flow
- effects of regional ground-water flow
- combined effects of many injection and withdrawal cycles
- spatial variations in aquifer properties

- compaction effects and associated land subsidence due to cumulative pressure changes during the injection-withdrawal history.

Eight cases were examined:

- hot water daily storage: hot water injected for 12 hr during the day and withdrawn for 12 hr during night
- hot water seasonal storage, semi-annual cycle: hot water injected for 90 days in spring; hot water pumped out for 90 days in summer for air conditioning by absorption chiller; hot water injected for 90 days in autumn; and finally hot water withdrawn for 90 days in winter for heating
- hot water seasonal storage, annual cycle: hot water injected for 90 days in summer and pumped out for 90 days in winter for heating; no injection or withdrawal during spring or autumn
- chilled water seasonal storage: chilled water at 4°C injected in winter for 90 days and pumped out for 90 days in summer for air conditioning; no injection or withdrawal during spring or autumn
- a two-well (doublet) system: during the storage period, water is pumped from one well, heated and then injected into the other well; during the utilization period, hot water is pumped from the second well and cooled used water is injected back into the first
- effects of clay lenses and permeability discontinuities
- possibility of consolidation or uplift
- natural regional flow.

The initial temperature of the aquifer, T_0 , was assumed to be 20°C for all cases. For heating, the injection temperature, T_i , was 120°C, 220°C, or 320°C. For Case 2 the calculations were performed for wells with half and full penetrations of the assumed 100-m-thick aquifer.

The following conclusions were drawn as a result of the tests:

1. The temperature of pumped water in the heating mode is approximately proportional to $(T_i - T_0)$ for a specified cycle.

2. For Case 2, isotherms within a vertical cross section of aquifer are pseudoelliptical both after 90 days injection at 220°C and after 90 days of production. However, the horizontal thermal gradient is approximately 50% less after production than after injection. The thermal front is not sharp due to heat conduction within the aquifer and into the confining beds (see Figures 2 and 3).
3. The recovery temperature is increased for each successive cycle as the aquifer is heated, making it an increasingly efficient hot water storage system. The process reaches quasi-equilibrium when an additional cycle does not raise the temperature appreciably. (More than five cycles are required to reach this condition.)

FIGURE 2. Calculated Isotherms in Aquifers with Partial Penetration

FIGURE 3. Calculated Isotherms for a Two-Well System with Full Penetration

4. The difference between energy injected and recovered is made up of energy diffused to heat up the aquifer plus energy lost. The percentage of energy recovered per cycle exceeds 80%.
5. Energy recovery percentages are higher for half penetration than for full penetration wells as shown in Figure 4. Semi-annual cycles 1 through 4 with half penetration show 91 to 92% recovery whereas with full penetration the results are 87 to 90%.
6. Minimum production temperatures are higher for half penetration than for full penetration wells. Semi-annual cycles 1 through 4 with half penetration yield temperatures of about 138 to 162°C whereas with full penetration the temperatures are about 124 to 150°C.

FIGURE 4. Energy Recovered as a Percentage of Energy Injected Versus Cycle Number

7. For water injected at 4°C, the maximum production temperature after 90 days is 13°C for cycle 1 and 9°C for cycle 5 (see Figure 5).
8. The production temperature, as a function of time, decreases at about the same rate for a single well system as for a two-well system with separation distance of 100 m.
9. Clay lenses and aquifer discontinuities distort the injection and production isotherms, but each may have little effect on percentage of energy recovered (see Figures 6 thru 8).
10. Subsidence and uplift range from 1 to 5 cm each based upon assumed 10-day injection and production periods. Both effects are dependent upon void ratio and effective stress.
11. A natural regional flow rate on the order of 1 m/yr will not adversely affect storage capabilities. Appreciable effects occur at high flow rates, e.g., about 100 m/yr.

Detailed energy and temperature data for a semi-annual cycle are given in Table 5.

FIGURE 5. Calculated Production Temperatures from Chilled Water Storage

EFFECT OF CLAY LENS -CYCLE 1

$T_{inj} = 220^{\circ}\text{C}$ $H = 50\text{m}$ (5 LAYERS)

$\Delta r = 2\text{m}$

FIGURE 6. Calculated Isotherms in an Aquifer with a Clay Lens.

EFFECT OF RESERVOIR INHOMOGENEITY - CYCLE 1

$T_{inj} = 220^{\circ}\text{C}$ $H = 50\text{m}$ (5 LAYERS) $\Delta r = 2\text{m}$

FIGURE 7. Calculated Isotherms in Aquifers with Simulated Inhomogeneities.

FIGURE 8. Calculated Energy Recoveries from Aquifer Storage.

TABLE 5. Energy Input/Output Data for Five Cycles

	<u>Cycle Number</u>	
	1	2
Energy Injected (J)	5.71×10^{13}	5.71×10^{13}
Energy Recovered (J)	4.96×10^{13}	5.09×10^{13}
Energy Loss from Aquifer (J)	5.34×10^{11}	6.81×10^{11}
Energy Diffused to Heat up Aquifer	7.1×10^{12}	5.5×10^{12}
Percentage of Energy Recovered	86.8	89.2
Production Temperature at End of Cycle (°C)	124	139
	3	4
Energy Injected (J)	5.71×10^{13}	5.71×10^{13}
Energy Recovered (J)	5.14×10^{13}	5.18×10^{13}
Energy Loss from Aquifer (J)	7.7×10^{11}	8.14×10^{11}
Energy Diffused to Heat up Aquifer (J)	4.9×10^{12}	4.46×10^{12}
Percentage of Energy Recovered	90.0	90.7
Production Temperature at End of Cycle (°C)	147	151
	5	
Energy Injected (J)	5.71×10^{13}	
Energy Recovered (J)	5.2×10^{13}	
Energy Loss from Aquifer (J)	9.1×10^{11}	
Energy Diffused to Heat up Aquifer (J)	4.2×10^{12}	
Percentage of Energy Recovered	91.1	
Production Temperature at End of Cycle (°C)	155	

Full penetration with 1 cycle = 180 days, $T_i = 220^\circ\text{C}$, $T_o = 20^\circ\text{C}$,
 $Q = 10^6$ kg/day, $H = 100$ m, $\Delta R = 2$ m and four layers.

Recently, the possibility of daily storage-retrieval cycles involving hot water aquifer storage has been investigated (ATES Newsletter, January 1979). The CCC model was coupled with another computer program which calculates heat conduction at the wellbore during injection and production. The coupled model was applied to an assumed aquifer using two hot water storage-retrieval schedules:

1. twelve hr of injection followed by 12 hr of production.
2. eight hr of daytime injection, 4 hr of evening production, 8 hr of night storage, and finally 4 hr of early morning production.

Preliminary results indicate recovery-storage ratios above 75%.

4.2 U.S. GEOLOGICAL SURVEY

Papadopoulos and Larson (1978) have used a numerical model to simulate aquifer storage of heated water. This model has been applied to Auburn University field experiments (described in the section "Field Experiments") to ascertain the reliability of the numerical approach. The observed experimental behavior has been satisfactorily reproduced. Heat capacity of the aquifer matrix and anisotropy of the aquifer permeability were significant system parameters.

The numerical model was originally developed for the USGS to calculate the effects of liquid waste disposal in deep saline aquifers (INTERCOMP 1976). The model uses finite difference techniques to solve simultaneously the equations describing fluid, energy, and solute transport in a ground-water system. For this study solute transport was not considered.

The first step in the simulation was to test the adequacy of the conceptual model for simulating ground-water flow conditions within the modeled area. Computed drawdowns nearly coincided with observed drawdowns over about 3500 min of pumping in the Auburn experiment. The second step introduced thermal characteristics of the aquifer into the model and simulation of the heat storage experiment proceeded. Despite

experimental difficulties encountered during the injection process, simulation of an approximate injection history produced satisfactory predictions of the amount of heat energy recovered.

The energy recovered above the ambient ground-water temperature was predicted to be about 3.8×10^{11} joules (3.6×10^8 BTU). This compares to a measured value of about 3.3×10^{11} joules (3.1×10^8 BTU), about 15% less. The predicted recovery ratio was 0.75 versus a measured ratio of 0.69. Because the confining bed was ruptured during injection, the amount of thermal energy actually injected into and retained by the aquifer could only be estimated, and the error of estimate is probably at least 15%.

Simulation results were relatively sensitive to the ratio of vertical to radial (horizontal) hydraulic conductivity. This ratio was a controlling factor with regard to the volumetric shape of the injected fluid. Heat capacity of the aquifer matrix also played a dominant role. Transient effects dominated system behavior, apparently due to the time frame of the experiment. Porosity and hydrodynamic dispersivity had a moderate effect on the steepness of the temperature front but had only slight influence on the spatial position of the front.

4.3 SWEDEN

Hellstrom (1978) modeled two thermal energy storage geometries based upon charging and discharging hot water. The first project investigated the possibility of storing hot water in eskers--long, narrow and highly permeable subglacial sedimentary deposits. The second project dealt with theoretical aspects of heat storage in the ground.

A computer program was developed to estimate energy balance for esker storage. At a given time, water flow was assumed to be constant and horizontal along the esker. The ground above and below the aquifer consisted of arbitrary horizontal layers with different heat transfer properties. At the surface, a fluctuating air temperature was assumed. Water was either supplied or withdrawn at two vertical boundaries. The injected water had a temperature of 90°C. The temperature of the

extracted water was averaged over depth. The energy equation was solved using the explicit finite difference method. To avoid "numerical diffusion" the timestep was chosen so that the thermal velocity always moved one cell-length in the x direction. Two pumping strategies were compared: 1) hot water injected at $x = 0$ and extracted at $x = 300$ m, and 2) hot water both injected and extracted at $x = 0$. In the first case, water flow is continuously positive; in the second, water flow is positive for 6 months and negative for 6 months. The temperature of the cold water was 40°C. The average temperature of extracted water was 75.3°C for extraction at $x = 300$ m and 78.9°C for extraction at $x = 0$. This result was explained by superior thermal shielding in proximity to the injection well.

The model was next modified to vary thermal velocity in proportion to the actual need or supply of energy. The thermal front was moved 300 m when charging and 275 m back when discharging, in order to avoid the cooled water close to the thermal front. Considering an aquifer 600 m long, 20 m high, and 100 m wide, the computed results for 6 years of operation were as shown in Table 6.

TABLE 6. Energy Input/Output from an Aquifer Model
over 6 Years

<u>Year</u>	<u>Energy in (J)</u>	<u>Energy out (J)</u>	<u>Recovery Efficiency</u> (E_{out}/E_{in})
1	2.70×10^{14}	0.85×10^{14}	0.32
2	1.38×10^{14}	0.93×10^{14}	0.67
3	1.32×10^{14}	0.97×10^{14}	0.74
4	1.29×10^{14}	0.98×10^{14}	0.76
5	1.27×10^{14}	0.99×10^{14}	0.78
6	1.27×10^{14}	1.00×10^{14}	0.79

Additional heat loss from the vertical boundary areas was estimated at 20% of the loss from horizontal areas. This would reduce recovery efficiency by about 5%. The main inaccuracy in this model is the assumption that flow is equal and in the x direction only. This does not allow for thermal stratification due to differences in density and viscosity.

An additional model was developed to quantify heat injection into and recovery from a 25-m-high vertical storage cylinder buried under 6 m of earth. The hot water at 90°C was charged and discharged at the top in order to avoid thermal stratification. It was assumed that water flow is equal and parallel to the vertical axis. The results obtained for 5 years of storage in 10 m and 20 m radius cylinders are shown in Table 7. Insulating the vertical side of the larger cylinder increased the recovery efficiency ratio in the fifth year by only 0.006.

TABLE 7. Energy Input/Output from Storage Cylinders
Over 5 Years

<u>Radius</u>	<u>Year</u>	<u>E_{in} (J)</u>	<u>E_{out} (J)</u>	<u>Recovery Efficiency</u> (E _{out} /E _{in})
10 m	1	0.178x10 ¹³	0.251x10 ¹³	0.141
	2	0.116x10 ¹³	0.336x10 ¹³	0.290
	3	0.108x10 ¹³	0.367x10 ¹³	0.341
	4	0.104x10 ¹³	0.383x10 ¹³	0.368
	5	0.102x10 ¹³	0.393x10 ¹³	0.387
20 m	1	0.703x10 ¹³	0.162x10 ¹³	0.231
	2	0.422x10 ¹³	0.193x10 ¹³	0.458
	3	0.385x10 ¹³	0.202x10 ¹³	0.526
	4	0.370x10 ¹³	0.207x10 ¹³	0.559
	5	0.360x10 ¹³	0.210x10 ¹³	0.582

4.4 OTHER MODELS

Other pertinent model studies are as follows:

John Claesson, University of Lund, Sweden, (ATES Newsletter, January 1979) has reported results of theoretical analysis and computer simulations of solid-fluid heat storage systems in the ground. Topics include stationary heat losses, buoyancy tilting of a vertical thermal front, entropy analysis of "numerical diffusion," numerical model of a plane doublet, and heat storage in a cylindrical aquifer region with vertical water flow.

Jean P. Sauty, Bureau of Geological and Mineralogical Research, France, (ATES Newsletter, January 1979) studied the effect of thermal dispersion on injection of hot water in aquifers. He concludes that apparent thermal conductivity is significantly increased by this effect both during injection and recovery.

Gringarten and Sauty (1975) and Yokoyama et al (1978) used complex potential functions to model aquifer heat injection and extraction (refer to Japanese field experiments).

Jan Reefstrup^(a) of the Technical University of Denmark has developed a two-dimensional, finite element model based upon the original thermal transport code originated at GE Tempo. He has simulated temperature and water velocity profiles for an injection experiment involving temperatures up to 100°C and injection rates up to 10 l/s.

Bengt Aberg^(a) of the Royal Institute of Technology, Sweden, has simulated hot water storage in eskers 20 m thick with overburden 6 m thick. Production and injection wells were 300 m apart. Down-gradient production was the only unique aspect of this model.

Bernard Joos^(a) of the Institute of Energy Production, Lausanne, has completed an analytical and laboratory study of natural convection

^(a) Ron Walter to Jim Minor, Trip Report: Neuchatel Thermal Storage Working Meeting (held in Neuchatel, Switzerland on June 7-8, 1979), Pacific Northwest Laboratory, June 12, 1979.

in saturated soils. He applied a 58°C heat source and an 18°C heat sink to opposite vertical sides of a saturated soil sample 30 cm wide and 27 cm high.

Pascal Iris^(a) of the School of Mines, France, completed a numerical simulation of the Campuget field experiment (refer to French field experiments). The model essentially verified field results and further demonstrated the unsuitability of the shallow unconfined aquifer for thermal storage.

At the Pacific Northwest Laboratory, a three-dimensional finite element ground-water flow model (Cole and Gupta 1979) was adapted for waste isolation safety assessments. Subsequently this model^(b) was extended and revised to solve partial differential equations describing single-phase flow, energy transport by conduction and convection, and solute transport by diffusion and convection. The model accounts for density and viscosity variations due to temperature and/or composition changes and includes the effects of hydrodynamic dispersion in both temperature and compositional movement. The modeled energy and mass balance includes the effects of hydraulic head differences in injection or withdrawal.

(a) Ron Walter to Jim Minor, Trip Report: Neuchatel Thermal Storage Working Meeting (held in Neuchatel, Switzerland on June 7-8, 1979), Pacific Northwest Laboratory, June 12, 1979.

(b) S. K. Gupta, C. T. Kincaid, C. R. Cole, F. E. Kaszeta and R. W. Nelson, "Three-Dimensional Finite Element Model for Coupled Solution of Flow, Energy Storage and Solute Transport in Porous Media," to be presented at the Third International Conference on Finite Elements and Water Resources, February 1, 1980, Oxford, Mississippi.

5.0 FIELD EXPERIMENTS

Recent field experiments with well doublets have been conducted in the United States, France, Germany and Japan. Although the most extensive field experience is reported by the Peoples Republic of China, quantitative details are just now becoming available. Over the intermediate term it is expected that field demonstrations will establish this technology for particular temperature ranges and applications.

5.1 TEXAS A & M UNIVERSITY

The project objectives are to design, develop and demonstrate a working prototype system in which water is pumped from an aquifer at 21.1°C (70°F) in winter, chilled to below 10°C (50°F), injected into a ground-water aquifer, stored for several months, pumped back to the surface in summer, and used to simulate air-conditioning (Redell and Davison 1978; Redell et al 1978). The project is divided into two phases: Phase I consists of construction of the facilities; Phase II deals with operation and analysis.

Pumping and injection wells have been drilled and equipped. A cooling pond for chilling the water has been constructed. Pipelines have been installed to connect the wells and the cooling pond. Observation wells have been drilled to measure water pressures and temperatures at various distances from the wells. Phase II was initiated in October 1978. As of November 27, 1978, 7571 m³ (2,000,000 gal) of water had been injected. This water was pumped out to test instrumentation and analyze water quality. Specific site and design characteristics are shown in Table 8. A well site log and well construction details are shown in Figure 9.

The cooling pond is 465 m² (5,000 ft²) and is capable of chilling an average of 6.3 l/s (100 gpm) from 21°C (70°F) to 4.4°C (40°F) over a 5-month period. The pond is lined with a butyl rubber liner to prevent seepage. Water is pumped from a well into the pond where a 37.9 l/s (600 gpm) pump circulates water through a series of spray nozzles during

FIGURE 9. Well Site Log and Construction Details for Both Injection and Pumped Wells.

periods when the wet-bulb temperature is less than 10°C (50°F). Once the water in the pond reaches a temperature of less than 10°C (50°F), 6.3 l/s (100 gpm) is taken from the pond and injected into a second well. The water is chlorinated and passed through a sand filter prior to injection.

TABLE 8. Characteristics of Prototype System at
Texas A & M University

Depth of alluvium	15.2 m (50 ft) to 18.3 m (60 ft) (average)
Test well stratigraphy	thick clay 0 - 11.6 m (38 ft) fine sand 11.6 m (38 ft) to 12.8 m (42 ft) gravel 12.8 m (42 ft) to 16.8 m (55 ft) tight blue shale 16.8 m (55 ft) and below
Ground water temperature	18.3°C (65°F) to 21.1°C (70°F)
Water table depth	3.05 m (10 ft) to 9.1 m (30 ft)
Well yields	15.8 l/s (250 gpm) to 63.1 l/s (1,000 gpm)
Ground water solute ions	Na ⁺ , Ca ⁺⁺ , Fe ⁺⁺ , Cl ⁻
Cooling pond area	465 m ² (5,000 ft ²)
Chilling rate	6.3 l/s (100 gpm) for 5 mos.
Water production rate	up to 12.6 l/s (200 gpm)
Cooling/injection period	October through March
Storage period (inactive)	April through May
Utilization period	June through September
Number of observation wells	12

Two production/injection wells have been drilled at the research site. The wells were completed in the shallowest ground water aquifer in the area, the flood-plain alluvium which exists extensively along the Brazos River. Dense clay from 6.7 to 11.6 m (22 to 38 ft) apparently forms a slightly permeable caprock for the sand and gravel aquifer. The water level in the sand and gravel is about 7.6 m (25 ft) below ground level.

Both wells were constructed identically. Each was drilled using a reverse circulation rotary drilling rig. Surface casing was set and grouted to a depth of 5.5 m (18 ft). A fiberglass casing and well screen were used to: 1) prevent corrosion, 2) allow strong chemicals to be used to remove any incrustations or plugging material, and 3) allow hot water at several hundred degrees Fahrenheit to be injected without

causing loss of strength. (Demonstration of hot water storage for winter heating is planned at a future date.)

A short-term pumping test (24 hr) was conducted on both of the wells. The injection well was capable of yielding 11.7 l/s (185 gpm) with a 4.27 m (14 ft) drawdown and the pumping well yielded 26.8 l/s (425 gpm) with a 2.44 m (8 ft) drawdown. Preliminary values of hydraulic conductivity are 183 m/day (600 ft/day) at the injection well and 229 m/day (750 ft/day) at the pumping well. The storage coefficients were 7.9×10^{-4} and 1.05×10^{-2} at the injection and pumping wells, respectively. The values of hydraulic conductivity are large, but typical of values previously measured for this aquifer. The storage coefficients indicate that the aquifer is confined near the injection well but unconfined near the pumping well. A more detailed pumping test analysis using 'leaky aquifer' techniques will be required to finalize values for hydraulic conductivity. Observation wells have been drilled near both the pumped and injection wells.

The first cold water injection (ATES Newsletter, May 1979) began on January 4, 1979. A total of 13,514 m³ (3.57 million gal) of 8.9°C (48°F) water was injected in January; 12,416 m³ (3.28 million gal) of 8.9°C (48°F) water in February; and 5,300 m³ (1.40 million gal) of 9.4°C (49°F) water in March. For the season, a total of 31,300 m³ (8.25 million gal) was injected at an average temperature of 8.9°C (48°F).

A major concern had been the possibility of aquifer plugging because the water was aerated during the chilling process. Prior to injection, the water was passed through a sand filter and all traces of iron oxides, other chemical precipitates and foreign material were removed. No evidence of aquifer plugging has occurred up to the present time. The aquifer is still taking water at the rate of 2.07 to 2.48 l/s m (10 to 12 gpm/ft), which was the original capacity.

The cold water is confined in a region from 12.2 to 16.8 m (40 to 55 feet) below land surface out to a radius of 30.5 m (100 feet) from the injection well.

The cold water was stored for two months (April and May) and a recovery cycle was scheduled for June. No major problems have occurred and the results are encouraging.

5.2 AUBURN UNIVERSITY

The Water Resources Research Institute of Auburn University is performing an aquifer injection and recovery experiment involving heated water (Warman and Molz 1977; Molz and Paar 1978; Molz et al 1978; and Molz and Warman 1978). Hot water is pumped into a confined aquifer, stored for a period of time, and pumped out. Hydraulic heat variations and water temperatures are recorded in 14 observation wells. The data are being used to test the predictive accuracy of numerical models which describe water and heat transport below the water table. These experiments are providing engineering experience in subsurface thermal storage and retrieval, with special emphasis on applicability to storage of water heated by solar energy.

In the first experiment, warm water was obtained from the Barry Steam Plant of the Alabama Power Company in Mobile County, Alabama. It was pumped from the discharge canal for the condenser cooling water through a 915 m (3000 ft) pipeline to the injection well. The well is surrounded by an inner grouping of 10 observation wells and an outer grouping of three boundary wells. The central injection/production well extends 9.1 m (30 ft) into the storage aquifer. An additional shallow observation well is screened just above the upper confining layer. Thermistors are positioned to record ground-water temperatures at six equally spaced depths in the 10 aquifer observation wells, at the top of the upper confining layer in the shallow observation well, and near the middle of the bottom sand formation in the three boundary wells. The 10 observation wells are located in the intended storage area, and hot water should not extend beyond the well at greatest distance from the injection well. The wells are screened in the bottom sand below the clay layers which confine the aquifer. Figure 10 is a schematic diagram of the well locations, the pipeline, and the discharge canal. Figure 11 is a fence diagram of the well field. The boundary wells record conditions

FIGURE 10. Schematic Diagram Showing the Details of the Project Site near Mobile, Alabama

at an arbitrarily defined boundary of the system. Readings are intended to serve as boundary conditions for testing mathematical models. Hydraulic heads are recorded in all observation and boundary wells.

The aquifer selected has a vertical thickness of about 21.3 m (70 ft) and its top is between 39.6 m (130 ft) and 61.0 m (200 ft) below ground surface. The matrix consists of medium to fine sand--85% by weight; silt and clay--15% by weight. Smectite and kaolinite were identified in the clay minerals fraction. Physical characteristics of the aquifer (and aquitard) are shown in Table 9.

Pumping tests disclosed finite hydraulic behavior, and it is suggested that the aquifer is coincident with a buried river channel.

Despite the use of a Laval particle separator to remove plus 40 micrometer sediment and a Waterbetter cartridge filter to extract plus 5 micrometer particles, sufficient minus 5 micrometer material remained in the injected water to cause clogging. The planned injection rate was 25.2 l/s (400 gpm). At the start this flow could be maintained with a pressure of 1.496 bar (7 psig) at the wellhead. Within 20 hours this pressure increased significantly due to clogging. Neither backwashing, by using compressed air to reverse water flow, nor chemical dispersion, with agents such as detergent, caused significant restoration of permeability. Loss of permeability was attributed to adhesion of clay particles within the aquifer channels.

After 420 hr (17.5 days) of pumping the upper confining layer was breached, probably due to the high injection pressure of 5.15 bar (60 psig). The breach was evidenced by falling heads in the aquifer observation wells and flow of water from the well above the aquitard. Furthermore, the water temperature at the top of the aquitard rose nearly 9.4°C (17°F). Despite the breach, it was possible to recover hot water from the aquifer without pulling in water from above the aquitard. This was accomplished by pumping at only 6.3 l/s (100 gpm).

The thermal recovery factor was defined as the ratio of thermal energy recovered above 21°C (69.8°F) to the thermal energy injected above ambient ground-water temperature, about 20°C (68°F). The average first injection temperature was 37°C (98.6°F) and the volume was 3804.4 m³ (1,005,000 gal). Energy injected was about 2.71×10^{11} J (2.57×10^8 BTU). The average second injection temperature was 35.8°C (96.44°F) and the volume was 3883.9 m³ (1,026,000 gal). Energy injected was 2.57×10^{11} J (2.44×10^8 BTU). An estimated 265 m³ (70,000 gal) of water at 35°C (95°F) was lost during backwashing which subtracted 2.09×10^{10} J (1.98×10^7 BTU) from storage. Thus, the net thermal energy injection was 5.07×10^{11} J (4.81×10^8 BTU). Energy recovered totaled 3.48×10^{11} J (3.3×10^8 BTU), which corresponds to a recovery factor of approximately 0.68.

The first 6-month experiment, schematically shown in Figure 12, involved the injection and recovery of about $54,900 \text{ m}^3$ (41.5 million gal) of water (Molz and Parr 1978; Allen 1978^(a)). The injection water was obtained from the formation water of an unconfined aquifer above the storage aquifer at 20°C (68°F), heated to a temperature of about 55°C (131°F), and injected into a 9.1 m (30 ft) section of the

FIGURE 12. Schematic of Second Aquifer Experiment at Auburn University.

(a) R.D. Allen, Pacific Northwest Laboratory Report on "Low Temperature Thermal Energy Storage Technical Review Committee Meeting," Denver, CO, November 6, 1978.

confined storage aquifer. The injection, storage, and recovery periods were 1900, 1213, and 987 hr, respectively. About 53,000 m³ (14 x 10⁶ gal) of water were recovered at a constant rate of about 15.8 l/s (250 gpm). The recovery period was terminated when the water being withdrawn from the storage aquifer fell from an initial temperature of 55°C (131°F) to 33°C (91.4°F), which was 13°C (23.4°F) above the ambient water temperature in the confined aquifer.

The average rate of decline in water temperature was 0.5°C/day (0.9°F/day). About 65% of the injected energy was recovered. The clogging problems that plagued the preliminary experiment were significantly reduced during the first 6-month experiment. However, the injection rate varied from about 12.6 l/s (200 gpm) to 6.3 l/s (100 gpm) depending on the degree of clogging. This improvement was apparently due to the relatively low level of suspended solids in the injection water. Periodic backwashing of the injection well by stopping injection and pumping up to 1136 l (300 gal) with a submersible pump also contributed to the improvement. No vertical mixing or buoyancy displacement of water was observed.

In the second 6-month experiment (ATES Newsletter, May 1979) approximately 58,000 m³ of water, heated to an average temperature of 55.4°C, was injected into the confined aquifer and stored for about 62.5 days. When the water temperature had declined to 32.8°C during the recovery period of the second experiment, 73.8% of the injected energy had been recovered at a total recovery volume of about 67,000 m³. The recovery period for this experiment continued until the outflow temperature reached 27.5°C and the total recovery volume was about 100,096 m³. The total injection, recovery, and storage periods were 1521, 1502, and 1993 hr, respectively. The clogging problem was controlled by backwashing the injection well. The frequency of backwashing was increased for the second 6-month experiment. This improved the injection performance.

The specific capacity of the injection well was significantly better in this cycle than in the previous experiment. This is encouraging since it appears that the degree of clogging will stabilize at an acceptable

level when water low in suspended solids is used for injection. However, clogging problems may be more difficult to solve at other sites. It still remains to be seen what effects higher temperatures will have on the hydraulic conductivity of typical formation soils. Efficient total-energy systems would use injection water with temperatures as high as 200°C (392°F).

A third cycle is planned, and will include storage and withdrawal periods of 1 month each. A fourth injection will use unheated water containing a chemical tracer solute, such as NaBr, to determine mass dispersion coefficients for comparison with previous values.

Temperature profiles through the warm water bubble during injection/storage/withdrawal experiments will be developed from data taken in the 14 instrumented wells.

The following observations and conclusions about site selection and operation (Molz and Warman 1978) were reached after the first 6-month experiment:

1. The natural velocity of ground water should be very low. If not, the gradient must be lowered by artificial means.
2. Long operation of a heat storage well will require cycling of water with extremely low suspended solids. (A hundred million gallons (3.786×10^6 l) of water with suspended solids of 1 part per million contains 836 lbs (379 kg) of suspended material.) It is likely that clogging will be one of the most serious problems concerning the intermediate to long-term operation of heat storage wells.
3. If an aquifer contains clay, even in small amounts, clay swelling may seriously impair injection. The pH and iron content of the water must be compatible with the particular clay mineral. Furthermore, exposure to distilled water can cause some clays to swell. Also, the injected water must neither precipitate any chemical compounds within the aquifer pores or onto the aquifer matrix nor dissolve the matrix material.

4. Hydraulic conditions must not be imposed capable of causing failure of the confining stratum (if a confined aquifer is to be used for storage purposes). Also, high temperature water may weaken aquitard materials or increase their permeabilities. The effect of temperatures in the 60 to 204°C (140 to 400°F) range on mechanical and hydraulic properties of aquitard materials should be studied.
5. The thermal recovery factor of 0.68 was considered encouraging in view of the small volume injected. Simulation studies (Papadopoulos and Larson 1978) predict high recovery factors for storage wells involving hundreds of millions of gallons of heated water.
6. Anomalous low temperatures have been measured in observation wells. The effect appears to be due to mixing of hotter water in the lower portion of the well (within the storage formation) with cooler water in the casing above the formation.
7. One procedure for minimizing chemical or mechanical clogging of an injection well is to use formation water. Ground water tends to be low in suspended solids, and the main difference between the injected water and the native water will be one of temperature.
8. In order to further develop the heat storage well concept, additional experimental studies are needed involving larger volumes of water and higher injection temperatures. The geochemistry - colloid chemistry problem must be studied carefully, and the effect of high temperatures on the mechanical and hydraulic properties of clay confining layers must be determined.
9. The Auburn experiment will provide field data which can be compared with computed data from the LBL/CCC numerical model^(a). This experiment and others may indicate that one or more perturbations would improve the model.

^(a) Lawrence Berkeley Laboratory is currently performing detailed calculations to model Auburn University experiments (ATES Newsletter, May 1979).

5.3 KREFELD, GERMANY

A test was carried out in 1973-74 by the Geological Survey of North Rhine/Westphalia (Kley and Nieskens 1975). A heat storage well penetrating a near surface aquifer was injected with 430 m³ of water at 45°C at a rate of 0.3 m³/hr. Numerous temperature measurements were made which enabled the construction of heat profiles. The authors concluded that about one-third of the energy was lost to the top, base, and surrounding material, and they attributed the losses to heat conduction. However, they found no evidence of horizontal thermal gradients. The authors calculated that a storage unit designed to heat 5,000 to 10,000 homes in winter could be amortized within 10 years on condition that hot water could be provided cost-free (as from nuclear power stations during summer).

5.4 CAMPUGET, FRANCE

Cormary et al (1978) have reported field test results of warm water storage in an aquifer. Parametric data are shown in Table 10.

TABLE 10. Characteristics of the Aquifer Storage
System at Campuget

Volume of water injected	20,200 m ³
Injection temperature (average)	33.5°C
Injection period	3 months
Aquifer thickness	3 m
Time of aquifer confinement	4 months
Recovery efficiency	20%
Recovery temperature range	15-30°C
Volume of withdrawal	17,000 m ³
Normal aquifer temperature	14°C

The aquifer was unconfined and located in Quaternary alluvium 3 to 10 m below the surface. Hydraulic conductivity was 10^{-3} m/s. A pumping well 200 m to the west created a 2% local gradient. Nine observation wells were distributed over $10,000 \text{ m}^2$ around the injection center.

Over a 3-month period (July through September 1977) $20,200 \text{ m}^3$ of water were injected at an average temperature of 33.5°C . The water was withdrawn from the aquifer and heated by solar collectors and heat pumps. The injection depth was 7 to 10 m.

Over a 1 1/2-month period (September-November 1977) no intervention occurred. At the storage center the temperature declined from 33.5°C to 30°C .

Next, over a 1 1/2-month period (November-December 1977) 5000 m^3 of water were withdrawn at temperatures decreasing from 30°C to 21°C (average 24.5°C). This represented 14% of the total heat stored with a temperature efficiency above 50% based upon:

$$\text{Efficiency} = \frac{T_w - 14^\circ\text{C}}{T_i - 14^\circ\text{C}}$$

A second waiting period of 1 month occurred in December and January 1977. The temperature decreased from 21°C to 19°C at the center. A final withdrawal period lasted 2 months in January through March 1978. A volume of $12,000 \text{ m}^3$ was pumped out at temperatures decreasing from 19°C to 14°C (average 16°C). This water contained 4.5% of the total heat stored, with 8% temperature efficiency. Overall, $17,000 \text{ m}^3$ of water were withdrawn at temperatures from 30°C to 15°C , and 20% of the injected energy was recovered.

During injection, observation wells showed a vertical temperature gradient 20 m from the injection center. The hottest zone was 3 to 7 m under the surface where the permeability was highest. During the first waiting period heat was globally dispersed over a 50 m range with asymmetry toward the source well, 200 m to the west. A displacement of isotherms

toward the south was attributed to heterogeneous permeability. Average pore velocity of water in the aquifer was measured at about 20 cm/day, by means of tracing salt experiments. The hottest zone remained at the injection center.

The main phenomenon during pumping periods was the steep decline in efficiency between the first and second withdrawals. This effect correlated with: 1) 70 cm of rainfall between October and March; 2) a decrease in thickness of the unsaturated zone (3 m in October, 1 m in January); and 3) decrease in air temperature (16°C in October, 6°C in January). Heat losses by horizontal dispersion and convection were increased by heat transfer across the thin unsaturated zone. During winter the steepest thermal gradient developed in the most permeable zone. A difference between the temperature of the solid matrix near the well and the temperature of the water pumped was also greatest in winter. This phenomenon seems to confirm the combined reasons for heat loss: preferential circulation in the upper aquifer and heat exchange across the unsaturated zone. In spite of heat losses, progressive thermal recharge of the underlying clay was measured.

During the tests no carbonate precipitation was detected. *Escherichia coli* bacteria developed. This growth was arrested with moderate chlorine injections. No clogging was observed.

Semi-quantitative evaluations of heat losses were: 1) 20 to 35% through the unsaturated zone; 2) 10% into the substratum; 3) 10 to 30% by convective transport toward the source well; and 4) 10% residual in the rock mass.

5.5 JAPAN

In Japan field experiments and numerical analysis have been conducted with respect to thermal energy storage in aquifers (Yokoyama 1978; ATE Newsletter, October 1978). Particular attention has been paid to the spacing of wells in order to avoid thermal and chemical pollution.

The test site consists of two dual-purpose wells and one observation well. In summer, cooling water is withdrawn; after direct cooling, waste water is sprinkled on the roof for heat collection by convection and radiation. After passing through a filtration tower, the water is further heated by a heat exchanger and then recharged through a second well. The process is reversed in winter.

Experiments with warm water recharging were carried out from July 16 to September 18, 1977. Even with daily discharging, researchers were able to maintain a constant water level. There was no evidence of clogging, and permeability appeared to remain constant. Between September 19 and December 25, 1977, there was no recharging. Warm water was then withdrawn and used to melt snow, while waste cool water was recharged.

The heat recovery coefficient was nearly 40% but declined when recharged cool water reached the discharge well. There was good agreement between experimental and numerical results; for all seasons, the quality of the recharge water remained at a near-natural level. In the model the following assumptions were made:

- The aquifer is uniform in thickness and confined imperviously above and below.
- Forced horizontal convection is the dominant heat transfer mechanism. Horizontal heat conduction is negligible in comparison.
- Natural vertical flow, due to convection and leakage through confining layers, is negligible.
- Vertical heat conduction across the interfaces between the aquifer and confining layers must be considered.

The authors concluded that when natural flow is slow compared with well flow rates, horizontal and vertical thermal diffusion are not significant, making seasonal regeneration feasible. Despite the rough assumptions for underground strata, numerical analyses based on a complex potential function were judged sufficiently accurate.

In later work, Yokoyama (ATES Newsletter, January 1979) reported that water at 18.3°C (average) was withdrawn from a heat source well and used to melt snow between January and March 1978. About 10,000 m³ of the melt water at 5.3°C (average) was injected into a heat sink well. In summer of 1978 chilled water at 14°C (average) was pumped from the sink well. The nearly 9°C temperature rise was attributed to inadequate initial volume of the melt water and to proximity of the heat source well.

5.6 PEOPLES REPUBLIC OF CHINA

The first American disclosure of recent aquifer technology in the Peoples Republic of China appeared in the ATES Newsletter of May 1979. Artificial recharge of ground-water systems, and utilization of subterranean reservoirs to store hot and cold water have been carried out extensively according to "a quick translation of major portions of the summary chapter of a technical publication (July 1977) of the Chinese National Geology Department at Beijing. Its purpose is to provide general information and it is not to be taken as an exact translation." -- C.F. Tsang, Editor

In substance the translation provides the following information.

In the late fifties, widespread industrial use of ground water in Shanghai caused land subsidence and a large drop in the water table. Several factories experimented with reinjection of cold water from air conditioning systems to replenish ground water. Over the next few years these efforts were generally successful in raising water table levels and increasing the outputs from production wells. In addition, reinjection and well construction methods were continually improved through experiments with different techniques, volumes, and injection periods.

During spring and summer of 1965, the Shanghai Cotton Mill Factory initiated a large scale artificial recharge experiment using four different water sources: deep well water, industrial waste water, filtered industrial waste water, and tap water. Researchers also experimented with continuous

versus intermittent withdrawal and with different reinjection-shut-in cycles. Temperature changes and water quality were monitored both before and after injection. These experiments indicated that there was little regional water flow in the aquifer and that there were only small changes in the temperature of water stored. These results justified later projects which used winter injection of cold water for summer use and summer injection of hot water for winter use.

Also in 1965, the Shanghai Water Company conducted extensive experiments using various reinjection methods and three specially designed reinjection wells, 95 m deep, to study changes in ground water level, water quality and temperature. Their experiments yielded relatively complete quantitative records which confirmed the effectiveness of using gravity recharge and underground production methods to raise ground water levels.

Based on these large scale experiments and their own studies, the City of Shanghai Hydrogeological Group concluded that reinjection was able to effectively control subsidence and ground water levels and that it was possible to store cold water in winter for summer use in air conditioning. These conclusions led to a city-wide reinjection program in which 70 factories used 134 deep wells for simultaneous recharge. As a result, the water level increased by more than 10 m.

Ground water produced during summer had a very low temperature and thus became a new source of chilled water for industrial use. At the conclusion of summer pumping there was still a net average increase in the land level of six centimeters; this was the first time in several decades of continuous subsidence that any surface uplift had been observed.

The program expanded in subsequent years and now several hundred wells are in use. Production and injection methods have been greatly improved and the program now includes summer injection of hot water for use in winter. Because of the success at Shanghai, several industrial cities and large villages have adopted similar reinjection and thermal energy storage programs.

6.0 RELEVANT TECHNICAL INFORMATION

Relevant technical information embraces particular topics, germane to aquifer thermal energy storage, but outside the main realm of the low temperature thermal energy storage program. These topics are: cogeneration of electricity and heat, high temperature storage, aquifer simulation, and petroleum experience in water injection.

6.1 COGENERATION OF ELECTRICITY AND HEAT

If high-temperature water and electricity are produced simultaneously to satisfy heat loads, two "leverage" effects will be realized which can significantly reduce national energy demands, (Meyer et al 1976). These effects are explained below.

- Energy is saved by producing less electricity and more heat. The logic follows. A conventional power plant generates 1 mwh of electricity and wastes 2 mwh of heat (0.45 mwh in stack loss and 1.55 mwh in cooling water loss) for each 3 mwh of input fuel consumed. For joint-product operation the input is increased to 4.2 mwh, electrical output remains 1 mwh, and 2.5 mwh of heat goes into the high temperature water output; instead of discharging useless 40°C (100°F) cooling water, the plant produces useful 175°C (350°F) water. On the basis of 1 mwh additional input, the energy input to the water is 2.08 mwh. Allowing for heat lost in storing and transmitting the hot water, the extra 1 mwh of heat input makes 1.3 to 1.5 mwh of heat energy available at the heat load. This assumes that heat lost from storage and transmission is between 0.58 and 0.78 mwh out of the original 2.08 mwh of heat in the hot water output (per additional mwh input). The efficiency of heat recovery is therefore 62 to 72%, a rather conservative range based upon experimental and numerical modeling results for aquifer thermal energy storage.

- Hot water is about twice as efficient as fossil fuels for space and water heating, and 1.4 times as efficient for process heat, based on ERDA estimates for the year 1985 (Meyer et al 1976).

In Denmark a significant portion of the demand for heat and electricity is supplied through "combined generation" (Qvale 1978). About 10% of residential heating is provided. This percentage will increase significantly as existing power plants are converted to this mode. In the longer term, new installations will be designed for combined generation. The use of diurnal and seasonal storage of warm water may lead to sizable savings of fuel and a lower required installed power capacity.

Two alternative storage modes are considered: 1) lakes and quarries, and 2) aquifers. In Denmark the top soil typically overlies permeable waterbearing layers of sand and gravel, with some clay layers interspersed, and this combined subsoil sequence varies between 50 and 500 m in thickness. This widespread aquifer appears promising for local storage of warm water. These sediments rest upon chalk 1000 to 3000 m thick.

6.2 HIGH TEMPERATURE STORAGE

Collins et al (1978) and Collins (1978) have considered technical problems of storing superheated water at 343.3°C (650°F) and 186.2 bar (2700 psi). The working fluid must remain liquid to maximize energy density. This is said to require storage at or below 1677 m (5500 ft) if only the earth's geostatic pressure is to confine the fluid. The reservoir pressure must be less than the fracture pressure which is about 0.17 bar/m of depth (0.75 psi/ft of depth). In the above example the storage pressure is about two thirds of the calculated fracture pressure. Water could be injected through a well into an aquifer. Areas where the thickness of the sedimentary column, above igneous/metamorphic basement rock, exceeds 1677 m (5500 ft) are potential regions for deep aquifer storage.

It is necessary to minimize heat loss from the storage reservoir. Deep underground storage of thermal energy, using a working fluid at

high temperature and pressure, can be achieved with relatively small conduction losses for cyclic injection, storage and withdrawal if the system is sufficiently large. The importance of reservoir radius is shown by the equation:

$$q_1 = \frac{3Qkp}{r^2}$$

where q_1 is the heat lost per cycle, Q is the total heat stored, k is the thermal diffusivity of the rock, p is the period of the injection-withdrawal, and r is the equivalent radius of the cyclicly heated region.

Preliminary evaluation of the back-flow capability of an aquifer storage well has been made. A single storage well in an unbounded aquifer would probably require pumping. Artesian backflow from a single storage well appears to be possible only from small, totally enclosed aquifers. The authors feel that this diminishes the potential for deep aquifer storage. However, downhole pumps could be installed to achieve fluid retrieval. This technology is being developed in the geothermal industry.

Even with downhole pumps, silicate mineral solubility and subsequent scale formation appear to be major problems confronting aquifer storage systems. Silica solubility in the vapor phase is much less than in the liquid phase; therefore, scale problems in the aquifer formation and wellbore could be minimized if the pressure of the fluid is not permitted to drop below the vapor pressure of water at the storage temperature. This requirement determines a minimum depth below which the fluid will remain single phase. This depth depends upon the storage temperature, flow rates, flow periods, and aquifer properties. Additional consideration should be given to pressure drops within a pump and the associated reduction in silica solubility.

The most important variables are storage temperature, flow rate, permeability, formation thickness, and the value of the so called skin factor, "S" (Collins 1978). The value of S depends upon drilling and

completion techniques used to install the well since it is determined primarily by the reduced value of the permeability near the wellbore. Silica deposition near the wellbore will further reduce the permeability which will increase the skin factor and increase the well depth required (or reduce the allowable flow rate).

Power requirements of the downhole pump depend upon the depth, flow rate and storage temperature. For example, at 300°C and a flow rate of 126 l/sec (2000 gpm) using typical aquifer properties the minimum depth required is 1524 m (5000 ft) and the pumping power is more than 25% of the net electric power which can be generated from the retrieved hot water. An aquifer with zero skin factor and very large permeability would still have to be at least 854 m (2800 ft) deep and the pump would need about 9% of the available power.

At lower temperatures the minimum depth and power required are reduced but the dependence upon the variables is much stronger. At 150°C and a flow rate of 31.6 l/sec (500 gpm) the minimum depth ranges from a few hundred feet to a few thousand feet depending upon the aquifer properties. Power requirements could be very small or as much as 15% of the net retrievable electric power.

The authors (Collins et al 1978) conclude that aquifer storage and recovery at high temperatures will require the use of downhole pumps with large power requirements. Therefore it appears that aquifer storage will not be competitive for heat storage for subsequent electric power generation. Furthermore, the problems of mineral solubility and reactivity, especially involving silicates, require examination and solution. Silica scale deposition in high temperature, high pressure steam turbines could seriously impact economy of operation. Repeated flushing with hot water, chemical treatments, and reinjection of water as a closed system have been proposed to minimize the scaling problem.

It is believed that the above negative conclusion may be premature. A binary plant operating at a lower temperature, e.g., 150° to 175°C, might reduce silica scale formation and pumping energy requirements would be decreased because of withdrawal from lesser depth.

6.3 AQUIFER SIMULATION

Moderate-scale field tests using synthetic aquifers could be developed to enable verification and modification of existing aquifer models. Synthetic aquifers could consist of unconsolidated or partially cemented, sized, artificial sedimentary formations, of limited vertical and horizontal extent, emplaced within excavations or natural dry basins. These synthetic aquifers could incorporate variations in permeability, lithology, uniformity, well number and spacing, injection and extraction rates, water temperature, injection and extraction intervals, caprock and baserock permeability. These experiments would be completely instrumented to establish migration rates and three-dimensional shapes of isothermal surfaces. Such heat transfer mechanisms as thermal conductivity, thermal diffusivity, convection (natural and forced), liquid flotation and spreading, and hydrodynamic dispersion could be evaluated with respect to the relative importance of each under various conditions. The effect of natural native water flow within an aquifer could also be evaluated, together with the feasibility of downstream withdrawal. The optimum degrees of aquifer penetration by injection and withdrawal wells could also be evaluated. These tests could also include measurements of subsidence and uplift due to fluctuations in aquifer water pressure.

6.4 PETROLEUM EXPERIENCE IN WATER INJECTION

Water injection related to petroleum recovery has developed data germane to thermal energy storage in aquifers (Subcasky 1978). Water quality is important since it involves physical and chemical factors which could change the permeability of the receiving formation or affect the equipment used to process and inject the water. Factors of concern include: water chemistry, water/rock interactions, particulate plugging, scaling, corrosion, bacteria, water treatment chemicals, and temperature effects. In addition, injection wells must be sealed where they transect potable water-bearing formations.

Changes in water temperature or pressure can cause precipitation of solid phases. For example, a pressure decrease may cause release of carbon dioxide which, in turn, increases alkalinity and decreases solubility of calcium carbonate. The solubility of calcium carbonate also decreases with increasing temperature. In contrast, the solubility of gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, increases with increasing temperature. A precipitate may deposit on conduit walls, increasing the hydraulic pressure gradient, or it may be suspended in the liquid, providing a potential plugging agent within the receiving formation.

Mixing of waters from two sources can cause precipitation due to comingling of diverse ions, e.g., Ba^{++} and $\text{SO}_4^{=}$ to yield BaSO_4 , or mixing of highly alkaline water with another containing high calcium or magnesium can cause precipitation of calcium carbonate and magnesium hydroxide.

Water/rock interactions may have significant effects. Minerals with layered structures like clays and micas can exchange cations with cations in solution and undergo changes in layer spacings, e.g., replacement of potassium in mica by sodium or calcium can increase the spacing by 50%.

Altering the electric field around a charged clay species by changing the electrolyte composition can cause dispersion or coagulation of particles. Dispersed particles can migrate and plug small pores.

Injected water may partially dissolve the host rock. Calcium carbonate can be dissolved by undersaturated or acid water. Siliceous minerals can be dissolved by alkaline and/or high temperature water. Reductions in pH or temperature can cause redeposition of silica and possible reduction of permeability.

Particulate plugging can also arise from material in the injection water before its introduction or from material formed or produced within the receiving formation. Possible sources of particulates in injection water include the following: silts, formation fines, corrosion products, scale deposits, bacteria and chemical precipitates. Water/rock or

water/water interactions within the formation can form or dislodge particles which subsequently reduce formation permeability. Particle size, shape, number; fluid velocity; and pore size, shape and number influence the effect. A filter cake may develop on the injection well face or plugs and bridges may develop within the formation.

Scaling is the formation of an insoluble deposit from a physical or chemical change in water or from mixing of two waters not in chemical equilibrium. Scaling may occur on the walls of processing or injecting equipment or within the formation itself. Scale may also slough, putting particles into suspension, or it may redissolve.

Corrosion is chemical attack upon metallic components by active agents within the water. Corrosion rate depends upon pH level, temperature, solute species and concentration, fluid velocity, and presence of corrosive gases, e.g., oxygen, carbon dioxide and hydrogen sulfide. Corrosion causes damage to processing and injection equipment which may reduce efficiency or cause failure. Corrosion products, usually iron oxides and sulfides, can also plug the receiving formation.

Bacteria can form slimes which may plug the formation or filters. Colonies on pipe walls can form oxygen concentration cells which accelerate corrosion and pitting. Sulfate reducing bacteria can release hydrogen sulfide--highly corrosive and toxic. Both oxygen and hydrogen sulfide may attack the injection, production and heat exchange systems.

The effective permeability of the formation is also related to the temperature of the injected fluid. A temperature rise causes decreases in fluid density and viscosity. The net effect may change the required pumping pressure. Rock solubility and reactivity are also temperature dependent.

Water treatment chemicals may be added to inhibit deleterious effects. These may include scale inhibitors, corrosion inhibitors, biocides, demulsifiers, solvents, acids, etc. However, these chemicals

should be chosen to avoid mutual reactions or reactions with water solutes/suspensions to form plugging precipitates.

The well doublet concept involves two water wells which comprise a closed hydraulic system. Using native aquifer water as the working fluid may inhibit or eliminate many of the potential problems discussed above. Furthermore, most thermal energy storage wells will be substantially shallower than most petroleum wells. Therefore, the influences of geostatic pressure and pressure changes will be less dominant. Absence of hydrocarbons may also eliminate some of the problems encountered in petroleum-related water injection.

7.0 FEASIBILITY STUDIES

Feasibility studies are in progress at Bellingham, Washington, Tennessee Valley Authority, Tennessee, and Twin Cities, Minnesota. Two separate Bellingham projects are considering waste heat from aluminum smelting and garbage burning, respectively. The TVA project is screening a large geographic area for sources of low temperature energy, potential aquifer sites, and potential energy consumers. The Twin Cities project is directed toward cogeneration of electricity and hot water. All four projects are stressing economic analysis.

7.1 BELLINGHAM, WASHINGTON

A proposed demonstration at Bellingham would store waste heat from the Intalco Aluminum Company smelting plant within an aquifer or other storage medium (Katter and Hoskins 1978; Allen 1978^(a)). Large quantities of hot water range in temperature from 121°C (250°F) to 204°C (400°F). Analytical trade-off studies indicate that this plant could provide heat for 12,000 equivalent residences at a cost predicted at one-third the average cost of fossil fuel. Optionally, heat may be consumed by an industrial park near the airport. Although available geologic information suggests the presence of a suitable proximate aquifer, an abandoned coal mine and unpressurized steel tankage are also candidates for storage. The coal mine is estimated to have a capacity of $264 \times 10^4 \text{ m}^3$ (700×10^6 gal), appreciably less than a typical aquifer.

A separate project to build and operate an aquifer storage prototype double well system at Bellingham was originated in late FY-1978 (Eissenberg and Hoffman 1979). Heat would be supplied to ground water by thermal exchange with a garbage burner. The initial objectives of this new project were to locate and determine the hydrological properties of a local aquifer and to delineate the engineering and economic factors relevant to constructing and testing a full-scale double-well aquifer-storage module.

(a) R.D. Allen, Pacific Northwest Laboratory Report on Low Temperature Thermal Energy Storage Technical Review Committee Meeting, Denver, CO, Nov. 6, 1978.

Economic analyses of the demonstrations are under way. Aquifer storage has the least potential cost. If test wells disclose favorable stratigraphy the first well doublet will be drilled to supply a water volume of about 3.8×10^6 l/day (10^6 gal/day).

7.2 TVA PROJECT

The TVA feasibility project consists of identifying for this region, 1) potential sources of excess low-temperature thermal energy; 2) criteria for storing thermal energy in aquifers; 3) potential aquifer storage sites; and 4) potential users of the thermal energy (Manaker 1978).

The project is to be accomplished in the following five tasks:

1. Identification of energy producers: A regional survey will be conducted of the Tennessee Valley Authority service area for low-temperature thermal energy producers in the commercial, industrial, institutional, and utility sectors. Facilities to be considered are: central generating stations, industrial steam plants, chemical processing plants, food processing plants, and smelting operations. In addition, solar collectors will be considered as a potential heat source and winter temperatures as a chill source. Approximate daily, monthly, and seasonal peak thermal energy outputs from each facility will be identified and documented, along with sufficient data regarding facility operation to assess the potential availability of energy for storage over an extended period of years.
2. Development of aquifer storage criteria: The criteria for transporting waste hot water and storing low-temperature thermal energy in aquifers on a seasonal, weekly, or daily basis will be developed. Areas to be addressed in developing the criteria for aquifers are their hydraulic, thermal, and geochemical properties. Also, the general environmental impacts (e.g., ground water effects) will be addressed. Conceptual storage system designs, siting requirements, thermal transport methods, and interface design conditions will be developed.

3. Storage system site survey: Specific siting requirements for aquifer storage systems, identified in the previous task, will be used to determine the availability of TES system siting areas in the TVA service area. Subsurface geology, topographical needs, and environmental impacts of the aquifer sites will be determined.
4. Survey of potential low-temperature thermal energy users: These may include: Tennessee Valley Authority; private, municipal, and cooperative utilities; communities (district heating/cooling); schools, hospitals and other institutions; and industries. Potential users will be grouped by location and type of usage to indicate areas with maximum potential for implementation of thermal energy usage.
5. Assessment of opportunities for thermal energy storage in the TVA region: The results of the previous tasks will be assessed to identify areas where suppliers, sites, and users may be combined to allow the implementation of low-temperature thermal energy storage systems. Technical constraints to actual implementation, such as the problems of system energy imbalances and interconnecting the three system components, will be identified and documented.

7.3 TWIN CITIES, MINNESOTA

Studies are under way to evaluate the feasibility of installing a new, large district heating (DH) system in the Minneapolis-St. Paul metropolitan area (Meyer and Hausz 1978). The system would be based upon cogeneration of power and heat by Northern States Power Company. The proposed new DH system would supply hot water, which is the common practice in Europe, to provide space heating, domestic hot water, air conditioning (absorption cycle), and low-temperature industrial process heat.

Heat storage wells (Meyer 1978) would be located in one or more aquifers near the Riverside Plant shown in Figure 13. For purposes of this study, availability of qualified aquifers is assumed. Aquifers do exist within reasonable distance, but none of these has yet been proven

FIGURE 13. Cogeneration Plant and Hot-Water Transmission Pipelines for Minneapolis District Heating System

to be a practical reservoir. For cogeneration on a large scale, Thermal Energy Storage (TES) at the central plant should be large enough to accept all hot-water production exceeding immediate demands, and to supply hot water demands that exceed production. Dependable storage will make possible the elimination of cooling towers or water for condensers. All useful heat produced, within efficiency limitations, as a byproduct of electric generation will be captured. The substantial cost of condenser cooling systems will be eliminated.

TES will be located at nodes and terminals along the major pipelines to help smooth load fluctuations and permit the pipelines to be operated at high capacity factors. The TES will also increase system reliability, serving as a backup in case of central-station or pipeline outage.

Figure 14 illustrates schematically the heat storage well concept (Meyer 1978) of annual-cycle TES at low cost and low heat loss. Two water wells are drilled to the range of 152.4 to 305 m (500 to 1000 ft) to provide sufficient hydrostatic head to maintain superheated water in liquid form, and to avoid aquifers used for water supply. The two wells of the doublet comprise a closed hydraulic system; water pumped from

FIGURE 14. Schematic Diagram of Heat Storage Well Doublet Operation

one well is injected into the companion well, several hundred feet away. The heat-storage medium is the porous rock comprising the aquifer and the water filling the pores, together with the relatively impervious aquifer caprock and underlying formation. The energy storage capacity will be very large, e.g., the aquifer may be 30.5 m (100 ft) thick, and the hot water may extend 91.5 m (300 ft) or more radially from the well. The TES capacity, the rate at which heat can be stored or withdrawn from storage, will be determined by the diameters and depths of the wells, the pumping capacity, and the flow parameters of the aquifer. A reasonable estimate is that a heat storage well doublet may have a 20-megawatt thermal capacity (Meyer 1978). Multiple wells will be employed to obtain larger capacities. The cost of a developed TES aquifer field will be determined by the design TES capacity.

Natural rocks and sand insulate the hot water stored in an aquifer. Three-fourths or more of the stored heat would appear to be recoverable after 6 months or longer (Meyer et al 1976; Tsang 1977). This remains to be demonstrated on the necessary scale, with water injected at temperatures above 100°C.

8.0 PRELIMINARY AQUIFER SELECTION CONSIDERATIONS

All preliminary aquifer selection considerations are based upon the findings and conclusions of authors cited in this report. Undoubtedly as the technology progresses, these qualitative considerations will be replaced by quantitative selection criteria.

1. Natural horizontal movement of ground water in the aquifer must be relatively small to effect thermal containment and recovery.
2. The volume and permeability available within the aquifer must be sufficient to make possible acceptance and delivery of the designated fluid quantity at the required rates.
3. The thermal conductivities of caprock and bedrock formations must be sufficiently low to effectively insulate the thermal storage reservoir. (This criterion would rarely be difficult to meet.)
4. The aquifer and confining rock formations must be capable of storing the working fluid at the required maximum containment pressure without excessive leakage and without hydraulic fracturing.
5. The aquifer system and overlying strata must not undergo significant vertical deformation or displacement during inflow or outflow.
6. The aquifer/aquitard system must not be susceptible to significant fatigue effects due to cycling of the working fluid.
7. The temperature of aquifer water should not be significantly affected by rainfall, melting snow, or surface air temperature.
8. A confined thermal storage aquifer must be hydraulically isolated from existing or potential potable water aquifers.
9. The aquifer should not contain significant quantities of calcareous minerals, mica, clay minerals, sulfates, or water soluble minerals.
10. The thermal storage aquifer must be located within economic fluid transport distances of the working fluid source and utilization points.

9.0 PRELIMINARY DESIGN AND OPERATING CONSIDERATIONS

Preliminary design and operating considerations presented here are believed to represent a relatively conservative consensus of current thought. Most of these considerations originated within the foregoing material. As with the aquifer selection considerations, design and operating considerations will undoubtedly be succeeded by quantitative criteria, at least in some generic categories.

1. Significant reduction of natural permeability due to chemical precipitation, mineral hydration, or transport and deposition of suspended solids must be avoided.
2. The temperature and pressure of the working fluid must not be high enough to destroy or materially alter the confining and transmission characteristics of the aquifer system by either hydrofracturing or dissolution.
3. Provision must be made for accurate and perpetual monitoring of flow rates, water levels, water temperatures, water chemistry, and subsidence or uplift of overburden.
4. The number of wells and depths of well penetrations into the aquifer will be determined by operating requirements of volume and efficiency.
5. If "hot" and "cold" wells penetrate the aquifer, the permeability between them must be sufficiently low, or the distance between them sufficiently large, to prevent significant comingling of fluids at different temperatures.
6. The requirement that percentage heat loss (or gain) from storage be minimized is to be satisfied by using a storage capacity much larger than the quantity of energy exchanged during a single cycle.
7. The working fluid must not contain corrosive solutes in high enough concentration to degrade the well pipe, pump components or surface heat exchanger.

8. High temperature, large throughput systems will require multiple wells of special design to avoid generation of excessive pressures.
9. Lateral movement of stored fluid caused by buoyant spreading of the heated fluid over denser and more viscous cooler natural water should be minimized to improve recovery.
10. For an aquifer with high vertical permeability hot water is to be injected at the top, cold water at the bottom, to counteract natural convection.
11. Aquifers may be artificially compartmentalized to isolate the introduced working fluid from either static or flowing ground water at a different temperature.
12. Bacteria inhibition by chlorine injection, or other chemical procedure, may be necessary.
13. Metal well casing may be replaced with plastic pipe within the aquifer to eliminate corrosion and minimize heat transfer between working fluid and well during storage intervals.
14. Formation ground water tends toward chemical equilibrium with the aquifer and also tends to be low in suspended solids. This water may be used as the working fluid to minimize the risk of chemical or mechanical degradation within the aquifer and within other portions of the system.
15. The aquifer water volume should remain sensibly constant with respect to time to minimize hydrological imbalances and possible adverse stress fields.
16. In high temperature storage, water is to be contained in the liquid phase to achieve maximum energy density. This will require a reservoir at the appropriate geostatic pressure.
17. A negligible percentage of the water volume is to be lost through aquitard caprock and foundation beds during an input/storage/output cycle.

18. The system shall not damage the environment with respect to thermal pollution, migration of toxic materials, land subsidence or uplift, or seismicity.
19. The working fluid will operate in a closed system insofar as possible to avoid the introduction of contaminant solutes or sediment.
20. Aeration of the working fluid should be avoided; conversely, deaeration may be required.
21. The thermal recovery factor must be sufficiently high to amortize, operate and maintain the installation.
22. The thermal storage system must be economically competitive with other technologies.

REFERENCES

- N. Avdonin, "Some Formulas for Calculating the Temperature Field of a Stratum Subjected to Thermal Injection," Neft-i Gaz. Vol. 7, No. 3, pp. 37-41, 1964.
- ATES Newsletter, C.F. Tsang, Editor "A Bimonthly Review of Aquifer Thermal Energy Storage," Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Vol. 1, No. 1, October 1978.
- ATES Newsletter, C.F. Tsang, Editor, "A Bimonthly Review of Aquifer Thermal Energy Storage," Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Vol 1, No. 2, January 1979.
- ATES Newsletter, C.F. Tsang, Editor, "A Quarterly Review of Aquifer Thermal Energy Storage", Earth Sciences Division, Lawrence Berkeley Laboratory, University of California, Vol. 1, No. 3, May 1979.
- C. R. Cole and S. K. Gupta, "A Brief Description of the Three-Dimensional Finite Element Ground-Water Flow Model Adapted for Waste Isolation Safety Assessments," PNL-2652, Pacific Northwest Laboratory, August 1979.
- R. E. Collins, "High Temperature Underground Storage of Solar Energy," presented at 3rd Ann. Thermal Energy Storage Contractors' Information Exchange Meeting, Springfield, VA, December 5 and 6, 1978, 6 pp.
- R. E. Collins, J. R. Fanchi, G. O. Morrell, K. E. Davis, T. K Guha and R. L. Henderson, "High Temperature Underground Thermal Energy Storage," Proceedings Thermal Energy Storage in Aquifers Workshop, Berkeley, CA, May 10-12, 1978, pp. 62-66, December 1978.
- Y. Cormary, P. Iris, J. Marie, G. de Marsily, H. Michel and M. Zaquine, "Heat Storage in a Phreatic Aquifer: Campuget Experiment (Gard, France)," Proc. TES in Aquifers Workshop, *ibid.*, pp. 88-93.
- D. M. Eissenberg and H. W. Hoffman, Low-Temperature Thermal Energy Storage Program Progress Report for Period October 1978 - March 1979. ORNL/TM-6936, 1979.
- A. C. Gringarten and J. P. Sauty, "A Theoretical Study of Heat Extraction from Aquifers with Uniform Regional Flow," J. Geophys. Res., Vol 80, No. 35, pp. 4956-4962, 1975.
- G. Hellstrom, "Aquifer Storage Projects in Sweden," Proc. TES in Aquifers Workshop, *ibid.*, pp. 71-74.
- H. J. Hibshman, "Air Conditioning Kennedy Airport with Winter Cold," Proc. TES in Aquifers Workshop, *ibid.*, pp. 56-61.

INTERCOMP Resources Development and Engineering, Inc., "A Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers," U.S. Geol. Survey Water Resources Invest. 76-61, 1976.

R. Jank, "Aquifer Storage Efforts in Germany," Proc. TES in Aquifers Workshop, *ibid.*, pp. 71-74.

L. B. Katter and R. L. Hoskins, "Application of Thermal Energy Storage to Process Heat and Waste Heat Recovery in the Aluminum Industry," presented at 3rd Annual TES Contractors' Information Exchange Meeting, *ibid.*, 8pp.

W. Kley and H-G. Nieskens, "Practical Ways of Heat Storage in a Porous Aquifer and Technical Problems of Energy Recovery," (in German), Z. dt. geol. Ges., pp. 397-409, Hannover, 1975.

A. M. Manaker, "Application of Low-Temperature Thermal Energy Storage in the TVA Region," presented at 3rd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, 3 pp.

B. Mathey and A. Menjoz, "Underground Heat Storage: Choice of a Geometry, and Efficiency," Proc. TES in Aquifers Workshop, *ibid.*, pp. 80-87.

C. F. Meyer, "Evaluation of Thermal Energy Storage for the Proposed Twin Cities District Heating System", presented at 3rd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, 9 pp.

C. Meyer, W. Hausz, B. Ayres and H. Ingram, Role of the Heat Storage Well in Future U.S. Energy Systems. GE76TMP-27, General Electric-Tempo. Center for Advanced Studies, Santa Barbara, CA, December 1976.

C. F. Meyer and W. Hausz, "Energy Management Objectives and Economics of Heat Storage Wells," Proc. TES in Aquifers Workshop, *ibid.*, pp. 17-28.

F. J. Molz and A. D. Paar, "Experimental Study of the Storage of Thermal Energy in Confined Aquifers," presented at 3rd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, 8 pp.

F. J. Molz and J. C. Warman, "Confined Aquifer Experiment-Heat Storage," Proc. TES in Aquifers Workshop, *ibid.*, pp. 46-50.

F. J. Molz, J. C. Warman and T. E. Jones, "Aquifer Storage of Heated Water: Part I--A Field Experiment," Ground Water, Vol. 16, pp. 234-241, 1978.

A. Nir and J. Schwarz, "Survey of Thermal Energy Storage in Aquifers Coupled with Agricultural Use of Heat under Semi-Arid Conditions," Proc. TES in Aquifers Workshop, *ibid.*, pp. 77-79.

S. S. Papadopoulos and S. P. Larson, "Aquifer Storage of Heated Water: Part II -- Numerical Simulation of Field Results," Ground Water, Vol. 16, pp. 242-248, 1978.

E. B. Qvale, "The Danish Seasonal Aquifer Warm-Water Storage Program," Proc. TES in Aquifers Workshop, *ibid.*, pp. 75-76.

D. L. Reddell and R. R. Davison, "Storage of Cold Water in Groundwater Aquifers for Cooling Purposes-Phase II," presented at 3rd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, 3 pp.

D. L. Reddell, R. R. Davison and W. B. Harris, "Thermal Storage of Cold Water in Groundwater Aquifers for Cooling Purposes," Proc. TES in Aquifers Workshop, *ibid.*, pp. 51-55.

M. Singer, "Annual Cycle Cold Energy Storage at John F. Kennedy International Airport (JFK) for Air Conditioning," presented at 3rd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, 10 pp.

W. J. Subcasky, "Petroleum Industry Experience in Water Injection," Proc. TES in Aquifers Workshop, *ibid.*, pp. 14-16.

C. V. Theis, "The Relation Between the Lowering of Piezometric Surface and the Rate and Duration of Discharge Using Groundwater Storage," Trans. Amer. Geophys. Union, Vol. 2, pp. 519-524, 1935.

C. F. Tsang, "Thermal Energy Storage in Underground Aquifers," Proc. 2nd Ann. Thermal Energy Storage Contractors' Information Exchange Meeting. CONF-770955, Gatlinburg, TN, September 29-30, 1977, pp. 91-98.

C. F. Tsang, T. Buscheck, D. Mangold and M. Lippmann, "Mathematical Modeling of Thermal Energy Storage in Aquifers," Proc. TES in Aquifers Workshop, *ibid.*, pp. 37-45.

C. F. Tsang, "Mathematical Modeling of Thermal Energy Storage in Aquifers," presented at 3rd Ann. Thermal Energy Storage Contractors' Information Exchange Meeting, *ibid.*, 7 pp.

J. C. Warman and F. J. Molz, "Subsurface Waste Heat Storage, Experimental Study," Proc. 2nd Ann. TES Contractors' Information Exchange Meeting, *ibid.*, pp. 24-27.

T. Yokoyama, H. Umekiya, T. Teraoka, H. Watanabe, K. Katsuragi, and K. Kasahara, "Seasonal Regeneration Through Underground Strata," Proc. TES in Aquifers Workshop, *ibid.*, pp. 94-106.

APPENDIX
NUMERICAL SUMMARY

APPENDIX

NUMERICAL SUMMARY

This appendix summarizes quantitative properties of aquifers and characteristics associated with conceptual designs, numerical models, and field experiments. It is to be stressed that the quantities reported below are drawn from published articles and do not necessarily represent either typical or extreme conditions, natural or artificial. These numbers are not offered as either aquifer selection or utilization criteria.

Aquifer reservoir capacities vary from 10^5 to $4 \times 10^8 \text{ m}^3$. Vertical thicknesses range from 3 to 100 m. Both unconfined and confined aquifers have been considered for low temperature storage. Thicknesses of overburden above unconfined aquifers range between 2 and 30 m, whereas overburden plus consolidated aquitard layers above confined aquifers range between 40 and 305 m in thickness. For storage of water at or above 343°C (650°F) the upper surface of the aquifer must be at a depth exceeding 1677 m to assure containment. At this temperature the storage pressure would be 186.2 bar.

Natural aquifer water temperatures vary from 7 to 40°C (excluding geothermal waters). Hydraulic conductivity ranges from 10^{-3} to $5 \times 10^{-4} \text{ m/s}$. Hydraulic gradients of 0.03% and 2% are reported. These may be associated with extreme differences in natural regional flow rate, e.g., 1 m/y and 100 m/y. The lower flow rate has negligible effect on thermal storage, but the higher flow rate causes appreciable losses. The pore velocity of water is reported to vary between 5 and 20 cm/day which would equal 18 to 73 m/y if maintained at constant rate. Measured thermal conductivities are: 5.5×10^{-4} and $6.1 \times 10^{-4} \text{ kcal/m s } ^\circ\text{C}$ for aquifer matrix plus water and aquitard, respectively.

For air conditioning applications using chilled water, injection temperatures considered were from 2 to 10°C and withdrawal temperatures

were from 7 to 13°C. For low temperature thermal energy storage, injection temperatures varied from 34 to 90°C and withdrawal temperatures varied between 14 and 79°C. For storage of water above the boiling point, injection temperatures were assumed from 120 to 343°C.

Injection and withdrawal rates were 6 to 50 l/s. These compare with stated pumping capacities of 8 to 38 l/s. Pumping injection pressures varied from 1.5 to 5.15 bar. Practiced injection and withdrawal intervals varied between 1.5 and 6 months. Storage intervals varied from 1 to 4 months. Particular system design parameters include: doublet well separation—100 to 300 m, well diameter—2.2 m, aquifer penetration, partial and full. Backwashing volumes to maintain hydraulic conductivity varied from less than 1136 to 26,500 liters.

Recovery efficiency ranges varied from 8 to 30% for shallow unconfined aquifers^(a) to 66 to 92% for deeper confined aquifers. Reservoir energy capacities up to 600 Tcal have been projected. However, one source postulated an energy delivery rate of 225 Mcal/s. This would correspond to about 583 Tcal/month.

An economic projection for district heating 5,000 to 10,000 homes in Germany concluded that an aquifer storage system supplied with cost-free hot water could be amortized within 10 years.

^(a) The recovery efficiency of 8 to 30% for shallow unconfined aquifers is believed to be misleading since the tests involved small volumes and excessively shallow depths.

DISTRIBUTION

<u>No. of Copies</u>		<u>No. of Copies</u>	
	<u>OFFSITE</u>		D. M. Eissenberg Oak Ridge National Laboratory PO Box Y Oak Ridge, TN 37830
	Assistant Director for Major Projects Division of Solar Energy U.S. Department of Energy Washington, D.C. 20545	11	John A. Gahimer Chief of Chemical and Thermal Branch Division of Energy Storage Systems Department of Energy 600 E Street, NW Washington, D.C. 20545
	Frank Baylin Solar Energy Research Institute 1536 Cole Blvd. Golden, CO 80401		Douglas Huxtable Rocket Research Company York Center Redmond, WA 98052
	Chicago Patent Group U.S. Department of Energy Attn: Arthur A. Churm 9800 South Cass Avenue Argonne, IL 60439		Irving Kantrowitz United States Geological Survey Water Resources Division 5 Aerial Way Syosset, NY 11791
27	DOE Technical Information Center DOE Library U.S. Department of Energy Mail Station G-043 Washington, D.C. 20585 P. Donnelly Argonne National Laboratory 9700 South Cass Avenue Argonne, IL 60439 Dan D. Edie Department of Chemical Engineering Clemson University Clemson, SC 29631		Donald L. Katz Department of Chemical Engineering The University of Michigan 2042 E. Engr. Bldg. Ann Arbor, MI 48109 L Kelso Division of Industrial Energy Conservation Department of Energy Washington, DC 20545

No. of
Copies

Donald Langmuir
Department of Geochemistry
Colorado School of Mines
Golden, CO 80401

Lawrence Berkeley Laboratory
Library
University of California
Bldg. 50, Room 134
Berkeley, CA 94720

Lawrence Livermore Laboratory
Technical Information
Department, L-3
University of California
P.O. Box 808
Livermore, CA 94550

Wayne Lundberg
Westinghouse Electric Corp
Advanced Energy Systems Division
PO Box 10864
Pittsburgh, PA 15236

T. Mahefkey
AFAPL/POE
Building 18
Wright-Patterson Air Force
Base, OH 45433

Arnold Manaker
Tennessee Valley Authority
1360 Commerce Union Bank
Chattanooga, TN 37401

William Masica
NASA-Lewis Research Center
Cleveland, OH 44101

Charles F. Meyer
General Electric-TEMPO
Center for Advanced Studies
PO Drawer QQ
Santa Barbara, CA 93102

No. of
Copies

Allan Michaels
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

Fred Molz
Water Resources Research Institute
Auburn University
Auburn, AL 36830

Jerzy R. Moszynski
Department of Mechanical
and Aerospace Engineering
University of Delaware
Newark, DE 19711

National Science Foundation
Division of Advanced Energy
Research and Technology
Room 1140
1800 G Street, N.W.
Washington, D.C. 20550

William Nice
NASA-Lewis Research Center
Cleveland, OH 44101

G. F. Pezdirtz
Director for Division of
Energy Storage Systems
Department of Energy
600 E Street, N.W.
Washington, DC 20545

Henry J. Ramey, Jr.,
Petroleum Engineering Department
Stanford University
Stanford, CA 94305

Donald Reddell
Texas A & M Research Foundation
FE Box H
College Station, TX 77843

No. of
Copies

Ival Salyer
University of Dayton
Research Institute
Dayton, OH 45469

Sandia Laboratory
Technical Library
Department 3141
Albuquerque, NM 87115

Tom Schneider
Electric Power Research Institute
3412 Hillview Avenue
PO Box 10412
Palo Alto, CA 94303

R. Sheneman
Division of Industrial Energy
Conservation
Department of Energy
Washington, DC 20545

Melvin Singer
New York State Energy Research
and Development Authority
Empire State Plaza
Agency Building No. 2
Albany, NY 12223

J. H. Swisher
Assistant Director for Physical
Storage Systems
Division of Energy Storage
Systems
Department of Energy
600 E Street, N.W.
Washington, DC 20545

Tennessee Valley Authority
Energy Research Section
1360 Commerce Union Bank Bldg.
Chattanooga, TN 37401

No. of
Copies

Saul Strauch
Division of Energy Storage
Systems
U.S. Department of Energy
600 E Street, N.W.
Washington, DC 20545

Roy Thornton
General Electric Company
Research and Development Center
PO Box 8
Schenectady, NY 12301

Chin Fu Tsang
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

James Warman
Water Resources Research Institute
Auburn University
Auburn, AL 36830

William Wilson
Sandia Laboratories
Livermore, CA 94550

Charles Wyman
Solar Energy Research Institute
1536 Cole Blvd
Golden, CO 80401

Director
Reactor Division
Department of Energy
Oak Ridge Operations
Oak Ridge, TN 37830

Office of Assistant Manager
Energy Research and Development
Department of Energy
Oak Ridge Operations
Oak Ridge, TN 37830

No. of
Copies

ONSITE

DOE Richland Operations
Office

D. K. Jones
H. E. Ransom

Pacific Northwest Laboratory

R. D. Allen (20)
C. H. Bloomster
C. W. Cable
D. B. Cearlock
R. N. Coy
J. R. Eliason
J. D. Etchemendy
J. W. Finnigan
Kenneth Fox
W. A. Frier
C. E. Hatch
P. L. Hendrickson
D. D. Hostetler
C. T. Kincaid
W. V. Loscutoff
J. E. Minor
D. A. Myers
M. E. Olson
H. L. Parry
J. R. Raymond
R. W. Reilly
J. A. Stottlemire
R. A. Walter
J. C. Zuck
Technical Information (5)
Publishing Coordination (2)
Water and Land Library (5)