SEASONAL THERMAL ENERGY STORAGE PROGRAM
PROGRESS SUMMARY FOR THE PERIOD APRIL, 1986,
THROUGH MARCH, 1988

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PREFACE

This is the progress summary for the Seasonal Thermal Energy Storage Program, administered by the Pacific Northwest Laboratory for the U.S. Department of Energy. This document describes all of the major research funded under this program during the period April, 1986, through March, 1988.

The report summarizes the activities and notable progress toward program objectives in seasonal thermal energy storage. Readers wishing additional information on specific topics are invited to contact Landis Kannberg at Pacific Northwest Laboratory.

The work described in this report represents one segment of a continuing effort to encourage development and implementation of advanced energy storage technologies. The results and progress reported here rely on earlier studies and will, in turn, provide a basis for continued efforts to develop seasonal thermal energy storage technologies.

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SUMMARY

Seasonal thermal energy storage (STES) is estimated to have the potential to supply from 2% to 4% of the nation's annual energy consumption. It has the greatest market in heat storage because of the availability of abundant waste heat from industrial processes. Another major market sector is industrial and space cooling.

Research is now focussed on development of aquifer thermal energy storage (ATES). ATES is the least expensive of all potential STES technologies, where adequate aquifers exist. ATES at temperatures over 80°C, suitable for many district heating and industrial processes, has many technical challenges and uncertainties including geohydrothermal performance, prediction and control of groundwater chemistry, and preserving environmental quality. ATES at lower temperatures, including chill storage, also has challenges and uncertainties, such as, mitigation of the negative effects of regional flow, geohydrothermal performance, microbiologic behavior, and preserving environmental quality.

Two large field projects are underway that provide information on many of these issues and provide field data to corroborate laboratory and numerical modeling efforts. University of Minnesota researchers at the St. Paul field test facility completed the second long-term test cycle during the reporting period. This test used a higher temperature (120°C) than any previous aquifer field test and was completed according to schedule. A thermal energy recovery factor of 0.62 was computed based on actual source water temperature. The recovery factor would be 0.69 if the source water had been at normal groundwater temperature (11°C). Scaling of calcium carbonate in the heat exchanger was controlled with the use of ion-exchange water softening. Although softened prior to injection, the recovered groundwater was nearly at equilibrium with the minerals present in the aquifer, with the exception of the sodium introduced to the aquifer through water treatment. Only 80% of the injected sodium was recovered, although sodium was expected to be a conserved substance. Uncertainty exists whether mixing or chemical reactions account for the unrecovered sodium. Aquifer thermal behavior during the second long-term test was consistent with earlier testing. High permeability zones were evident by their rapid thermal rise (as hot groundwater flowed through these zones). Less

permeable layers were heated by conduction from adjacent zones having higher permeability. Zones distant from the permeable layers were unaffected during the test.

The chill ATES system at the Student Recreation Center at the University of Alabama continued to be monitored by University researchers. Steps were taken to improve the performance of the system. The steps included revising the operating strategy to counteract the negative effects of regional groundwater flow at the site. The system has met all the sensible cooling loads of the Recreation Center since its initial operation. During 1986-87 approximately 80% of the injected chill was recovered. However, nearly 2.5 times as much groundwater was pumped during recovery as during injection to meet the cooling load. Part of the reason for this is the severe weather during the year (warm winter and hot summer). But an equally significant problem is the loss of stored chill; being swept away by regional groundwater flow. Based on first results, the revised operating strategy, implemented in 1987-88, appears to be having a beneficial effect. During 1986-87, the system posted an annual coefficient-of-performance of 5.0 and reduced summer peak electrical consumption for cooling by an estimated factor of 20 compared with conventional technology. This results in an estimated annual savings of approximately \$17,000.

ATES-specific numerical models are necessary to design and assess ATES systems. A suite of codes was identified for ATES simulation. The codes are applicable to a spectrum of potential ATES simulation. The mainstay of the suite is the ATESSS (Aquifer Thermal Energy Storage System Simulator) code, developed for initial site screening and design optimization. Other codes have been, or are being, collected to deal with specific design issues at various levels of sophistication. ATESSS was used during the reporting period to assess various design options for mitigating regional flow effects at the Student Recreation Center and a planned chill ATES system at a General Motors Plant in Tuscaloosa, Alabama. These simulations indicated that a well field that is collinear with the hydraulic gradient may provide good thermal recovery at a smaller cost than designs that use up-gradient pumping to control regional flow. ATESSS was also used to assess the role of impermeable layers in aquifers. Nomographs for assessing the importance of impermeable layers were

developed. It was determined, for instance, that for a seasonal cycle an aquifer composed of many alternating layers of permeable and impermeable media will have first-cycle thermal recovery efficiencies of 93% for layers 0.25-m thick, 62% for layers 5.0-m thick, and 85% for layers 25-m thick.

All remaining models identified for the suite are available in the U.S. except for CHARM1, the first version of a geochemical/transport code being developed by The Netherlands as part of its contribution to International Energy Agency (IEA) Annex VI of the Energy Conservation Through Energy Storage Programme. The U.S. is contributing to this Annex in several ways including providing an up-to-date geochemistry model database, providing experimental data on fundamental geochemical reactions and their kinetics for sandstones, and leading a subtask to assess microbiologic issues.

Geochemical laboratory testing is underway to determine fundamental geochemical behavior for sandstones, primarily those from the St. Paul field test facility site. This testing increases the knowledge of groundwater geochemistry, contributes to our understanding of geochemical behavior at the St. Paul site, and helps satisfy Department of Energy (DOE) IEA agreements. Results of the testing to-date indicate the influence of fines (small particles in the sandstone) on geochemical reactions and their rates. The fines appear to be a source of calcium for dissolution during storage, despite the inability to identify any calcium mineral forms in the sandstone samples. The laboratory results are consistent with those of earlier field tests, and explain some of the ambiguities. Increased sulfate concentrations were observed during storage for both field and laboratory tests. Laboratory tests explained that feldspar dissolution was the source of potassium in recovered groundwater. Finally, dissolved silicon is controlled by dissolution of, and equilibrium with, quartz. This last finding is important because 1) it reduces the number of geochemical constituents of interest for ATEs site characterization, and 2) if silica scaling becomes a problem at the site, additional water treatment will be required because the aquifer can serve as a nearly inexhaustible supply of silica. One nagging question remains. What is the role of mixing in the aquifer on geochemical dynamics?

Two new environmental studies were undertaken. An assessment of ATEs effects on microbiota was conducted and, as a result, a field monitoring program was initiated at the chill ATEs site on the University of Alabama. Aquifers are habitat to an abundant and diverse microbial population. Unfortunately, little information is available on these organisms. It is known that indigenous organisms are subject to environmental factors including: aquifer porosity, nutrient availability, oxidation-reduction conditions, pH, temperature, and adsorption on aquifer rock matrix. While impacts on indigenous organisms are of concern, immediate interest is focussed on pathogenic microorganisms, especially *Legionella*. Monitoring for coliform bacteria at the St. Paul field test facility site has determined that no coliform bacteria survive the high-temperature testing at that site. However, it is expected that microbiologic activity at the Student Recreation Center at the University of Alabama will interact with a verdant microbiologic community. Therefore, monitoring for both indigenous and pathogenic organisms has been initiated. The results of the preliminary assessment has been provided to fellow IEA participants in Annex VI and results of future monitoring at the University of Alabama will be provided semiannually to IEA participants and more widely through topical reports.

International activity in ATEs has increased, with pilot projects underway at many sites. European and Scandinavian countries are the most active at this time (primarily in heat storage), although China has many chill ATEs systems in service.

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SEASONAL THERMAL ENERGY STORAGE PROGRAM PROGRESS SUMMARY
FOR THE PERIOD APRIL, 1986, THROUGH MARCH, 1988

1.0 INTRODUCTION

Energy plays a major role in the economic prosperity and security of the our nation. The effects of disturbances in the quantity and price of energy, in the many forms it is used in our society, were made apparent during the years following the 1973 oil embargo. The remnants of that disturbance are with us today; in the current price of fuel, the major shifts in our energy infrastructure, and in our uncertainty in making and effecting decisions required to meet future energy needs.

One thing experience has taught us; our ability to predict energy availability, demand, and price is limited. It is, therefore, important that the nation have a broad based suite of technologies available to meet the possible needs of the future. The technologies that should be developed are those that have the best hope of being both necessary and sufficient to meet our changing energy needs; ensuring our energy security, making our economy as efficient as possible, and preserving our nation's environmental quality.

The U.S. Department of Energy (DOE) is active, at the direction of Congress, in developing such a suite of technologies. One of these technologies is thermal energy storage.

This report discusses recent progress in the DOE program, directed by Pacific Northwest Laboratory^(a), to develop seasonal thermal energy storage (STES). STES has been identified as one method to substantially improve energy efficiency and economics in certain sectors of our economy. It provides a potentially economic means of using waste heat and climatic energy resources to meet a significant portion of our growing energy need for building and industrial process heating and cooling. Environmental benefits accompany the use of STES in many applications. Furthermore, STES can contribute to reduced

(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute.

reliance on premium fuels that are often obtained from foreign sources. Lastly, by improving the energy economics of industry, STES can contribute to improved U.S. industrial competitiveness.

The report is provided in four sections; the first being this introduction. Section 2 of the report describes the program and briefly documents its organization, goals, history, and long-term plans. Section 3 describes the progress during the period from April, 1986, through March, 1988. Section 4 provides a short update on international development of STES.

2.0 OVERVIEW OF THE SEASONAL THERMAL ENERGY STORAGE PROGRAM

The mission of the DOE's Office of Energy Storage and Distribution (OESD) is to develop and advance energy conversion, storage, control, and delivery technologies that benefit the nation by:

- increasing national security
- enhancing energy independence
- assuring public safety
- improving the quality of the environment
- enhancing U.S. competitiveness.

Seasonal thermal energy storage technologies are among those being advanced because they can substantially reduce total energy consumption, leading to greater energy independence and improved environmental quality. Once technical and economic risks have been reduced through proven performance, STES is expected to be a highly economical option that will contribute to U.S. competitiveness by reducing energy costs in industrial and commercial operations.

2.1 PROGRAM OBJECTIVES, SCOPE AND STRATEGY

The mission of the STES Program is to develop technology for economic storage and recovery of energy on a seasonal basis. Seasonal thermal energy storage is being pursued as part of the OESD technology portfolio because of its potential to contribute to the OESD mission. It has been estimated that STES is technically suitable to provide up to 10% of the nation's energy needs (Anderson and Weijo 1988). Residential and commercial building heating, cooling, and domestic water heating consumed 15 quads of energy^(a) in the U.S. in 1983, primarily as natural gas and petroleum distillates (U.S. Department of Energy 1986). It has been estimated that over 2 quads of energy are available as industrial waste heat. A substantial portion of this is well suited for STES. Furthermore, use of climate energy from renewable sources (i.e., solar

(a) 1 quad = 10^{15} Btu, $\approx 10^{18}$ Joules or $\approx 3 \times 10^{14}$ kWh.

heat and winter chill) provides additional potential for meeting building heating and cooling needs using STES. It has been estimated that over 2 quads of residential and commercial cooling exist, a portion of which could potentially be integrated with winter chill STES. A 1979 study (TRW 1979) estimated that, if aggressively pursued, STES could be expected to supply 2 quads of building heating and cooling by the end of the century. While energy economic conditions have changed in the last few years, the enormous potential for STES remains.^(a)

Developing STES technologies requires a focussed program based on STES technology development needs and priorities and a correct perception of the Federal role in energy technology development. Therefore, STES Program efforts are focussed on acquiring and transferring knowledge to those seeking to use STES for industrial, commercial, and residential heating and cooling.

2.1.1 Objectives

The objectives of the STES Program are:

- Establish a technical and economic knowledge base for private and public sector development and implementation of STES technologies.
- Transfer this knowledge base to industrial and commercial developers for implementation.
- Ensure the adequacy of the knowledge base by monitoring and assisting early STES implementation.

The knowledge base includes an understanding of geotechnical processes, STES system interactions, and relevant engineering features. The characterization of STES geotechnical behavior and the development of sound engineering guidelines for satisfactory long-term storage require detailed numerical analyses, laboratory experimentation, and field testing. Likewise, the analysis of alternate or more-advanced storage concepts requires technical and economic characterization and screening, development of testing procedures for critical high-risk components or subsystems, proof-of-principle testing, and field performance monitoring.

(a) One quad of energy was worth approximately \$11 billion at fuel prices available to commercial building owners in 1985.

Transfer of the knowledge gained through targeted research and development (R&D) and field testing is vital if the OESD mission is to be accomplished. Mechanisms for this transfer include involvement of groups seeking to implement the technology in R&D activities, cost-shared implementation of STES systems in pilot projects, assembly and publication of R&D results, and preparation of guidelines for analysis, design, and construction of STES systems.

Feedback on field performance of STES systems, particularly prototype commercial installations, is essential to identifying real-world challenges that may not have been apparent during research and development and for validating the knowledge base. Such feedback can only be obtained if researchers remain active throughout the technology-transfer phase and are involved in early application and monitoring of STES systems.

2.1.2 Scope

The program scope encompasses concepts that seasonally store heat or chill from waste or other surplus sources to reduce peak period energy demand, reduce electric utility peaking requirements, or contribute to the establishment of favorable economics for district heating and cooling systems. Aquifers, ponds, earth, lakes, and engineered structures (e.g., tanks and excavated caverns) are examples of physical systems with potential for seasonal storage.

Achievement of significant private and public development of STES will require research and development to establish technical and economic feasibility and institutional acceptability of a variety of STES concepts. Seasonal thermal energy storage in aquifers has been determined to have the greatest potential due to its low cost and the existence of suitable aquifers underlying more than 60% of the nation. Therefore, emphasis has been placed on aquifer thermal energy storage (ATES). Consequently, research programs have been initiated to characterize the technical features of ATES and identify and resolve the technical issues that increase risk beyond that acceptable to entrepreneurs. These risks involve virtually all aspects of ATES, including both technical as well as institutional issues. The various ATES issues are listed in Table 2.1 along with the factors they influence, their relative importance, relative

TABLE 2.1. Relative Ranking of Issues Affecting ATES Development

Issue	Influences	Rating ^(a)		Ranking
		Importance	State of Knowledge ^(b)	
Fundamental knowledge				
Geohydrology	Energy recovery (economics, viability)	5	3.5	3.5 SS ^(c)
	Well field design (performance/economics)			
Geochemistry	Injectability (well performance)	4	1.5	5.0 SS
	Water quality (environmental)			
	Water treatment (economics)			
Microbiology	Water quality (environmental)	3	1	4.0
	Water treatment (economic)			
	Injectability (performance)			
Design knowledge				
Source/load integration	Performance (economics, viability)	4.5	1.5	4.5 SS
System optimization	Performance (economics, viability)	4.0	2.0	4.0
Well field design	Energy recovery (economics, viability)	5.0	3.0	3.5
Water treatment	Water quality (environmental)	4.5	3.0	3.5
	Performance (economics, viability)			
Institutional factors				
Environmental acceptability	Permitting (viability)	4	2	3.5 SS
Legal ownership	Risk perception	3.5 ^(d)	1	3.5

(a) 1-5 from low to high.

(b) Inverse of risk

(c) "showstopper" - A factor capable of solely determining the viability of a project.

(d) Difficult to assess at present

state-of-knowledge, and research ranking. The various rankings are subjective, based primarily upon the experience to-date at operational ATEs systems around the world.

2.1.3 Strategy

The STES Program employs a sequence of activities to acquire and transfer the knowledge necessary to implement the technologies. The sequence generally progresses from conceptual investigations through pilot tests depending on the promise and technical risks associated with the concept. The successive steps include:

- identify and rank promising STES technologies
- identify and prioritize the technical, economic, and institutional issues facing technology implementation
- establish cohesive programs to characterize and resolve the issues
- transfer research and development results (including findings, methodologies, tools, guidelines, design aids, new concepts, and other knowledge) to STES implementors
- verify and augment this knowledge by assisting and monitoring implementation of pilot, and early commercial, STES systems.

The limits of the DOE role in STES development influence the nature of research and development conducted as part of the program. Most STES technologies use or are near groundwater resources that are the subject of state and local environmental quality statutes. This fact increases the institutional risk associated with implementation and cannot be overlooked in our efforts to establish an adequate knowledge base for STES implementation. Program involvement in implementation of STES technologies is limited to instances where technical knowledge is insufficient or unreliable or where a unique opportunity exists to extend or validate the existing knowledge base.

Program research and development generally concentrates on knowledge necessary to design STES systems or address state or Federal regulatory concerns. To the extent possible, field R&D is done at sites in regions that are early candidates for commercial development of STES technologies. In this manner, appropriate research and development is obtained in regions of the country where it will be most applicable and where early technology experience will be most beneficial.

2.2 LONG-TERM PROGRAM ACTIVITIES

The historical STES Program activities are illustrated in Figure 2.1. Evaluation of ATES began in 1975 at the Mobile field test site near Mobile, Alabama. A number of other STES development and evaluation efforts have been conducted over the years ranging from field studies and demonstration projects (subsequently discontinued) to studies of regulatory issues. Most program activity occurred in the late 1970s and early 1980s when energy conservation research and development was of high priority and correspondingly high budgets were available. Beginning in 1982, funding levels dropped dramatically and the scope of research and development abruptly shifted away from demonstration projects. Recent funding levels have stabilized, allowing consideration of program long-term goals and activities.

The organization of the STES Program has changed as the direction and scope of DOE funded efforts have changed. In 1987 all DOE-OESD thermal energy storage (TES) efforts were reorganized. Six project classifications were developed within which various projects were collected. The classifications include:

- System Development - system evaluation or development in the field (i.e., pilot or commercial-scale systems).
- Mathematical Modeling - development of tools to simulate important physical and chemical processes affecting system performance and behavior.
- Media Investigation and Development - characterizing the physical and chemical behavior of thermal storage media and its confinement.

FIGURE 2.1. Historical STES Program Activities

- System and Component Studies - preliminary investigation of TES systems and components, especially concept feasibility assessments and bench or field characterization of a major TES component.
- Heat Transfer Enhancement - development of means to improve heat transfer to and from TES elements (includes media, container, or ancillary equipment, such as indirect heat exchangers).
- Environmental and Institutional Studies - characterization and resolution of TES issues affecting environmental or institutional acceptability.

The organization of STES projects within this classification system is shown in Figure 2.2. Several of the projects serve multiple classifications. This is especially true of field projects where the information concerning several fundamental scientific issues is obtained along with data on operational behavior from testing in a realistic environment. Other projects are single-purpose studies.

The long-term plans for STES research are shown in Figure 2.3. Planned activities are shown according to the classification identified above for the next 5 years. The schedule for performance of these activities is aggressive; they can only be completed if sufficient funding is available.

The major thrusts for the next 5 years are threefold: 1) complete investigation of fundamental ATES phenomena and development of design aids (such as computer models), 2) begin assertive technology transfer and assist implementation by cost-shared feasibility studies and pilot-scale field tests/demonstrations, and 3) begin investigation of other promising STES technologies, such as ice storage, rock borehole, and earth STES. The first two thrusts are required to commercialize ATES technology. The investigation of other STES technologies is directed at providing STES alternatives for locations at which ATES is not viable or is not the most economic option.

FIGURE 2.2. STES Project Organization

Element	Project	FY88	FY89	FY90	FY91	FY92	
System Development	• High Temp. ATEs • Chilli ATEs - Stu. Rec. - GM Plant	Site Mods. 3rd L-T Cycle		Post Test	Final Report		
		Monitor Perf.			Final Report		
		Site Study	Design	Construct	Monitor	Final Report	
Math Modeling	• Geohydrothermal • Geochemical* • ATEs Expert System	ATESSS & Optim. Suite		Linked Hydrochem		Manuals	
		System Simulator					
		CHARM1	MINTEQ	CHARM3	Manuals		
		Explor. Devel					
Media Investigation & Development	• Geochemical* Dynamics • Microbiologic* Behavior	Version 1		Review	Version 2	Release	
		Version 1		Review	Version 2	Release	
		Version 1		Review	Version 2	Release	
System & Component Studies	• System PERF/Econ. • ATEs/Heat Pump • Alternate STES • Tech. Transfer/Devel.	Sediment/Water Kinetics		Guidelines	Water Treatment		
		IEA STU Rec. Monitoring		Final Rept.	GM Site	Blockades	
		Exist. Sites		New Applications	Alt. Configs.		
		Assess. Augmented Design Guides		Field Monitoring			
				Earth Assess. Design Guide			
				Ice Charac. & Monitors Design Guidelines			
Environmental & Institutional Studies	• Water Quality & Treatment • Legal & Regulatory Issues	Prime Applic. Site Identif. Proj. Devel.		Reports & Pubs.			
				Proj. Devel.			
		Assess.		Reg. Review Water Treatment Guide			
		Energy Ownership Liability					

FIGURE 2.3. Long-Term Plans for STES Research

3.0 SEASONAL THERMAL ENERGY STORAGE PROGRESS

This section provides a summary of progress in DOE-sponsored efforts to develop and advance STES technologies. Project progress is reported within subsections organized according to the project breakdown described earlier.

3.1 SYSTEM DEVELOPMENT

Two major projects comprised the system development efforts during the reporting period: the St. Paul high-temperature ATEs field test facility (FTF) project at the University of Minnesota and the Student Recreation Center chill ATEs project at the University of Alabama. These two projects form the cornerstone of ATEs field test activities, providing information to validate many of the models and laboratory studies embodied in other program elements.

3.1.1 St. Paul High-Temperature Field Test Facility - University of Minnesota

The two primary purposes of testing at the St. Paul FTF are to: 1) evaluate the technical issues associated with design and reliable operation of a high-temperature ATEs system, and 2) obtain data on fundamental geotechnical processes to validate laboratory and bench-scale geochemical testing and geohydrothermal modeling. The St. Paul FTF is designed to inject and recover 5 MW (thermal) of heat supplied from the campus steam heating system. The system uses a well doublet for supply and storage wells. Five monitoring wells are employed to obtain temperature and pressure data and water samples. The layout of the system is shown schematically in Figure 3.1.

Testing prior to the reporting period included four short-term cycles (nominally 25 days total), and one long-term test cycle (180 days total). The second long-term test cycle was completed during the reporting period. Table 3.1 provides a summary of the important physical characteristics of the tests conducted to-date. Following completion of the second long-term cycle, groundwater was pumped from the storage and supply wells to restore the aquifer to near original condition, a requirement of state environmental permits. Finally, preparations began for performance of a third long-term test.

FIGURE 3.1. Schematic of University of Minnesota Field Test Facility as configured for Long-Term Cycles

TABLE 3.1. Summary of ATEs Test Cycle Conducted at the University of Minnesota Field Test Facility

	Short Term				Long Term	
	1	2	3	4	1	2
Duration, days						
Injection, pumping	5.2	8	7.7	7.7	59.1	59.3
Injection, total	17	10	10.4	12	74.7	65.0
Storage	13	90	9.7	10.1	64	59.1
Recovery, pumping	5.2	8	7.7	7.7	58	59.7
Recovery, total	5.2	8	8	7.7	58.8	59.8
Temperature, °C						
Source water	11.0	20.5	36.1	52.6	19.7	33.1
Injected water	89.4	97.4	106.1	114.8	108.5	117.7
Recovered water	59.2	55.2	81.1	89.1	74.7	85.1
Returned water	59.0	54.4	76.6	75.7	68.0	60.4
Flow rate, L/s						
Injection	18.4	17.6	18.3	17.9	18.0	18.3
Recovery	18.1	17.8	17.3	17.8	18.4	17.9
Volume, 10 ⁴ m ³						
Injection	0.83	1.22	1.22	1.19	9.21	9.39
Recovery	0.81	1.23	1.18	1.19	9.22	9.21
Energy recovery factor,						
using source temperature	0.59	0.46	0.62	0.58	0.62	0.62
using ambient temperature	0.59	0.52	0.71	0.75	0.65	0.69
Year performed, 19xx	82	83	83	83	84/85	86/87

Preparations included application for a new environmental permit, redesign of the injection well to permit injection in only a portion of the aquifer, and design of the interconnection to a campus building to obtain experience on operation with a realistic building load.

The geochemistry and temperature history during the second long-term test were the technical factors of primary scientific importance. The geochemistry was important for two reasons. First, it is essential that calcium carbonate scaling does not occur in the heat exchanger. This is accomplished at the test site by simple ion-exchange treatment (sodium for calcium) of the groundwater prior to heating and subsequent injection for storage. This water treatment reduced calcium from approximately 1 mM/L^(a) to less than 0.1 mM/L.

During storage underground, back reactions and mixing occur. Unfortunately, little is known about the rate or degree at which these phenomena occur. Such knowledge is important because of environmental concerns and the costs associated with continued water treatment at the levels used for the test. The chemistry of the water recovered from storage was very close to that expected from calculations of equilibrium concentrations at the recovery temperature. The principal anion concentrations for the source, softened, injected, and recovered groundwater for the two long-term tests are given in Table 3.2. The effects of water softening on injected water is apparent from the substantial reduction in calcium ion concentration. However, the calcium ion concentration in the recovered water is substantial (essentially at equilibrium), suggesting that considerable water softening could be required on subsequent cycles. Data for magnesium show similar behavior.

Sodium, however, was a different story. It was expected that sodium would be a conservative tracer (i.e., would not react with resident minerals in the aquifer). However, only 80% of the injected sodium was recovered through normal cycle pumping. While several interpretations can be given to this phenomenon, it is speculated that mixing with natural groundwaters accounts for the difference in concentration. It is noteworthy that if natural waters were simply mixed with injected waters at a ratio of 1:5 (as suggested by the sodium results) with no further geochemical change, mixing alone could account for a significant portion of the calcium observed in the recovery water.

(a) millimole per liter

TABLE 3.2. Average Concentration (mM/L) of Calcium, Magnesium, Sodium, and Silica of Source, Softened, Injected, and Recovered Water Samples Long Term Cycles 1 and 2

	<u>Calcium</u>	<u>Magnesium</u>	<u>Sodium</u>	<u>Silica (as Si)</u>
Source				
LT1 ^(a)	1.261	0.651	0.316	0.188
LT2 ^(b)	0.994	0.527	1.917	0.289
Softened				
LT1	0.099	0.086	4.390	0.188
LT2	0.020	0.013	5.209	0.289
Injected				
LT1	0.075	0.055	4.925	0.192
LT2	0.026	0.014	5.202	0.286
Recovered				
LT1	0.363	0.190	3.704	0.635
LT2	0.289	0.134	4.263	0.729

(a) Long Term Cycle 1

(b) Long Term Cycle 2

Determining the role of mixing is very important because it influences the long-term water treatment needs, environmental acceptability of the concept, and the significance of geochemical reactions with resident minerals. The St. Paul site offers a particularly interesting test of available theories because there is very little calcium detectable in geologic cores from the primary storage zone. However, the role of mixing is difficult to discern from the data because of complex interactions between the geological variability at the site, the varied temperature history of the injected fluid as it resides in storage, and the uncertainties in our knowledge of geochemical behavior. The role of mixing can only be determined after careful examination of the data gathered, geochemical modeling, and continued testing.

The thermal behavior during the second long-term test was similar to that of earlier cycles. Temperatures of injected and recovered fluid are plotted for the first and second long-term tests in Figure 3.2. The higher source water, injection, and recovery temperatures for the second test are due, in large part, to the thermal conditioning done in the storage zones at both the supply well (well B) and the storage well (well A) during the first long-term test. The recovery temperatures for both long-term test cycles are essentially parallel, demonstrating the consistency of results on subsequent cycles and the value of heating of the storage zones during previous cycles.

The U.S. Geological Survey (USGS) is participating in the project by conducting site geohydrothermal monitoring and modeling. Although the details of their studies will be reported through USGS reports, a comparison between model results and observations is tabulated for all the tests in Table 3.3. The code, SWIP, used in a three-dimensional mode, was able to predict both total thermal energy recovery (computed with source, as opposed to natural temperatures) and final temperatures relatively accurately. Although not shown, predicted temperatures of the recovery fluid matched observations quite well. This is reasonable because the geohydraulic setting is relatively simple and SWIP is a competent, fully three-dimensional, geohydrothermal model.

Thermal monitoring of the aquifer storage zone has confirmed prior observations of the effects of the advective and diffusive heat transport at the site. Vertical thermal profiles of monitoring well AM3 [located 14 m south of the storage well (well A)], taken several times during the cycle, are shown in Figure 3.3. The zones of high permeability at the top of the Franconia formation and in the Iron-ton-Galesville formation are evident by the high temperatures reached at the end of injection. The less permeable zones continue to increase in temperature throughout injection while the more permeable zone of the Iron-ton-Galesville formation maintains nearly constant temperature throughout the last half of the injection. The impermeable zone near the middle of the Franconia formation displays no temperature change, confirming its hydraulic and thermal isolation from the more permeable zones.

FIGURE 3.2. Temperature Versus Cumulative Flow for Segments of Long-Term Cycles 1 and 2

TABLE 3.3. Comparison of Modeled and Observed Final Recovery Temperature and Energy Recovery

(a) Cycle	Final Temperature, °C		Energy Recovery	
	Observed	Modeled	Observed	Modeled
ST1	39.4	39.4	0.59	0.60
ST2	39.4	43.8	0.46	0.49
ST3	56.7	58.3	0.62	0.58
ST4	63.9	64.4	0.59	0.62
LT1	45.6	45.6	0.62	0.61
LT2	55.4	59.5	0.62	0.62

(a) ST1 = Short-term cycle 1, ST2 = Short-term cycle 2, ST3 = Short-term cycle 3, ST4 = Short-term cycle 4, LT1 = Long-term cycle 1, LT2 = Long-term cycle 2

FIGURE 3.3. Vertical Temperature Profiles in the Storage Zone of Well AM3 at Several Times During Long-Term Cycle 2

The thermal profiles also reveal that the Franconia formation is an inferior storage zone compared to that of the Ironton-Galesville formation. Recovery temperatures are substantially lower from the Franconia formation; possibly due to the impermeable interbedding in the zone and buoyancy-driven natural convection in high-permeability, high-temperature zones. One of the changes planned for the third long-term test is to modify the injection well so that only the Ironton-Galesville is used for storage. It is estimated that thermal recovery efficiency will increase by 6% because of this change. Injection into the Ironton-Galesville has an additional benefit; it is a relatively consistent, simple, geochemical environment, making interpretation of the water chemistry data and eventual mineralogic characterization of the storage zone, more tractable.

The environmental permit for the first two long-term cycles requires that the groundwater surrounding the supply and storage wells must be pumped until the temperature approaches the natural level. Pumpout of the storage well (well A) was initiated in September, 1987, and completed in December, 1987, when the temperature of the effluent dropped below 20°C (8°C above the natural temperature). Pumpout of the supply well (well B) began in April, 1988, and must be completed by July 31, 1988. The temperature trend of the pumpout water from well A dovetails with that of recovery during the second long-term cycle (as shown in Figure 3.4) although nearly a year elapsed between the end of recovery and initiation of pumpout. This attests to the low-temperature, long-term thermal storage capacity of suitable aquifers following thermal conditioning or cycling.

FIGURE 3.4. Temperature Versus Cumulative Flow for Long-Term Cycle 2 Recovery and Well A Pumpout. (Note: 10 months passed between recovery and pumpout).

Planning is well underway to perform a third long-term test. A new permit has been requested from the Minnesota Pollution Control Agency. If granted as requested, the permit will enable a test cycle nearly twice as long as the earlier tests and will not restrict the outlet flow rate or duration. This is necessary to accommodate the variable heat demand expected for Peters Hall, the campus building to be served by the recovered ATES heat. The design for interconnection with the building is being completed. Bid specifications have been prepared for modification of the storage well (well A) to restrict flow to the Iron-ton-Galesville formation.

3.1.2 Student Recreation Center Chill ATES - University of Alabama

Air conditioning constitutes a significant portion of the energy used in the U.S. for commercial and residential buildings; in excess of 2 quads per year. A system to store winter chill to meet summer air conditioning requirements has been implemented in the Student Recreation Center at the University of Alabama. The system, the first fully operational unit in the U.S., is being monitored to determine the behavior, performance, and shortcomings of such systems in general.

Chill ATES has the potential to provide both commercial and industrial space cooling. Recent walkouts at two Chrysler Corporation assembly plants because of high temperatures on the assembly floor further indicate there is a need for inexpensive space cooling systems for large industrial buildings. Furthermore, as reported in Section 4.0, the Chinese are using chill ATES extensively to cool commercial and industrial buildings.

The system is shown schematically in Figure 3.5. It was installed during building construction in 1981 and became operational in 1982. The system has met all the buildings cooling requirements since it became operational. However, performance was initially much less than expected due to movement of the stored chill away from the storage (cold) wells caused by high regional groundwater flow at the site.

FIGURE 3.5. Schematic of the Chill ATES System at the University of Alabama Student Recreation Center

During the reporting period, the operation of the system was modified to control underground movement of the stored chill. A new strategy was developed for system operation consisting of three elements:

- During water chilling, supply wells 2 and 3 (warm) and storage wells 4 and 5 (cold) are used almost exclusively.
- During building air conditioning, water from storage wells 4 and 5 is recovered, and circulated through the building cooling system, but the majority is not reinjected. This water is available for use for other purposes, such as irrigation.

- Water is pumped directly from supply wells 2 and 3 (warm) and discharged downgradient during air-conditioning periods, either to the irrigation system or to the storm sewer.

The various elements of this strategy are implemented based on temperatures monitored in the well field.

The revised operating strategy was initiated in July, 1987, and has noticeably improved performance. Recovery temperatures were observed to improve by over 2°C within a few days after implementing the strategy. Improved performance should aid in dealing with a large humidity load that has only been partially met with the existing building cooling system, which controls temperature but not humidity. The only other problems encountered with the system have been related to undetected control errors. For instance, two valves were closed for an extended period resulting in discharge to a single well. Unable to accommodate the entire flow, the receiving well overflowed until detected and corrected.

The system maintained an annual air-conditioning coefficient-of-performance (COP) of 5.0 for the period from August 1, 1986, through July 31, 1987. As noted above, all air conditioning needs of the building were met. Table 3.4 provides month-by-month groundwater pumping volumes and thermal energy values associated with these flows for the cooling tower (charging) and building (discharging). During the period from August, 1986, through July, 1987, over 80% of the chill energy charged in the aquifer was recovered. However, the volume of groundwater pumped from the aquifer during discharge to cool the building was nearly 2.5 times greater than that injected during charging. This implies relatively low storage efficiency based on equal fluid volume injected and recovered. Storage efficiency is expected to improve as a result of the changes in operating strategy.

The thermal and electrical energy requirements are provided for the same time period in Table 3.5 for the cooling tower (chill charging, includes pumping energy), and for the building (discharging, includes pumping energy but not that of building circulating air handlers). The COP is listed for these two

TABLE 3.4. Comparison of Rejected and Recovered Groundwater Flow and Energy for the Student Recreation Center, University of Alabama, August, 1986, through March, 1988

Date	Cooling Tower		Building		Energy Recovered From Aquifer, 1000 Btu
	Water Flow, 1000 Gal	Energy Rejection, 1000 Btu	Water Flow, 1000 Gal	Energy Rejection, 1000 Btu	
Aug. 86	0.0	0	4188.4	204090	97978
Sep. 86	0.0	0	5317.5	198999	111063
Oct. 86	0.9	114	3481.6	67952	49448
Nov. 86	556.0	90376	1670.2	48180	47443
Dec. 86	3092.9	538531	96.0	5980	15880
Jan. 87	4785.2	992824	0.0	0	0
Feb. 87	1762.7	352410	11.3	661	1888
Mar. 87	737.2	140682	528.7	60940	83923
Apr. 87	811.1	137983	1347.3	128308	191352
May 87	0.0	0	3848.6	289716	282947
Jun. 87	0.0	0	4098.9	412190	424629
Jul. 87	0.0	0	4441.7	394436	293155
Subtotal (12 mon.)	11746.0	2252920	29030.0	1811451 (80.40%)	1599705 (71.01%)
Aug. 87	0.0	0	5327.2	391747	200277
Sep. 87	0.0	0	4664.5	213550	128600
Oct. 87	273.1	48188	1801.5	71418	159537
Nov. 87	972.5	169886	1086.9	51767	77184
Dec. 87	1552.7	257676	199.6	13340	31684
Jan. 88	6141.5	1104684	97.6	8969	17123
Feb. 88	4034.9	682598	184.6	18138	32850
Mar. 88	1343.1	213198	751.9	58519	123750
Subtotal	14317.8	2476231	14114.8	827449 (33.42%)	771005 (31.14%)

TABLE 3.5. Comparison of Coefficient-of-Performance for Cooling Tower and Student Recreation Center Building - August, 1986, through March, 1988

Date	Cooling Tower			Building		
	Energy Rejection, 1000 Btu	Energy Input, kWh	Coefficient of Performance	Energy Rejection, 1000 Btu	Energy Input, kWh	Coefficient of Performance
Aug. 86	0	0	0.0	204090	5120	11.7
Sep. 86	0	0	0.0	198999	5992	9.7
Oct. 86	114	255	0.1	67952	4462	4.5
Nov. 86	90376	3798	7.0	48180	2415	5.8
Dec. 86	538531	21866	7.2	5980	251	7.0
Jan. 87	992824	23187	12.6	0	0	0.0
Feb. 87	352410	11592	8.9	661	20	9.7
Mar. 87	140682	5801	7.1	60940	905	19.7
Apr. 87	137983	4434	9.1	128308	2004	18.8
May 87	0	0	0.0	289716	4679	18.2
Jun. 87	0	0	0.0	412190	5030	24.0
Jul. 87	0	0	0.0	394436	4840	23.9
Subtotal	2252920	70934	9.3	1811451	35719	14.9
Aug. 87	0	1	0.0	391747	5611	20.5
Sep. 87	0	0	0.0	213550	10040	6.2
Oct. 87	48188	2641	5.3	71418	2183	9.6
Nov. 87	169886	5913	8.4	51767	1526	9.9
Dec. 87	257676	8010	9.4	13340	419	9.3
Jan. 88	1104684	29479	11.0	8969	242	10.8
Feb. 88	682598	18673	10.7	18138	345	15.4
Mar. 88	213198	7985	7.8	58519	1356	12.6
Subtotal	2476231	72704	10.0	827449	21724	11.2
Total	4729151	143637	9.7	2638900	57442	13.5

separate operations for each month of operation in Table 3.5. The annual component use of electrical energy is depicted as a pie chart in Figure 3.6. The entire ATES cooling system posted an annual COP of 5.0. It is estimated that this value is at least twice as good as that of conventional alternatives when full year operation is properly considered (i.e., part load, intermittent load, and off-design operation included, as appropriate). Of special interest is the very low on-peak electric energy requirements, as represented by the high peak summer operating COP of over 20.

The monitoring system was also modified during the reporting period. Six additional monitoring wells were added to the field, downgradient from the storage wells, to aid in monitoring the translation of the stored chill (see Figure 3.7). Temperature measurements in these wells will assist in determining the best operating mode for the system. The only major problem with the monitoring system is the susceptibility of the analog/digital boards

FIGURE 3.6. Energy Consumption by Major Components in the University of Alabama Student Recreation Center Chill ATES System - August, 1986, Through July, 1987

FIGURE 3.7. Aquifer Field with Location of Production Wells and Monitoring Wells (Six New Head Monitoring Wells are Circled)

in the computer to suffer damage during electrical storms, even though optical isolation is employed. Hence, the computer is only operated when manned.

The performance and field behavior of the Student Recreation Center chill ATES system will continue to be monitored for another year to obtain further

data on the system after the revisions noted earlier. This monitoring will also augment recently initiated microbiological studies on the groundwater at the site (reported in Section 3.5).

The performance of this system has stimulated significant interest by other groups. A General Motors carburetor plant in Tuscaloosa, Alabama, has installed nearly \$200,000 worth of cooling equipment sized to take advantage of chill ATES. Plans call for additional design studies to investigate well-field configuration and system operating alternatives. Another Tuscaloosa building complex, a Veterans Administration hospital, is currently studying a wide range of cooling options; one of which is chill ATES. Finally, a U.S. Postal Service distribution center in Melville, New York, recently installed a chill ATES system that is currently undergoing acceptance testing.

3.2 MATHEMATICAL MODELING

Consistent with the thrust of work in other program elements, mathematical modeling is currently focussed on simulation of ATES geotechnical processes. Specifically, research is underway to develop a suite of codes suitable for simulation of geohydrothermal behavior and geochemical behavior. Once developed, these tools will be applied to assist research and repackaged, if necessary, for use by architect/engineer firms. Special attention is being given to development of geohydrothermal tools focussed on assessing ATES feasibility and preliminary design. Additionally, development of an expert system has been initiated to provide geotechnical ATES expertise to groups unfamiliar with the technology.

3.2.1 Numerical Modeling of ATES

In the past, the UES Program has supported the development and enhancement of state-of-the-art three-dimensional computer codes to extend our basic understanding of the processes of fluid, energy, and solute transport in aquifers to the unique conditions that occur in ATES. The PT (Pressure/Temperature) code was developed at Lawrence Berkeley Laboratory (Tsang and Doughty 1985) and successfully predicted the results of field experiments at Mobile, Alabama,

(Tsang et al. 1981) and Dorigny, Switzerland. These simulations provided data that showed how the design of wells can mitigate thermal losses resulting from buoyancy. Enhancements in the SWIP (Survey Waste Injection Program) code (Intercomp Resource Development and Engineering, Inc. 1976) by the U.S. Geological Survey allowed it to simulate the field experiments conducted at St. Paul, Minnesota (Miller 1985). Recently, HST3D (Heat and Solute Transport) (Kipp 1987), a significantly improved version of the SWIP code, has been applied to the St. Paul site by researchers at PNL. The CFEST (Coupled Fluid, Energy, and Solute Transport) code was developed at PNL (Gupta et al. 1982) and has been used to simulate the Mobile, Alabama, field experiment. These codes provide a sophisticated predictive capability for understanding the basic processes of fluid, energy, and solute transport in aquifers. However, sophistication of these codes requires highly-trained professionals to appropriately apply these models.

Recently, the UES Program has focussed on the development of codes that could be used by a broad audience of design engineers with limited technical background in the fields of groundwater hydrology, subsurface heat transfer, and computer-based modeling. These codes will reduce the risk associated with attempting to apply ATEs technology by providing preliminary evaluations of a site's suitability for ATEs at minimal cost to design engineers. The projected users of these codes are the design engineers responsible for the preliminary design evaluation of energy storage systems. These codes will allow a preliminary evaluation to be performed before involving groundwater hydrology and geochemistry specialists.

The current suite of codes for analysis of ATEs systems covers a broad range of potential ATEs design issues. Table 3.6 provides a list of the principle computer codes for analyzing ATEs systems.

The ATESSS (Aquifer Thermal Energy Storage System Simulator) considers transport and storage of energy in stratified aquifers with multiple wells (Vail, Kannberg, and Kincaid 1985). Additionally, ATESSS includes heat pump and counterflow heat exchanger algorithms to accurately quantify the trade-offs between flow and temperature. ATESSS is user-friendly and runs on an

TABLE 3.6. Computer Codes for ATEs

<u>Code</u>	<u>Purpose</u>
ATESSS (isothermal mode)	Assist well field design (placement of wells to mitigate the impact of regional flow)
ATESSS (nonisothermal mode)	Estimate thermal recovery for ATEs systems with single or multiple wells, with or without a heat pump or heat exchanger being used for heating and/or cooling
ATES EXPERT	Recommends whether a specific site and energy need are suitable for ATEs. If insufficient data are available to assess the suitability of a site, a list of additional data required and likely sources of such data are provided.
HST3D	Estimate an aquifer's thermal recovery efficiency. Estimate the effects of buoyancy and viscosity changes on thermal recovery. Well operating strategies are designed to compensate for buoyancy flow.
WELL FIELD DESIGNER	Define the well field layout that will minimize the regional flow in the zone around an ATEs facility with the minimal total pumpage.
CHARM1 ^(a)	Evaluate the potential for geochemical problems (precipitation and dissolution) of aquifer minerals in the aquifer and surface heat transfer apparatus. Aid in the design and sizing of precipitators and/or water softeners for ATEs systems.
GRADIENT	Derive the regional gradient from multiple piezometric head measurements.

(a) This code is currently under development by Dutch participants in International Energy Agency Annex VI of the Energy Conservation through Energy Storage Programme. The suitability of the code for U.S. application will be assessed when the final version of CHARM is released.

IBM PC or compatible hardware, thereby making it available to a large number of design engineers.

The ATEs facility at the University of Alabama Student Recreation Center was simulated with ATESSS. This site is subject to a significant regional flow; thermal efficiencies are being decreased due to the drift of the injected

water away from the injection wells, which are also used to recover the water. The ATESSS simulations showed that by using the upgradient wells to mitigate the regional drift, a significant improvement in the fraction of injected water subsequently recovered was possible (from 47% to 75%). The modifications to the existing system suggested by ATESSS have been performed at the site. Ongoing monitoring will serve to validate code predictions.

A cooperative University of Alabama, General Motors (GM), and PNL design study was conducted to evaluate alternative ATES chill cooling systems for the GM Manufacturing and Research Facility in Tuscaloosa, Alabama. PNL analyzed different well field patterns with ATESSS. A promising design for aquifers with strong regional gradients was identified in these simulations. By locating all the wells in a line in the same direction as the regional flow, injected heat/chill can be allowed to drift to downgradient recovery wells. This design does not require the additional operating costs of constantly pumping additional wells to compensate for regional flow and could result in efficiencies approaching those of sites with no regional flow.

Recently ATESSS has been used to develop a series of plots showing the fraction of the total injected water that will drift away from the injection well due to regional flow. Such plots for single well, doublet well, and multiple well systems will allow design engineers to quickly assess the impact of regional groundwater flow at a specific site. The code, GRADIENT, was written to derive the regional gradient from multiple piezometric head measurements obtained at or near the site. The regional gradient is combined with data on hydraulic conductivity to define the regional flow velocity.

An evaluation of the ATESSS code was performed by both PNL and external reviewers. In response to the comments of the reviewers, several modifications have been made in ATESSS. A heat pump algorithm option is now available in addition to the original counterflow heat exchanger. Code modifications also allow simulation of aquifers being used for both heat and chill storage.

Currently, simulations are being performed for an ATES system coupled with a heat pump for two sizes of buildings in Rapid City, Iowa, and Spokane, Washington. Preliminary results have shown that standard design criteria for

groundwater heat pumps are not adequate for ATES/heat pump systems. Heat pump systems utilizing ATES require smaller design flows and concomitant lower pumping costs.

The ATESSS code was used to quantify the impact of vertical stratigraphy on ATES system's thermal efficiency (Kannberg and Vail 1987). Most aquifers were formed by the gradual deposition of many layers of different geologic materials. Each of these layers (called "strata" by geologists) may have a unique hydraulic conductivity. Therefore, when water is injected through a well into a "stratified" aquifer, the injected water will move at a different rate in each of the layers. The number and thickness of these strata has a significant impact on the potential for conductive losses. For instance, it was discovered that an aquifer composed of many alternating layers of permeable and impermeable media will have first-cycle thermal recovery efficiencies of 93% for layers 0.25-m thick, 62% for layers 5.0-m thick, and 85% for layers 25.0-m thick. Representative layer thicknesses estimated from preliminary geologic data can quickly identify those aquifers most suitable for ATES.

The development of an expert system for ATES (called ATES EXPERT) has been initiated to augment "textbook knowledge" with specific knowledge relevant to ATES. This expert system will advise a design engineer as to the suitability of a site and confirm an energy need for an ATES facility. If additional data are required for evaluating a site, the expert system will list these data and their potential sources. This knowledge resource will allow design engineers to make initial assessments of ATES at minimal cost without involving specialists in other fields, such as geohydrology and geochemistry. ATES EXPERT attempts to incorporate the "rules-of-thumb" employed by geohydrologists, geochemists, and energy systems analysts with the experience gained to date with actual ATES systems into a set of IF-THEN rules. ATES EXPERT combines its knowledge base with a commercial expert system development package for use on IBM-PC compatible computers.

WELL FIELD DESIGNER combines numerical optimization methods with a simple groundwater flow model to assist in defining the well field pumping rates that will reduce the regional flow in a specified region to be used for storage.

This provides the design engineer with the capability of assessing the pumping costs required to counteract a regional flow system. This code also runs on IBM-PC compatible machines.

In summary, a suite of models has been identified and are being used at test sites and for candidate system design to assess their value and validity and provide guidance to researchers and developers. The tools will be refined as necessary over the next 2 years and issued when proven. It is anticipated that ATESSS will be one of the first tools formally released for ATES-specific applications.

3.2.2 Geochemical Modeling

Commercial development of heated ATES will require the evaluation of water treatment issues at each site. The water treatment needs will be driven, first by geochemical behavior, and second by microbiologic behavior. Simulation of the geochemical equilibrium conditions and reaction kinetics is vital to effective design of the water treatment system as well as successful interaction with environmental regulatory bodies.

Researchers at PNL are cooperating with other foreign participants in an effort to develop a better understanding and predictive capability in water quality issues associated with ATES as part of Annex VI of the International Energy Agency (IEA), Energy Conservation Through Energy Storage Programme. This Annex, titled "Environmental and Chemical Aspects of Thermal Energy Storage in Aquifers and Research and Development of Water Treatment Methods," has a subtask devoted to the development of a multidimensional, linked geochemical and transport code for simulation of ATES. Researchers at PNL have supported this subtask by screening various submodels for the code, by simulating the ATES geochemistry at selected foreign sites, and by preparing a geochemical submodel for use by the other participants. A letter report has been provided the IEA on the first of these activities.

Researchers at PNL have included additional heat capacity data to the MINTEQ model database (the database selected for use by all Annex VI participants) to increase the accuracy of solubility calculations. They have also

used the BALANCE model in conjunction with the MINTEQ identification of equilibrium and oversaturated phases to provide estimates of the mass transfer quantities. Furthermore, these codes are being used to aid interpretation of laboratory and field observations. Further improvement of this estimating method awaits development of a capability to simulate the kinetics of the primary reactions.

Plans call for continued participation in Annex VI, Subtask A, for improvement of geochemical kinetic submodels, and for development of a simple linked transport/geochemical model for assisting ATES feasibility studies and preliminary design.

3.3 MEDIA INVESTIGATION AND DEVELOPMENT

The primary activity in this program element at this time is laboratory geochemical characterization. The primary purpose of these laboratory tests is to develop a reliable, accurate database on geochemical reactions to predict the groundwater chemistry and host mineralogy changes associated with heated ATES. It is necessary to understand and predict these changes to design effective water treatment systems, estimate capital and operating costs for water treatment, and ensure adequate environmental quality.

Researchers at PNL are serving two programmatic needs in their geochemical research. First, they are providing much needed geochemical reaction data for the eventual commercialization of ATES. Second, they are providing the U.S. DOE contribution on Annex VI of the IEA Energy Conservation Through Energy Storage Programme, titled "Environmental and Chemical Aspects of Thermal Energy Storage in Aquifers and Research and Development of Water Treatment Methods." Pacific Northwest Laboratory participates in three subtasks of Annex VI and leads an additional subtask dealing with microbiological issues.

Researchers at the University of Minnesota also conduct geochemical research to monitor and understand the geochemical behavior during testing at the St. Paul field test facility. The results of that research are summarized in the discussion of the St. Paul field test facility in Section 3.1.1. Discussion here will focus on work performed at PNL.

3.3.1 Geochemical Dynamics of ATEs

The focus during the reporting period was on obtaining experimental data on the interaction between heated groundwater and sandstone, specifically that from the St. Paul field test facility. These studies were designed to provide maximum insight into the geochemical behavior at the St. Paul field test facility, provide basic data to Subtask B of IEA Annex VI dealing with acquisition of experimental data on geochemistry at elevated temperatures, and provide data for developing and validating geochemical models for ATEs applications.

The sequence of activities conducted during this reporting period as part of the experimental effort included the following:

- The laboratory was equipped with necessary supplies and special equipment, such as Parr reaction vessels and a roller-equipped oven.
- Samples from the Franconia-Ironton-Galesville (FIG) storage formations were inventoried and petrologically identical samples were selected for testing.
- A synthetic groundwater, typical of that injected at the St. Paul field test facility, was developed for use in the experiments.
- Experiments were conducted to investigate the influence of temperature (90°C and 120°C), time (1 to 20 days), and fines content (with and without) on water chemistry and kinetics.
- Post-test characterization of the samples was conducted including x-ray diffraction and scanning electron microscope analysis.
- Results were interpreted.

Examination of available cores led to the selection of a 5-kg sample from the Galesville formation for experimentation. Core comprising the sample was friable (loosely cemented) and easily disaggregated. Between 80% to 90% of the grains comprising the core were less than 125 μm in diameter. Successive sequences of crushing and sieving produced samples in which all of the disaggregated sandstone was less than 125 μm in diameter. Additional sieving was

performed on one collection of samples to remove fines (material whose size was less than $62.5\ \mu\text{m}$). Fines were removed by washing and comprised about 15% of the bulk sample. Thus, two groups of samples were prepared: bulk samples, crushed and grossly sieved; and washed samples, crushed, sieved, and washed of fines.

The synthetic groundwater was prepared by successive dissolution of appropriate quantities of selected solids [MgCO_3 , K_2CO_3 , MgSO_4 , NaHCO_3 , and Ca(OH)_2] in 800 ml of deionized water, and bubbling of CO_2 to obtain a stable solution having a pH of between 6.4 and 6.7. Sediment samples and synthetic groundwater at a water-rock ratio of 7:1 were reacted in teflon-lined Parr reaction vessels at either 90°C or 120°C for various time periods ranging from 1 to 20 days. After reaction, the vessels were quenched to room temperature and opened. The pH was monitored within 20 seconds of opening and for the next 30 minutes. Reaction solution samples were obtained immediately after opening and prepared for analysis (anion analysis by ion chromatography, cation analysis by inductively coupled plasma atomic emission spectroscopy, and carbon analysis by carbon analyzer for total organic and inorganic carbon). Reaction solids were mounted and gold-coated for SEM analysis. Energy-dispersive x-ray spectroscopy was conducted to confirm phase identification by x-ray diffraction.

Results from these experiments are broken into two areas: mineral characteristics and solution chemistry. X-ray analysis of the fines indicate the presence of quartz and dolomite, but no CaSO_4 polymorphs. Petrographic analysis of the bulk sample showed predominantly quartz and feldspar. Examination of the crushed sandstone before and after reaction showed reduced surface roughness of quartz and potassium feldspar clasts, clear evidence of reaction.

Changes in the concentration of various inorganic dissolved constituents (Ca, SO_4 , Si, and K) as functions of time for bulk and washed samples reacted at different temperatures are depicted in Figures 3.8 through 3.11. The concentration of all these constituents increased with time. In all cases, the constituent concentrations changed most rapidly for bulk samples (i.e., those containing fines), attesting to the importance of fines in geochemical dynamics of these sediments. The correlation of changes of all constituents

FIGURE 3.8. Concentration Versus Time for Calcium (Ca) During Laboratory Geochemical Tests. Note rapid increase in Ca concentration for bulk sample due to presence of fines.

FIGURE 3.9. Concentration Versus Time for Sulfate (SO₄) During Laboratory Geochemical Tests. Note rapid increase in sulfate concentration for bulk sample due to rapid reaction with fines.

FIGURE 3.10. Concentration Versus Time for Silicon (Si) During Laboratory Geochemical Tests. Rapid initial increase in Si concentration for bulk sample (due to fines) is matched by the washed sample after time (possibly due to abundance of Si).

FIGURE 3.11. Concentration Versus Time for Potassium (K) During Laboratory Geochemical Tests. Rapid increase in K concentration for bulk samples supports importance of fines in reaction kinetics.

was evaluated each against the other through the use of Pearson Correlation Matrices. Calcium concentration was strongly correlated with sulfate (see Figure 3.12) and fluoride. There was a noticeable absence of correlation between inorganic carbonate (CO_3) and sulfate. These results suggest dissolution of a calcium-sulfate mineral (such as gypsum) and a fluoride-bearing calcium mineral (such as apatite or fluorite). Mass balance considerations also suggest that a calcium-bearing clay mineral is precipitating. Similarly, a strong positive correlation was observed for silicon and potassium (see Figure 3.13), and a negative correlation of these with magnesium. This suggests dissolution of abundant quartz and potassium feldspar accompanied by precipitation of a magnesium-bearing clay mineral. However, conclusions regarding mineralogic controls require additional characterization of the solid phases and kinetic and equilibrium modeling of the system chemistry.

The results discussed above are consistent with earlier findings from field tests at the St. Paul field test facility. The laboratory experimental results clarify earlier ambiguities concerning the probable source of potassium (feldspar dissolution) in recovered groundwater. Similarly, both field and laboratory results show increased sulfate concentration. The results also lead to tentative conclusions concerning geochemical behavior at the site. Dissolved silicon is controlled by dissolution of and equilibrium with quartz. This is significant in two respects. First, the number of minerals for which kinetic data are required to adequately characterize the system is reduced. Second, if quartz dissolution or subsequent silica scaling in the heat exchanger proves to be a problem, continuous groundwater treatment would be required. Potassium is supplied primarily by hydrolysis of feldspar, with possible contributions by ion exchange with glauconite. Calcium and sulfate may be supplied by dissolution of a very minor calcium sulfate component of the host rock, concentrated in the fines. Calcium concentration is not limited by calcite (calcium carbonate). If correct, these findings imply two additional conclusions. First, the amount of water treatment required on successive cycles will decrease as the source of calcium decreases. Second, the source of calcium was undetected in the sandstone samples examined. This increases the importance

FIGURE 3.12. Variation of Sulfate with Calcium During Geochemical Laboratory Tests

FIGURE 3.13. Variation of Potassium with Silicon Concentration During Geochemical Laboratory Tests

of laboratory testing to determine factors controlling the solubility of calcium and concomitant water treatment requirements in heated ATES systems.

The laboratory results do, however, raise certain questions concerning the influence of mixing of treated, injected groundwater with resident natural groundwater. Earlier, it was speculated that mixing could account for much of the calcium observed in the recovered water. Yet, general agreement of laboratory results, in which no mixing was possible, with the field results suggests that mixing may not be as significant a factor as earlier speculated. Resolution of this issue must await more complete calculations of geochemical equilibrium concentrations, kinetic rates, mass balances, and closer scrutiny of the field data.

3.4 SYSTEM AND COMPONENT STUDIES

In the past, studies have been conducted to help define the potential of a number of alternate STES systems. While some of these systems have been judged as promising, funding limitations have required that research be devoted to ATES technical issues. Unfortunately, even studies of promising ATES configurations were beyond the reach of available funds during the reporting period. Therefore, there has been no reportable progress in this program element during the reporting period. The only ongoing task is the cursory assessment of heat-pump augmented ATES.

Plans call for funding STES system and component studies in several different areas. The study of ATES with heat pumps will be completed. A study of alternatives for ATES chill generation will be conducted to identify options to cooling towers, to reduce operating and first costs. Investigation of ice generation and storage systems will be renewed with a review of progress in the U.S. and abroad since such studies were set aside several years ago. Finally, it is desirable to stimulate application of ATES technology; possibly providing feasibility assessment grants and by following these up with site-specific geotechnical assessments, as appropriate.

3.5 ENVIRONMENTAL AND INSTITUTIONAL STUDIES

Any system that uses a natural geologic or geohydrologic setting will encounter institutional issues. These issues may include environmental and health protection regulations, local and state water allocation adjudication, and questions of access and ownership of the stored thermal resource. It is anticipated that studies in all these topics, as well as potential topics dealing with established building codes and zoning statutes, will be required as part of the program. Research is currently focussed on environmental issues; specifically, microbiologic effects of ATES. At present no studies are underway to address the legal access and ownership issues. Such studies will be undertaken at a future date.

3.5.1 Microbiologic Effects of ATES

The primary project currently underway is the investigation of microbiologic conditions at ATES systems, especially "open" ATES systems where surface air contacts groundwater during the heat or chill charging or recovery process. Special attention is being given to pathogenic organisms because they pose the greatest health threat to humans.

Groundwaters are habitat to an abundant and diverse microbial population. It is known that these organisms are important to destruction of hazardous wastes in groundwaters and they are likely important for other purposes. Unfortunately, the organisms have received little study. Thus, their complete role in the subsurface ecosystem is uncertain. The activity of indigenous subsurface microorganisms is subject to a number of environmental factors (Hicks and Stewart 1988) including:

- aquifer porosity
- nutrient availability
- oxidation-reduction conditions
- pH
- temperature, and
- adsorption of microorganisms on the aquifer rock matrix.

Of these factors, temperature changes have the greatest effect on microorganisms. Microorganisms have species-specific temperature ranges that determine their level of activity. In an ATES system, temperature changes beyond

a certain level can cause various organisms to become dormant or die. Other changes, such as water treatment or induced changes in groundwater chemistry, can also impact microorganisms' activity and diversity. It is also true that microbiologic activity can change the water chemistry, affecting geochemistry and causing dissolution or precipitation of minerals.

As noted in Section 4.0, ATEs systems have been constructed and operated in a number of countries. Experience abroad does not suggest that ATEs has significantly affected the aquifer microbiologic ecology. However, no significant microbiologic monitoring has been conducted at most sites.

While ATEs effects on indigenous organisms is of interest for environmental and operations reasons, pathogenic (disease causing) organisms are of greater concern. Organisms that are not indigenous to an aquifer can survive and grow. The effect of ATEs on the survival, propagation, and release of *Legionella* (as one of the more probable and topical pathogens) was of specific interest. It was the major focus of assessment efforts because it is ubiquitous in aquatic environments, is highly pathogenic, and has been identified in many cooling tower and domestic water sources. Furthermore, chill ATEs systems (as currently in operation at the Student Recreation Center in Alabama), appear to have a greater potential for increasing *Legionella* survival, as well as the survival of other organisms. It is known that *Legionella* survival (not activity level) increases with decreasing temperature.

It must be recalled, however, that ATEs is not the only system that offers the potential to transport microorganisms resident in groundwater. Irrigation systems, for example, and other systems could be expected to cause largely the same effects on the geomicrobial ecology as an open-cycle chill ATEs system and have as great, if not greater, potential for transport of microorganisms resident in groundwater. Yet, operation of such systems has not been linked to significant changes in microbial populations or negative health impacts. Finally, it must be recalled that the region affected by a reasonably sized ATEs system is small, rarely encompassing more than a fraction of an acre for a commercial building.

Clearly, ATEs has the potential to affect the growth, propagation, diversity, and viability of microorganisms inhabiting aquifers. The specific changes that occur, their impact (both negative and positive), as well as methods to control the effects, are relatively unknown and require further study.

A monitoring effort was initiated at the Student Recreation Center at the University of Alabama, as a result of the assessment described above. This monitoring will be conducted over the next 18 months to assess the indigenous and exogenous microorganisms populating the chill ATEs system, as well as other selected campus HVAC systems that employ cooling towers.

4.0 INTERNATIONAL STES ACTIVITIES

As mentioned earlier, a number of countries are active in STES development. While a number are active in ATES development, historically there have been developments of other STES systems, primarily in Scandinavia. A 1985 IEA report (Lundin 1985) identified a total of 62 large thermal energy storage projects in IEA countries, most of which were seasonal systems. Of these 62, aquifers comprised 20, ground storage comprised 17, tank storage - 11, rock caverns - 6, and pit storage - 5. More recently, the number of aquifer systems has increased. Because most recent activity has been in ATES, discussion here will focus on ATES activities. It should be recalled that ATES may only be suitable at up to 60% of the sites in the U.S. Therefore, STES using storage media other than aquifers will be the only STES options in many locales.

The developments in the various countries are discussed by nation. In addition to the nine nations listed, additional development is known to be underway in Japan, England, and Italy. Furthermore, U.S. researchers have received, and responded to, requests from Soviet researchers for information on U.S. studies.

4.1 THE NETHERLANDS

The Netherlands has constructed a low-temperature heat ATES system for use with a heat pump for a building in the town of Bunnik (Bredero Energy Systems 1986). In this system, heat from solar collectors (285 MWh/yr) and a computer room (96 MWh/yr) are either injected into a shallow aquifer at a temperature of 30°C for storage (316 MWh/yr) or used directly in a heat pump (55 MWh/yr). A gas-fired heat pump is used to increase the 305 MWh/yr of heat recovered from the aquifer at a temperature from 26°C to 14°C to 576 MWh/yr. A gas-fired boiler augments this with 85 MWh/yr to provide the annual building heating requirement of 661 MWh/yr. The ATES portion uses a single well doublet and is assumed to have an energy recovery factor^(a) of 0.80. By design, one-third more water is recovered than injected to achieve this energy

(a) thermal energy recovered divided by thermal energy injected

recovery. Although this system became operational in the spring of 1985, limited information is available. Early reports from small-scale initial tests indicate that there was some minor clogging of the well due to leakage of air into the mains, precipitation of iron in water, and filtration of iron in one portion of the well. There was no clogging of the heat exchanger. From early results it was also determined that buoyancy-driven circulation in the well and aquifer resulted in loss of all injected soft water. There was no scaling with calcite when using the original (unsoftened) groundwater and, therefore, the clogging risk determined by geochemical equilibrium calculations, was overestimated for this system. Precautions will be taken in the future to prevent air leakage in the circulating system and the well will be blocked with a packer to retard buoyancy-driven circulations. Measurements of the chemical and hydraulic behavior and energy performance at this site will continue until the end of 1989.

4.2 SWEDEN

Sweden has installed four ATES systems, has two under construction, is designing two more, and has field tests underway at yet another (Kannberg 1986). All of the systems involve low-temperature storage in conjunction with heat pumps. Information is only available for a few of the sites.

At an ATES site in Klippan, energy is extracted from a lake at 15 to 20°C and used to heat groundwater, which is then injected into a water table aquifer for storage. Information from 1986 indicates that the injection wells clogged during operation of this system. Although a temporary solution was used to inject the water, a permanent solution has not been obtained.

At Kristianstad, Sweden, an ATES system was designed for low-temperature heating and cooling in conjunction with a heat pump. Little information is available at this site; however, it is known that the system requires more cooling than heating. This has resulted in breakthrough of heated water into the cold storage well reducing the cold recovery temperature.

At Falun, Sweden, pumping was conducted from a line of wells to draw nearby warm lake water into the groundwater. By continued pumping, it was reasoned that the warm groundwater would be recovered in winter for heating applications. Actual pumping temperatures when the warm groundwater plume reached the pumping wells (1985) were far less than expected, possibly as a result of flooding at the site in 1984. There is some suspicion that iron is precipitating in the piping as well.

A low-temperature heat pump/ATES heating and cooling system has been designed for installation at Brunnsviken, Sweden. While little information is currently available on this project, it is planned that this system will provide 2100 MWh/yr of heating and 2600 MWh/yr of direct groundwater cooling. The waste cooling heat from the administration and computer buildings will be a source of very low-temperature (15°C) heat for storage in the aquifer.

4.3 DENMARK

A high-temperature (100°C) ATES site in Denmark has been studied since 1975 when geohydraulic and heat transport investigations began (Kannberg 1986). The first low-temperature energy test occurred with injection at about 35°C. The energy recovery was 55% of that injected. The first high-temperature cycle began in 1983 and provided nearly 9.2 MWh to the local district heating system. Operations at the site continue through the present but not without difficulties. Early operations at the site were plagued by flow of heated water up the outside of the injection well casing to the surface, breaching the confining layer. A second injection well was necessary to correct this problem. As with most high-temperature ATES systems, water treatment to control precipitation of calcium carbonate was necessary. The treatment method involved mixing acid with the source groundwater, followed by vacuum degassing to remove CO₂. Vacuum leaks that introduced oxygen into the system, and poor acid control enhanced corrosion in the system, making system piping and water treatment control system changes necessary.

4.4 SWITZERLAND

A unique ATES concept is being tested near Lausanne, Switzerland (Kannberg 1986). The SPEOS concept involves solar-heated groundwater injection into an aquifer at one elevation through perforated radial spokes from a large diameter center well. As originally conceived, source water for heating and injection is obtained from a similar but deeper radial spoke arrangement using the same center well. During recovery the process is reversed with water withdrawn from the upper radial spokes and reinjected in the lower radial spokes, after cooling in a heat exchanger. In this manner the system, as originally planned, works somewhat like a stratified tank. Work on the project began in 1979, with the heat source being solar energy. Problems related to scaling caused by precipitation of calcium carbonate required strong acid treatment. Additionally, regional groundwater flow at the site is quite significant and limited measures have been undertaken to control this flow. Two early test cycles were conducted. Injection temperatures have ranged from 30°C to 80°C and recovery ranged from 52°C to 19°C. The recovery factors for the two cycles were 0.41 and 0.42, respectively (using the natural groundwater temperature of 12°C). Over 1300 MWh were injected on the last cycle with 643 MWh recovered. A subsequent test in 1986-87 involved injection of 850 MWh at 85°C. Unfortunately, due to geohydraulic conditions at the site, only 12% of the energy was recovered at an average temperature of 53°C. It has been determined that a clay layer between the two levels of radial spokes causes heated groundwater to spread radially above the clay layer increasing thermal losses. Recently (1987-88) the heated water has been injected in the lower radial spokes, reversing the flow arrangement. This was more successful. As of March 8, 1988, 1999 MWh of energy has been injected at an average temperature of 68°C and 75% recovered with recovery still underway.

4.5 FRANCE

Perhaps the most aggressive ATES project is being conducted by the French (Housse and Despois 1985). A 20-MW, very high-temperature (180°C) ATES system has been installed near Thoiry, France, approximately 90 km southwest of Paris.

The system will take heat from a nearby waste incineration plant during the summer to charge the store. The aquifer is located at a depth of approximately 1500 m (over 8 times deeper than the aquifer used in the St. Paul tests). The project has made use of French directional drilling technology, practiced in the petroleum industry. A single injection well is surrounded by three peripheral source wells. On-site water treatment tests were conducted followed by plant design. Water treatment is required not only to control calcium carbonate scaling but also for silica scaling, an issue not yet demonstrated to be a problem at lower-temperature ATES sites. At last word, preliminary testing was being conducted in the late spring of 1987. It was anticipated that the system would be operational for summer heat charging in the summer of 1987. This project is part of an ambitious French program to use waste heat and electricity from French nuclear plants and other sources to displace oil consumed for winter heating of buildings. At 20 Mwt, the system has nearly four times the power rating of the St. Paul field test facility, thought to be the largest in the world to date.

4.6 CHINA

The only known countries investigating or using chill ATES are the Republic of China, Canada, and United States. Chill ATES has been practiced in China for nearly 20 years and now is used in many large cities for both chill storage and low-temperature heat storage (Sun 1986). Although most of the applications have been in sand and gravel aquifers, some systems have used limestone karst aquifers. At good sites, recovery efficiencies up to 75% have been obtained. The use of ATES is often combined with other purposes such as control of subsidence and salt water intrusion.

Chill ATES began in China inadvertently. The water table was being drawn down dramatically in Shanghai during the summer as water was extracted for cooling textile mills. Subsidence had begun to be a problem. To correct this problem, cold river water was injected into the aquifer during the winter to artificially recharge the aquifer. The Chinese discovered that the recovered

water was substantially cooler than normal. Chill ATES has been implemented at a large number of sites in China as a result of this experience for the sole purpose of providing reduced temperature groundwater for industrial cooling. In Shanghai alone, over 32 textile factories use ATES, primarily for cooling. It is estimated that they save nearly 81,000 tons of coal that would normally be required for running absorption cooling systems. Water warmed during cooling operations is reinjected and used for heating in the winter, saving another 10,000 tons of coal. Also in Shanghai, chill ATES is used for air conditioning at least 10 cinemas and an airport lounge.

4.7 CANADA

In Canada, two government office buildings have been equipped with ATES systems. One of these, in Scarborough, near Toronto, is connected to a solar collection system to provide both heating and cooling. A second chill ATES system has been installed at the Atmospheric Environment Service building in Downsview, Ontario. The aquifer used at Scarborough is 50-m deep and 10-m thick. Four wells have been drilled and completed for both injection and pumping. To date the system has only been used for cooling but operators have found the system very flexible and use for both heating and cooling is planned. The project at Downsview has proceeded through site characterization and the installation of six wells. Problems with completion of these wells has delayed the project.

4.8 WEST GERMANY

Environmental regulations prohibit the development of aquifers for commercial or industrial applications. Therefore, German researchers have constructed a system using artificial ATES. This pilot plant was installed at the University of Stuttgart. The store has a volume of 800 m³, and uses stream gravel (from the Rhine River) as the solid matrix. The system stores solar heat for recovery with a heat pump. Since project initiation, a number of interesting observations have been made concerning operating issues. First, the PVC piping suffered deterioration from bacteria, presumably originating in the stream gravel. The surfaces where the bacteria had grown became

hydrophilic^(a) instead of hydrophobic^(b). They further observed that the presumed clean quartz sand from the Rhine River possessed a surprising amount of soluble minerals. An increase in sulfate was observed in the circulating water that may be caused by pyrite dissolution.

4.9 FINLAND

The primary ATEs project in Finland uses artificial recharge at Rajamäki. The system was operated at low temperatures from 1974 to the present, with a short high-temperature test from September, 1981, through January, 1982. The project was not originally conceived as an ATEs system, but, rather a groundwater cooling system for a factory. A portion of the groundwater pumped from the aquifer and heated in the factory is reinjected upgradient into a high-permeability aquifer (esker). The supply wells pump at a rate of 3350 m³/day and 1200 m³/day is reinjected in the five shallow, large-diameter (2 m) injection wells located 700 m away. The hydraulic gradient in the aquifer is 3.5 o/oo. The normal groundwater temperature is 6°C. The average injection temperature has been 23°C (13°C to 32°C) and the average supply temperature has risen to 12°C (8°C to 17°C), indicating that the heated groundwater is flowing downgradient from the injection well to the supply well.

A high-temperature test was undertaken in conjunction with the low-temperature groundwater cooling project at Rajamäki. This test was to examine the effect of tilting and stratification in the aquifer, as well as to determine the effect of heat on geochemical reactions and microbiological processes. At a nearby site, hot water averaging 70°C (65°C to 75°C) was injected at a rate of 132 m³/day for 132 days into the shallow aquifer (injection zone was 6 to 8 m below the water table, which is 3 m below the ground surface). Simultaneously, groundwater was pumped at a rate of 275 m³/day from a well 15 m away, downgradient, at a depth of 7 to 9 m below the water table. The heated water stratified in the aquifer with the upper and medium layers at 60°C to 70°C while the more permeable lower level remained relatively cold. After conclusion of

(a) hydrophilic - "water loving", capable of uniting with or absorbing water.

(b) hydrophobic - "water hating", incapable of uniting with or absorbing water.

the test, it was determined that the aquifer had preserved the heat in the ground reasonably well. Finnish researchers have used this data to calibrate and validate numerical models of the geohydrothermal behavior.

5.0 REFERENCES

- Anderson, M. R., and R. O. Weijo. 1988. Potential Energy Savings From Aquifer Thermal Energy Storage. PNL-6588, Pacific Northwest Laboratory, Richland, Washington.
- Bredero Energy Systems. 1986. Office Building at Bunnik: Aquifer Storage of Solar Energy. Bredero Energy Systems, Bunnik, The Netherlands.
- Gupta, S. K., C. T. Kincaid, P. R. Meyer, C. A. Newbill and C. R. Cole. 1982. A Multi-Dimensional Finite Element for the Analysis of Coupled Fluid, Energy and Solute Transport (CFEST). PNL-4206, Pacific Northwest Laboratory, Richland, Washington.
- Hicks, R. J. and D. L. Stewart. 1988. Environmental Assessment of the Potential Effects of Aquifer Thermal Energy Storage Systems on Microorganisms in Groundwater. PNL-6492, Pacific Northwest Laboratory, Richland, Washington.
- Housse, B. A., and J. Despois. 1985. "Prototype de Stockage Souterrain de Chaleur a Haute Temperature a Thiverval-Grignon (France)." In Proceedings of the III International Conference on Energy Storage for Building Heating and Cooling, pp. 71-74. Public Works Canada, Ottawa, Canada.
- Intercomp Resource Development and Engineering, Inc. 1976. A Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers, Part I -- Development, 76-61. U.S. Geological Survey Water Resources Investigations.
- Kannberg, L. D., 1986. "Aquifer Thermal Energy Storage in the United States." In Proceedings of the 1986 Annual Meeting of the American Solar Energy Society, Inc., pp. 522-525. American Solar Energy Society, Boulder, Colorado.
- Kannberg, L. D., and L. W. Vail. 1987. "Effects of Stratification on Thermal Energy Storage." In Proceedings of 22nd Intersociety Energy Conversion Engineering Conference (IECEC), pp. 1288-1292. American Institute of Aeronautics and Astronautics, New York, New York.
- Kipp, K. L., Jr. 1987. "HST3D: A Computer Code for Simulation of Heat and Solute Transport in 3-Dimensional Ground-Water Flow Systems." Water Resources Investigations 86-4095, U.S. Geological Survey, Denver, Colorado.
- Lundin, S.-E., ed. 1985. Large Scale Thermal Energy Storage Projects, in Operation or Under Construction, Location and Abstracts. Swedish Council for Building Research, Stockholm, Sweden.
- Miller, R. T. 1985. Preliminary Modeling of an Aquifer Thermal Energy Storage System. U.S. Geological Survey Water Supply Paper 2270, pp. 1-19, U.S. Geological Survey, Minneapolis, Minnesota.

- Sun, Y. September, 1986. "Aquifer Energy Storage Applications in China." STES Newsletter. C. F. Tsang, ed., Vol. VIII, No. 4. Lawrence Berkeley Laboratory, Berkeley, California.
- Tsang, C. F., and C. Doughty. 1985. Detailed Validation of a Liquid and Heat Flow Code Against Field Performance. LBL-18833, Lawrence Berkeley Laboratory, Berkeley, California.
- Tsang, C. F. et al. 1981. "Aquifer Thermal Energy Storage: A Numerical Simulation of Auburn University Field Experiments." Water Resources Research 17:647-658.
- Vail, L. W., L. D. Kannberg and C. T. Kincaid. 1985. "A Computer Code for Analyzing the Performance of Aquifer Thermal Energy Storage Systems." In Proceedings of the International Conference on Energy Storage for Building Heating and Cooling, ENERSTOCK 85, pp. 144-148. Public Works Canada, Toronto, Canada.
- TRW. 1979. Thermal Energy Storage Application Areas. McLean, Virginia.
- U.S. Department of Energy. 1986. FY 1988 Energy Conservation Multiyear Plan. Washington, D. C.

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