PNL-5507
UC-94e

18L

Underground Energy Storage Program

1984 Annual Summary

June 1985

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

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

Battelle

PNL-5507

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

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

NTIS Price Codes
Microfiche A01

Printed Copy

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

PNL-5507
UC-94e

UNDERGROUND ENERGY STORAGE PROGRAM

1984 ANNUAL SUMMARY

L. D. Kannberg

June 1985

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

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This is the 1984 Annual Summary for the Underground Energy Storage Program, which is administered by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy. This document describes all of the major research funded under this program during the period from April 1984 through March 1985.

The report summarizes the activities and notable progress toward program objectives in Seasonal Thermal Energy Storage (STES). Readers wishing additional information on specific topics are invited to contact Landis Kannberg at PNL.

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

L. D. Kannberg, Manager
Underground Energy Storage Program

ACKNOWLEDGMENTS

Progress achieved during the April 1984 through March 1985 reporting period is attributed to multiple subcontractors working with the Underground Energy Storage Program staff. These included W. Schertz, A. Michaels, and D. Breger of Argonne National Laboratory, Argonne, Illinois; M. Walton and M. Hoyer, Minnesota Geological Survey, Minneapolis, Minnesota; C. M. Redman of New Mexico Solar Energy Institute, Las Cruces, New Mexico; C.-F. Tsang of Lawrence Berkeley Laboratory, Berkeley, California; W. J. Schaetzle of W. J. Schaetzle & Associates, Tuscaloosa, Alabama; C. E. Brett, University of Alabama, Tuscaloosa, Alabama; and W. E. Soderberg and S. Richards, University of Minnesota, Minneapolis.

The program task and project leaders from the Pacific Northwest Laboratory also merit acknowledgment. These researchers include P. J. Mitchell, J. R. Raymond, L. W. Vail, S. C. Blair and R. D. Allen.

D. Segna, U.S. Department of Energy, Richland Operations Office, and I. Gyuk, U.S. Department of Energy, Washington, D.C., have provided direction to the program and served as program monitors at their respective operations centers.

Credit for typing the draft and final versions of this report goes to S. J. Arey of PNL. A. J. Currie of PNL edited the report.

The dedicated efforts of all these individuals are acknowledged and greatly appreciated.

SUMMARY

Underground Energy Storage (UES) Program activities during the period from April 1984 through March 1985 are briefly described. Primary activities in seasonal thermal energy storage (STES) involved field testing of high-temperature [>100°C (212°F)] aquifer thermal energy storage (ATES) at St. Paul, laboratory studies of geochemical issues associated with high-temperature ATES, monitoring of chill ATES facilities in Tuscaloosa, and STES linked with solar energy collection. The scope of international activities in STES is briefly discussed.

The first long-cycle test (60 days each injection, storage, and recovery) was initiated in November 1984 at the St. Paul Field Test Facility (FTF). This test was preceded by addition of an ion exchange water treatment system and another monitoring well. The water treatment system operated well after an initial shakedown period. Four short cycles of ATES testing had been completed at the St. Paul FTF in December 1983. Results of these earlier tests were promising. A fluid volume (equal to that injected) was recovered after injection at successively higher temperatures approaching 100°C. The ratios of recovered energy to injected energy for each of the cycles were 0.59, 0.42, 0.62, and 0.58, respectively. The water quality improved with each successive cycle. During the injection phase of the first long-cycle test, over 92 million liters of water at an average temperature of 108.5°C (227°F) were injected. An average injection rate of 6.7 MW was maintained, providing 9.5 GWh of stored energy. The recovery portion of the first long-cycle test will be completed in late May 1985.

Laboratory testing of soft water flow through core samples from the St. Paul FTF has yielded results similar to those obtained from earlier testing. Intrinsic permeability of sandstone core was observed to decrease as temperature increased, although such behavior has not been obvious during testing at St. Paul. Examination of short-cycle St. Paul FTF filters indicates that the injectability of the water improved with successive cycles. Geochemical models based on laboratory-derived reaction rate coefficients were reasonably

accurate in predicting important groundwater chemistry changes; however, the geochemical data base for many minerals is very incomplete, and concentrations of some groundwater chemical constituents were unpredictable.

Numerical modeling efforts were limited to 1) investigation of the SPEOS concept, as implemented at the Dorigny site near Lausanne, Switzerland; 2) preliminary investigations of tracking the thermal front in ATES systems with resistivity measurements; and 3) modification of the aquifer thermal energy storage system (ATESS) model. Simulations of the Dorigny SPEOS system identified many of the causes of the relatively poor recovery efficiency experienced during the first cycle at that site. Modeling studies of the use of resistivity as a monitoring tool indicated that it could be used successfully, if the electrodes are properly configured. However, site lithologic, mineralogic, and groundwater chemistry variabilities may compromise the usefulness of the method. The ATESS model was modified to revise its treatment of geohydrologic inhomogeneities and resulting effective thermal dispersion.

Monitoring of a chill ATES facility at the Parisian Department Store was frustrated by numerous lapses in operating system controls and in data acquisition. Despite monitoring and control problems, the system has provided a substantial amount of cooling during the summer, replacing one of the two conventional chillers. Unfortunately, available monitoring data indicate recovery of only 28% of the injected chill, while over twice as much water was withdrawn as injected. This relatively poor performance is thought to be the result of control problems, local natural groundwater flow, and thermal stratification. Monitoring was discontinued in September 1984.

A more extensive chill ATES monitoring project was initiated at the Student Recreation Center on the campus of the University of Alabama in Tuscaloosa. The chill ATES system at this site began operation in 1983, but system performance could not be determined from the limited monitoring data available. Design and installation of a new monitoring system was initiated in the fall of 1984 and was nearly complete at the end of March 1985. General system monitoring was conducted during the winter of 1984-85. Limited geohydrologic data were also gathered during the interim period. Additional geohydrologic data are required before an evaluation can be completed of the geohydrologic system's effects on site performance.

The final report on an experimental study of cooling by ice sublimation with solar-dried zeolites was completed at the New Mexico Solar Energy Institute. The experiment proved the feasibility of the concept, but parasitic energy requirements, system complexity, and other technical issues are drawbacks to the system as currently configured. Methods to substantially reduce these drawbacks are under consideration. A workshop on adsorption cooling is also under consideration.

Studies of STES with solar energy collection for district heating were supported. These studies concentrated on evaluating systems in New England using solar collectors with rock borehole storage. The studies not only investigated this promising integration of solar and STES technologies, but also contributed to DOE participation in Task VII of the International Energy Agency's (IEA) Solar Heating and Cooling Programme.

Underground energy storage program researchers and DOE staff participated in international exchange of technical information on a number of STES concepts and systems. Many nations are making substantial investments in research, demonstration, and pilot commercial projects in STES. Pacific Northwest Laboratory continued its participation, on behalf of DOE, in the IEA Task III (ATES field testing) of the Energy Storage Programme.

CONTENTS

FIGURES

TABLES

UNDERGROUND ENERGY STORAGE PROGRAM
1984 ANNUAL SUMMARY

1.0 INTRODUCTION

As a nation we are challenged with the need to develop alternative energy sources and find ways of using existing energy supplies more efficiently. Our economic and strategic security may be at risk if we do not accept and meet this challenge.

The U.S. Department of Energy (DOE) established a program to encourage timely implementation of underground energy storage concepts as one of many means to meet this challenge. The overall goal of the DOE program is to reduce the technical and economic uncertainties inhibiting development and implementation of promising underground energy storage (UES) concepts. If this were achieved, the residential, commercial, and industrial energy users could reduce energy consumption, increase the efficiency of existing energy supply capacity, reduce their reliance on scarce energy resources, and take greater advantage of alternative energy sources.

Studies have shown that two UES concepts--Seasonal Thermal Energy Storage (STES) and Compressed Air Energy Storage (CAES)--are technically feasible and can offer significant cost savings under certain conditions for utilities, industry and, in some cases, commercial building developers and operators. Both of these technologies contribute to the reduction in national consumption of petroleum resources and more efficient utilization of present electric generation capacity. It has been estimated that STES is technically capable of reducing peak national demand for energy by as much as 7.5%. Estimates indicate that CAES could save up to 100 million barrels of oil annually.

Seasonal storage and retrieval of thermal energy, using heat or cold available from waste or other sources, shows great promise to reduce peak demand, reduce electric utility load problems, and contribute to establishing favorable economics for district heating and cooling systems. The numerous motivations for storing large quantities of thermal energy on a long-term basis include 1) the need to store solar heat that is collected in the summer for use in the winter months; 2) the cost-effectiveness of utilizing heat now wasted in electrical generation plants; 3) the need to profitably use industrial waste heat; and 4) the need to more economically provide summer cooling for buildings. Aquifers, ponds, earth, lakes, and engineered structures have potential for seasonal storage.

Storage in aquifers appears to be one of the most economical and widely applicable seasonal thermal energy storage techniques. Most geologists and groundwater hydrologists agree that heated and chilled water can be injected, stored, and recovered from aquifers. Geologic materials can be good thermal insulators, and potentially suitable aquifers are distributed throughout the U.S. Many potential energy sources exist for use in an aquifer thermal energy storage (ATES) system. These include solar heat, power plant cogeneration, winter chill, and industrial waste heat sources such as aluminum plants, paper and pulp mills, food processing plants, refuse incineration units, cement plants, and iron and steel mills. Energy sources ranging from 50°C (122°F) to over 250°C (482°F) are available for heating. Potential energy uses include individual- or district-scale space heating, industrial or institutional plant heating, and heat for processing/manufacturing. Studies and small-scale field experiments have reported energy recovery ratios above 60% for seasonal storage; values over 70% are expected to be readily obtainable.

Other STES methods also appear feasible. Ice generation or harvesting followed by seasonal storage may augment or replace substantial portions of building space air conditioning, which accounts for summer electrical peak demand for many utilities. Alternatives such as lakes, ponds, and moist or dry earth for thermal storage are also viable for exploiting the seasonal characteristics of energy availability and requirements. These methods are probable candidates where siting conditions are favorable.

In 1975, the Pacific Northwest Laboratory (PNL) was selected as DOE's lead laboratory in researching and developing CAES technology. Comparable efforts in STES began at PNL in 1979. As lead laboratory, PNL has managed a comprehensive research and development program to advance both STES and CAES to the point of adoption by the private sector. The U.S. Department of Energy ceased sponsoring CAES research and development in 1984.

This report documents the work performed and progress made toward resolving and eliminating technical and economic barriers associated with STES technologies. The reporting period extends from April 1984 to March 1985. Work performed prior to April 1984 was documented in previous annual reports (Smith et al. 1978; Kreid and McKinnon 1978; Loscutoff et al. 1979; Loscutoff et al. 1980; Minor 1980; Kannberg et al. 1981; Minor 1981; Kannberg et al. 1982; Kannberg et al. 1983; and Kannberg 1984). The Underground Energy Storage Program approach, structure, history, and milestones are described in Section 2.0. Section 3.0 summarizes technical activities and progress in the STES component of the program.

2.0 UNDERGROUND ENERGY STORAGE PROGRAM

Pacific Northwest Laboratory, operated for DOE by Battelle Memorial Institute, was selected as lead laboratory to investigate two concepts. Such concepts can achieve reduced energy consumption, more effective use of current energy generation capacity, reduced reliance on scarce energy resources, and enhanced use of alternative energy sources. The lead laboratory assignment included responsibility for development and management of programs in two particularly promising technologies, STES and CAES. The resulting configuration of the DOE-funded UES Program is shown in Figure 2.1. The CAES Program was initiated in FY 1975; STES was begun in FY 1979. These programs were conducted independently until the end of FY 1981. Reductions in the scope and magnitude of DOE activities in FY 1982 made it desirable to consolidate programmatic management of efforts into the UES Program. All DOE-sponsored CAES research and development ceased in early 1984. Therefore, the remainder of this document will discuss only STES.

2.1 APPROACH

The general strategy for encouraging timely implementation of UES technologies was to identify the major factors inhibiting development and implementation and then perform the necessary R&D to eliminate technical concerns, clarify nontechnical concerns, and assist private or public groups in the implementation of these technologies. For STES the following factors inhibit implementation:

- STES methods have not been thoroughly characterized and are considered unproven.
- Potential STES users are unfamiliar with the technology, do not perform R&D, and are technically conservative.
- Some of the most promising STES methods are highly site-specific and require substantial exploratory site investigation; their development can involve extensive interaction with regulatory agencies.

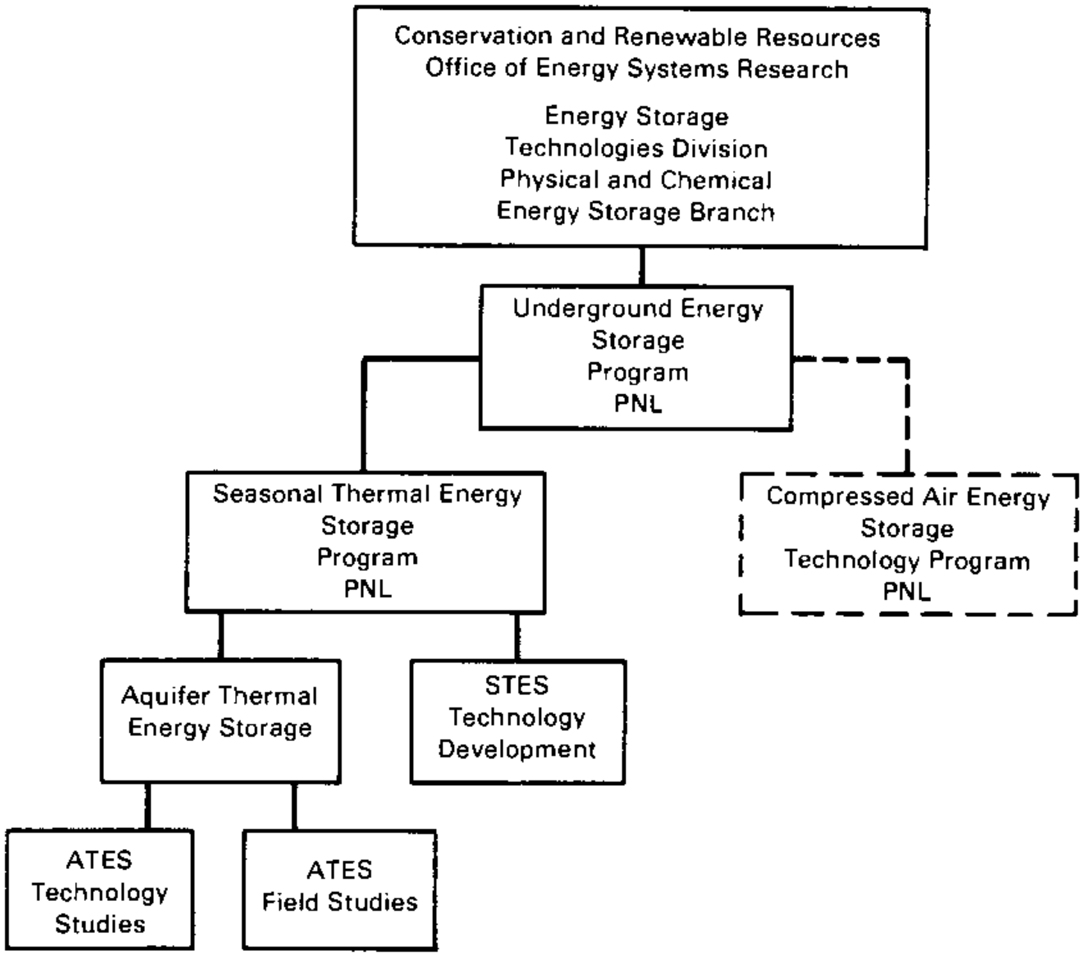


FIGURE 2.1. Department of Energy Programs to Pursue Development of Underground Energy Storage

- The economic character of STES methods has not been well defined and varies significantly among sites.
- The annual nature of STES cycles makes technology development a multiyear effort.
- STES technologies typically require significant front-end expenditures.
- STES methods are typically not patentable.
- The wide range of STES system configurations, especially when integrated with heat pumps, makes system selection difficult and confusing.

Early studies indicated that STES utilizing aquifers would be by far the most economical STES concept and that promising sites could be found across much of the U.S. It was further recognized that aquifers promised the greatest technical challenge because of the wide range in potential site conditions and because of the breadth of technical issues that would have to be explored and resolved. Therefore, aquifer thermal energy storage became the prime technology for study in the STES Program.

2.2 HISTORICAL SCOPE AND MILESTONES

The historical scope of the DOE-sponsored STES studies is shown in Figure 2.2. Seasonal thermal energy storage studies began in 1975 with field testing at Mobile, Alabama. Other supporting analyses have also been conducted, including studies in numerical modeling, laboratory testing, system studies, economic analyses, and geochemical studies. In 1979 a major effort to demonstrate STES technology was initiated at three sites in the U.S. In 1981 changes in the direction and funding of DOE studies resulted in termination of two of the studies and redirection of the third (at St. Paul, Minnesota) to that of a high-temperature test facility.

The major UES projects conducted in 1984 are indicated in Figure 2.3. It is the policy of the Energy Storage Technologies Division of DOE to select a few critical milestones for tracking progress in the various programs. These milestones for the UES Program are shown in Figure 2.4.

2.3 RESOURCE REQUIREMENTS

The funding requirements over time for STES and CAES are shown in Figure 2.5. Historically, funding has been substantially higher than current levels. The current scope of activities stresses more cost-sharing in STES field activities and reduced investigation of STES economics, system behavior, and new STES concepts.

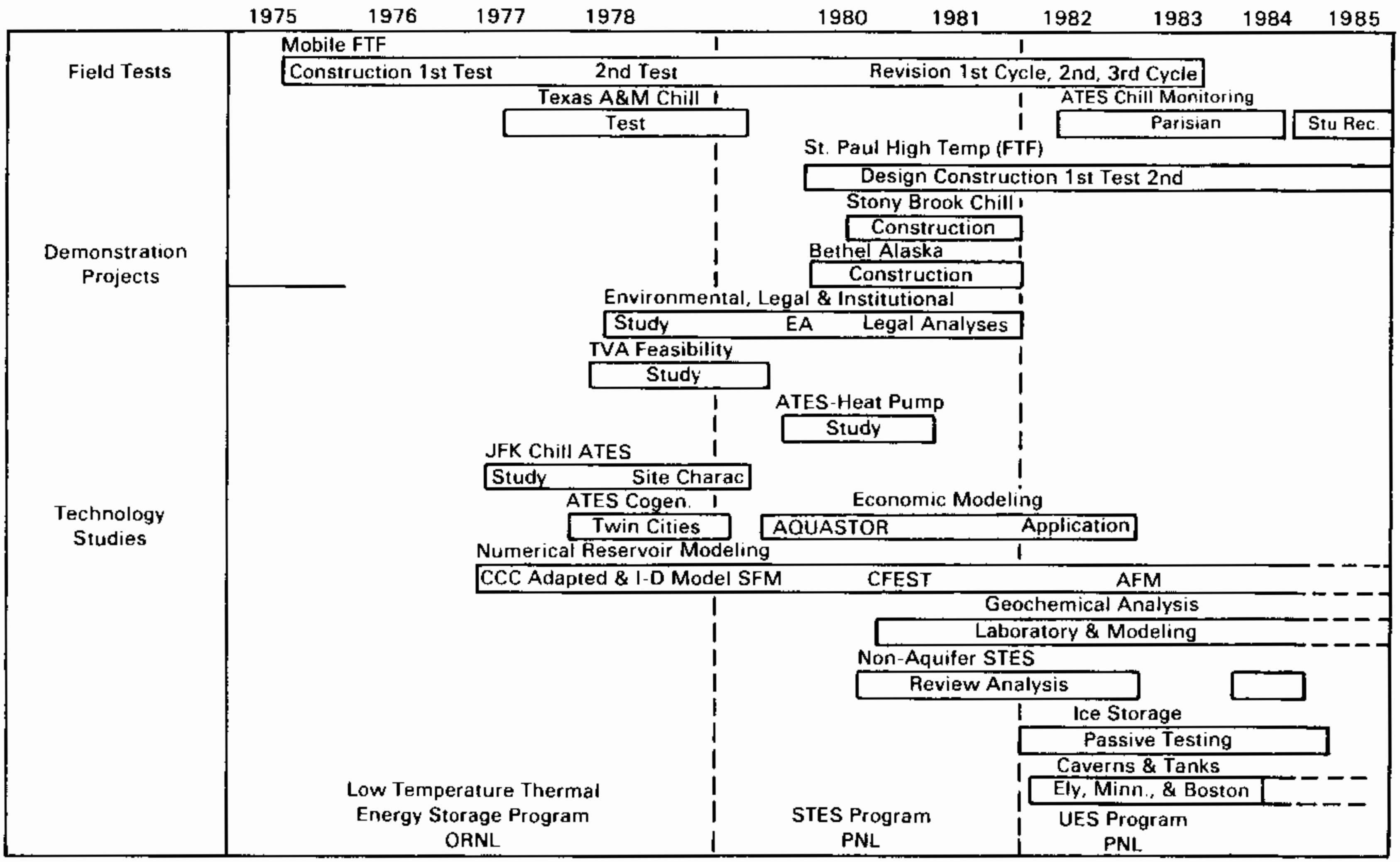


FIGURE 2.2. Department of Energy Seasonal Thermal Energy Storage Program History (dashed line indicates low level of effort)

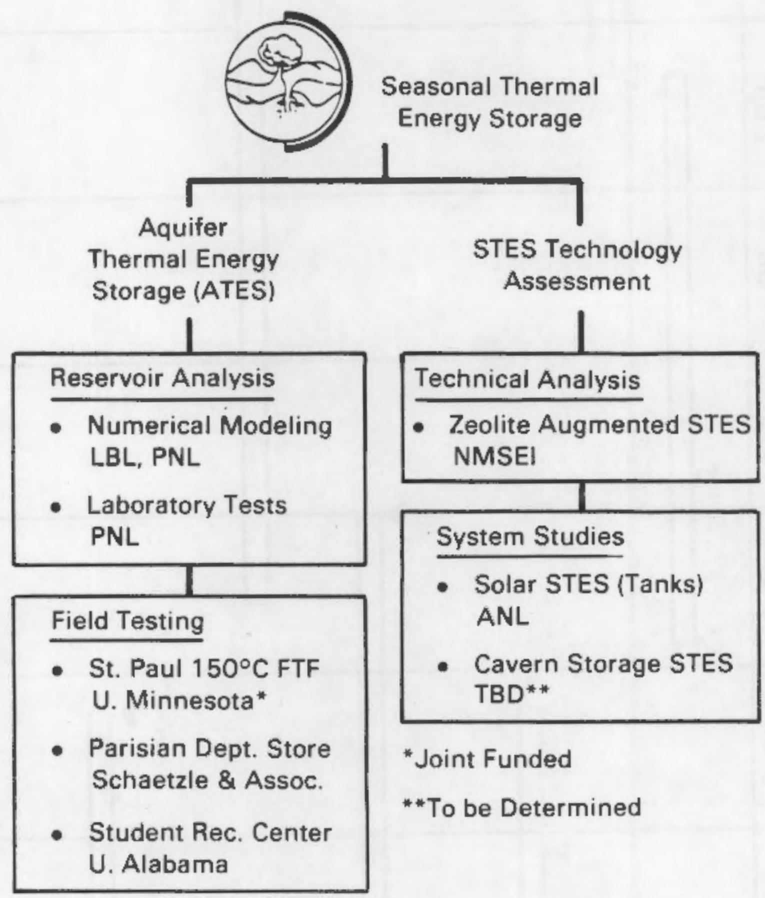


FIGURE 2.3. Underground Energy Storage Program Structure

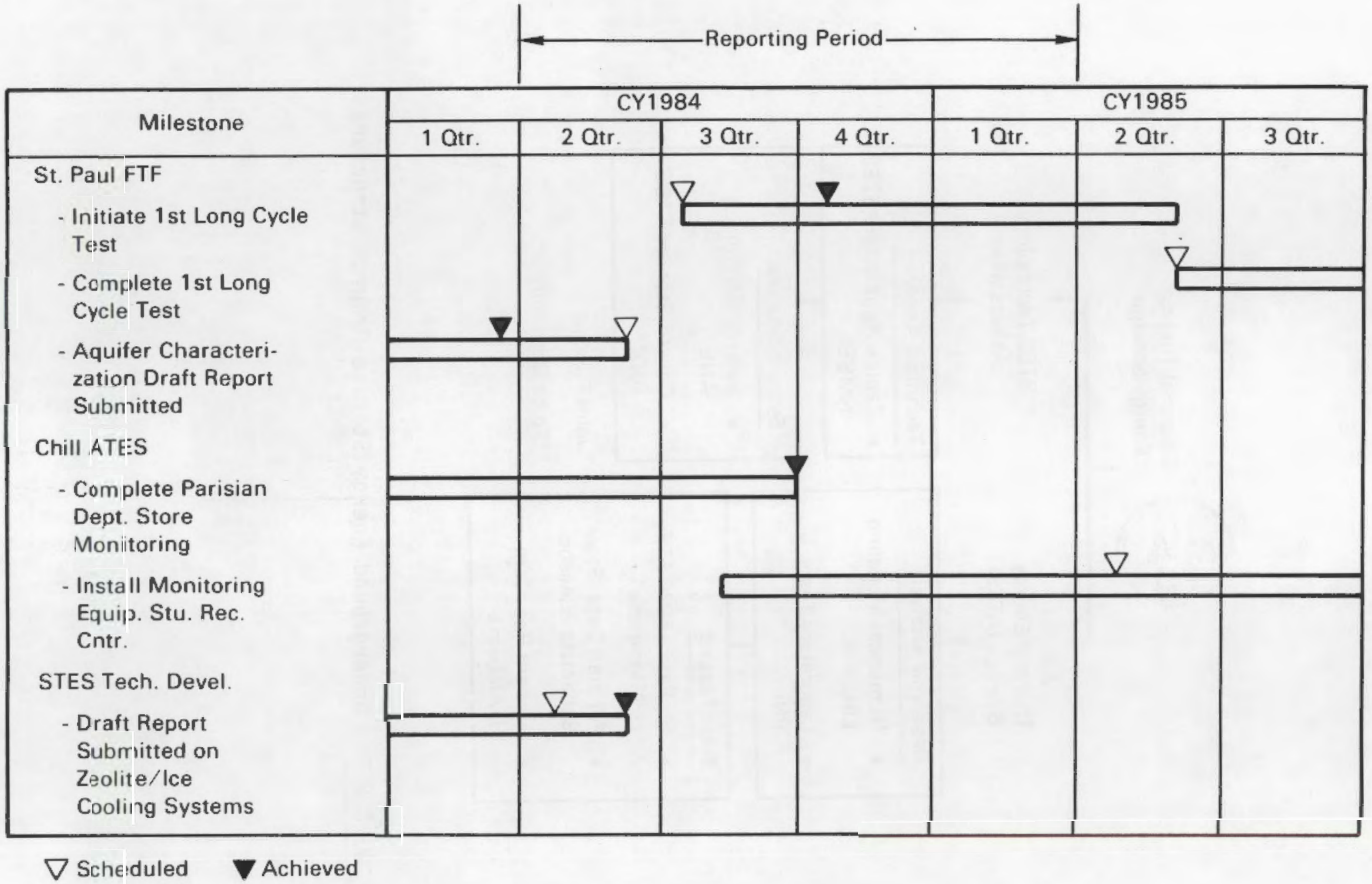


FIGURE 2.4. Underground Energy Storage Program Major Milestones During Reporting Period

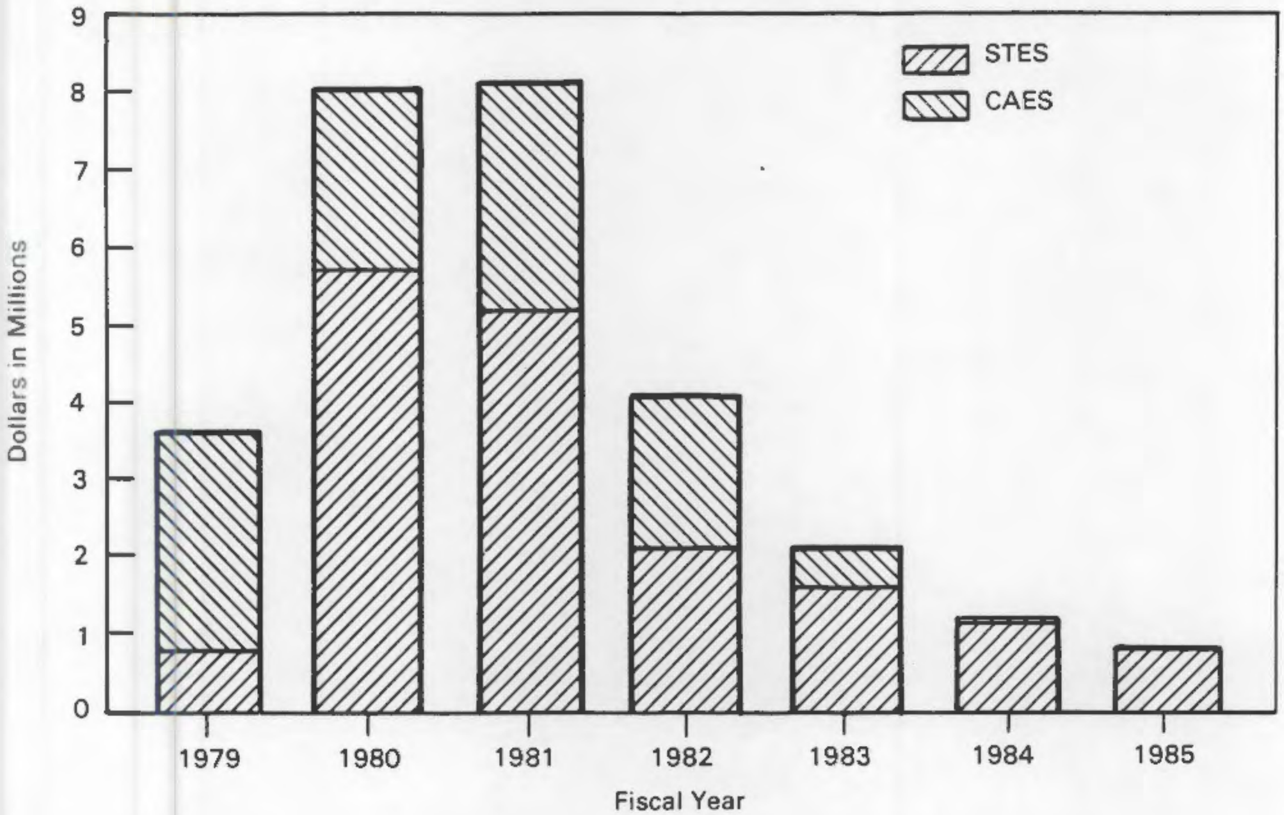


FIGURE 2.5. Underground Energy Storage Program Funding History

3.0 SEASONAL THERMAL ENERGY STORAGE

Many nations are currently involved in the research and development of STES technology. Principal among these are Denmark and Canada with their activities related to ATES, and other Scandinavian and European nations in other STES technologies. Typically, development and implementation of STES in these countries is part of national energy conservation efforts funded by the respective governments. With the exception of the U.S., there appears to be no privately funded development of STES; however, current projects include interaction with private organizations in a technology transfer effort.

The studies performed in the U.S. have concentrated on ATES because of its relatively low life-cycle cost and its wide siting opportunities. In particular, a DOE-sponsored study of high-temperature ATES [>100°C (212°F)] has been the major STES-funded activity during the reporting period. Additional studies have been conducted on related ATES technical issues and other STES technologies. Many of these additional studies have attempted to take advantage of public or commercial interest in constructing STES-related systems. It is expected that this will be a growing activity of the program.

The STES Program is divided into two major elements: ATES Technology Studies and Technology Assessment and Development. The former deals with the technical research and development of ATES and includes laboratory testing, numerical modeling, and field testing of ATES reservoir performance. The latter involves technical studies of other STES concepts.

The major activities of the STES Program are illustrated in Figure 2.3. Subsequent sections briefly discuss progress on these activities during the reporting period. This is followed by a short discussion of the international activities in STES.

3.1 ATES TECHNOLOGY STUDIES

Aquifer thermal energy storage technology studies include laboratory and numerical modeling studies as well as field studies. The field studies require the largest portion of the STES budget, receiving about 70% of all STES funding in FY 1985. As such, field activities will be discussed at greater length than other activities.

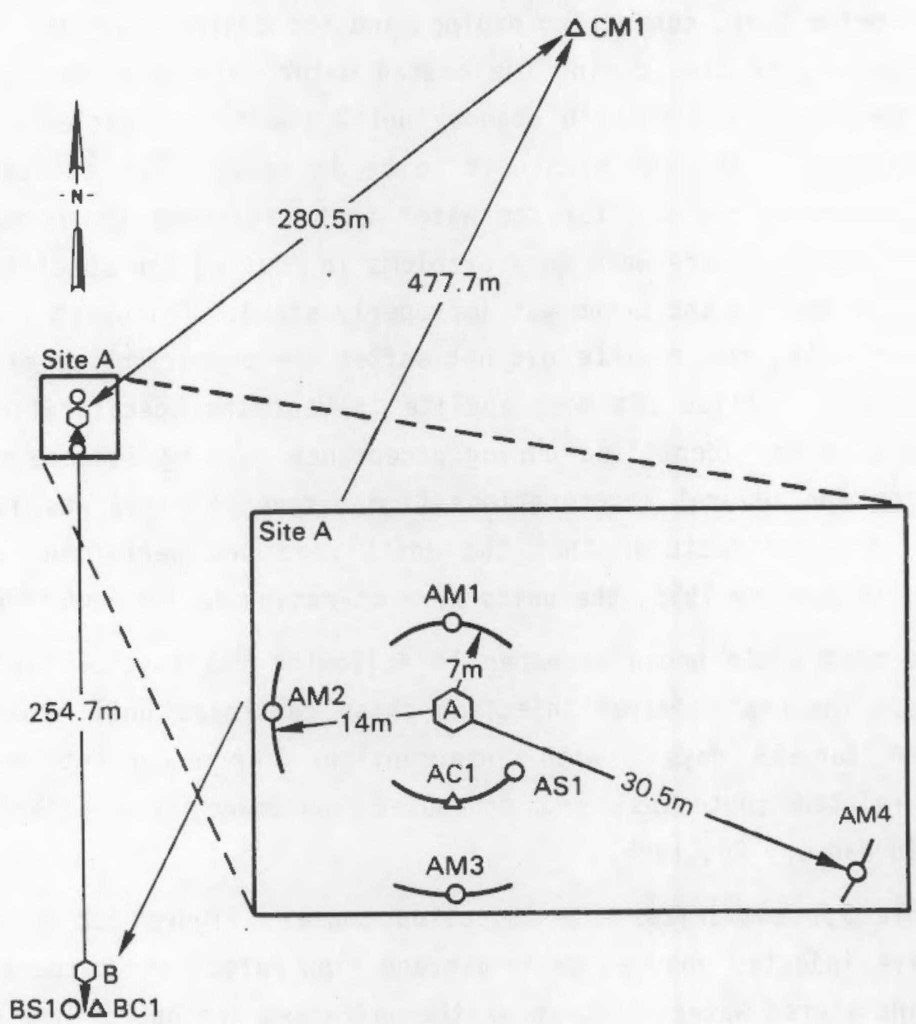
3.1.1 St. Paul Field Testing[a]

The St. Paul Field Test Facility (FTF) is designed to inject and recover heat at a rate of 5 MW (thermal), using a well doublet spaced at 255 m, operating at 18.9 ℓ/sec injection rate and maximum water temperature of 150°C (302°F). The first phase of testing at the St. Paul FTF consisted of four short-term test cycles of heated water injection-storage-recovery, which were completed in December 1983. Two long-term test cycles are planned for the second phase of testing, should funding permit. The first long-term test cycle began in November 1984 and will conclude in May 1985.

A variance allowing the injection of ground water for the long-term tests (60 days of injection, storage and recovery) was granted in August 1984. This permit allows the use of ion-exchange water softening on the groundwater. Nearly continuous system operation is possible with the use of softened water because scaling caused by heating hard water is eliminated. Some major provisions of the variance are: 1) a limit of 180 mg/ℓ of sodium concentration; 2) 2 years of post-test monitoring; and 3) pumping the treated waters out of the aquifer to waste at the conclusion of testing.

Preparations for the first long-term test cycle included drilling a new monitoring well (AM4) located 30.5 m (100 ft) from the storage well and installing an ion-exchange water softener. The location of AM4 and other monitoring wells is shown in Figure 3.1. Well AM4 is completed to a depth of 248.5 m (815 ft) in the upper portion of the Eau Claire formation. The well is fitted with a four-pair and an eight-pair thermocouple string, as well as three screened intervals for monitoring pressures in the Franconia-Ironton-Galesville (FIG) aquifer at 234.8-, 211.3-, and 190.9-m (770-, 693-, and 626-ft) depths. A downhole deviation survey indicates that the bottom of the hole is located 7.92 m (25.98 ft) N23°07' W of the top. A downhole submersible gas-driven bladder pump is installed in the pipe screened in the Galesville formation.

[a] The discussion of the St. Paul FTF was prepared by Dr. M. Hoyer of the Minnesota Geological Survey and subsequently edited at PNL.



Location Diagram of Test Wells and Monitor Wells

A = Heat Injection Well

B = Water Supply Well

AC1, BC1 = Core Borings

AS1 and BS1 = Supplemental Monitor Wells for AC1 and BC1

AM1, 2, 3, and 4, CM1 = Monitor Wells

5 Monitor Wells, 2 Production Wells
2 Core Boring Wells

FIGURE 3.1. St. Paul Field Test Facility Well Locations

The water softener consists of three units containing the ion-exchange resin, a brine tank, connecting piping, and the control system. Two units are in service at any time during the heated water injection phase. The third unit is recharged and then in standby until the timing cycle is completed. Specifications called for each unit to be in service for at least 8 hours between regenerations and for the water to be softened to approximately 0 grains hardness. There were many problems in meeting the specifications. The orifice for drawing the brine was improperly sized. Following installation of the proper unit, the zeolite did not soften the proper volume of water. The manufacturer installed 20% more zeolite to meet the specifications. These problems were not identified during acceptance testing because operation of the system for several regenerations (i.e., several days) was required to convince the manufacturer that the units were not performing properly. Finally, in January 1985, the units were operating to the specifications.

The test cycle began November 14 following the initial testing of the softener. The heated water injection phase continued until injection had proceeded for 59 days. With interruptions for equipment repairs, weather-related shutdowns, and scheduled shutdowns, the injection was completed January 28, 1985.

Table 3.1 summarizes the injection phase. Figure 3.2 presents the cumulative injected volume, daily average flow rates, and temperatures of the source and stored water. Severe weather affected the operations primarily by limiting the available steam, cutting the attained temperature of the injected water in January (Figure 3.2). Some weather-related mechanical problems were also experienced.

Temperature arrivals at observation wells AM1, AM2, AM3, and AS1 were similar to those observed during the short-term test cycles for both the Ironton-Galesville and upper Franconia parts of the aquifer. The first temperature front to arrive at new monitoring well AM4 occurred after approximately 8 days of injection and was within the central part of the Ironton-Galesville aquifer. The temperature at AM4 reached >100°C (212°F) within the Ironton-Galesville aquifer after approximately 25 days. The temperature at AM4 did not reach that of injection in the upper Franconia part of the aquifer.

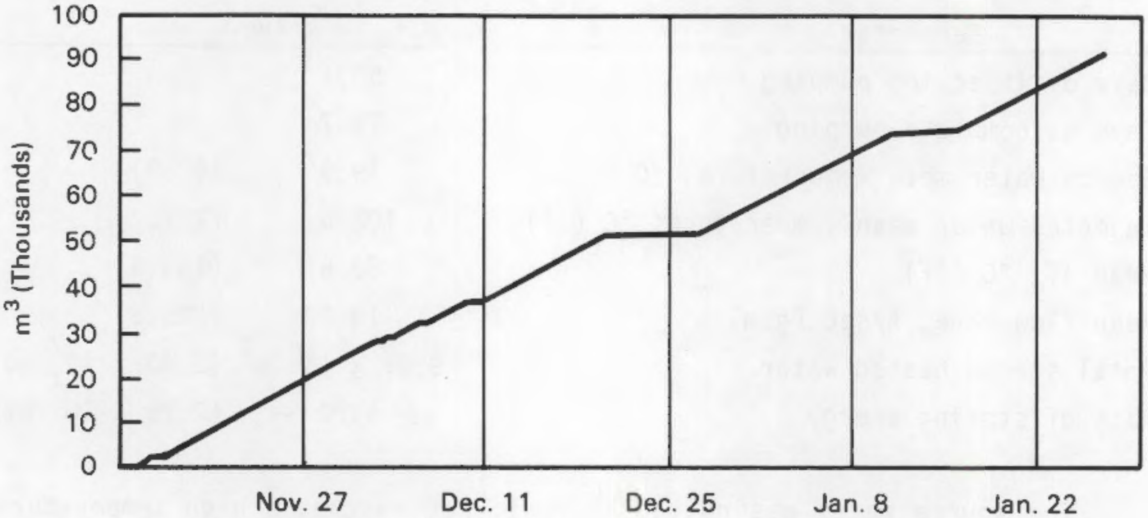
TABLE 3.1. Preliminary Summary of Long-Term Test Cycle, Injection Phase

Parameter	Value	
Days of injection pumping	59.1	
Days to complete pumping	74.7	
Source water mean temperature, °C (°F)	19.9	(67.8)
Injected water mean temperature, °C (°F)	108.5	(227.2)
Mean ΔT, °C (°F)	88.6	(159.4)
Mean flow rate, ℓ/sec (gpm)	18.03	(285.5)
Total stored heated water	9.21×10^4 m^3	(2.43×10^7 gal)
Rate of storing energy	6.70 MW	(2.29×10^7 Btu/hr)

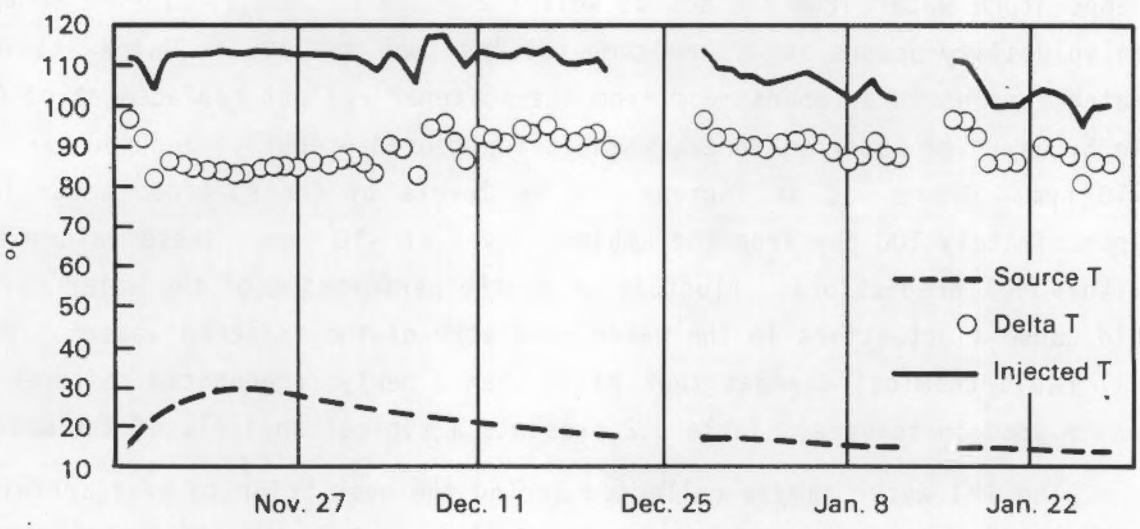
The source water was not isothermal, but reached a high temperature of 30.5°C (87°F) about 8 days into the test cycle and then declined slowly to 13.0°C (56°F) by the end of the injection period (Figure 3.2). Trends of Ca and Mg concentrations, as well as alkalinity in the source water, changed inversely with the temperature. However, hardness values for the source water were quite close to what they would have been with entirely ambient temperature water from the source well (~200 ppm as $CaCO_3$). The major change in solubility occurs at higher temperatures than the source water attained. Water samples taken downstream from the softener reflect replacement of Ca and Mg by Na. The water softener, when it functioned properly, reduced hardness to <10 ppm. There was an increase in Na levels of the softened water to approximately 100 ppm from the ambient level of <10 ppm. These values agree with model predictions. Fluctuation in the performance of the water softener did cause fluctuations in the water chemistry of the injected waters. Nearly all rapid chemical changes took place when a newly regenerated softener unit was placed in service. Table 3.2 presents a typical analysis of the water.

The AM4 water sample collected during the week prior to heat arriving at well AM4 proved to be soft water. Samples taken from AM4 after this date also proved to be soft water.

Two computer codes are being used to model the long-term test cycles: the SWIP code, which was used for the short-term cycles, and the HST code



a. Cumulative daily flow in m^3



b. Daily average-source water and injected water temperature and delta T

FIGURE 3.2. Long-Term Test Cycle Injection Phase

TABLE 3.2. Analysis of Water Samples from the Long-Term Test Cycle Collected January 17, 1985

Parameter	Source Water	Softened Water	Heated Water
Temperature, °C (°F)	12.9 (55)	15.0 (59)	92 (197)
pH	7.13	7.09	7.86
SC (mho/cm)	380	387	463
DO (mg/ℓ)	0.3	0.2	0.1
Alkalinity (meq/ℓ)	4.46	4.46	4.44
SiO_2 as Si (mg/ℓ)	4.21	4.21	4.15
SO_4 as S (mg/ℓ)	1.49	1.54	1.57
Cl (mg/ℓ)	1.57	2.41	2.34
F (mg/ℓ)	#	#	#
NO_3 as N (mg/ℓ)	ND	ND	ND
NO_2 as N (mg/ℓ)	ND	ND	ND
PO_4 as P (mg/ℓ)	ND	ND	ND
Ca (mg/ℓ)	47.25	<D.01	0.89
Mg (mg/ℓ)	16.99	0.52	1.05
Na (mg/ℓ)	8.06	100.57	100.01
K (mg/ℓ)	7.65	3.81	5.16
Fe (mg/ℓ)	0.69	0.01	<0.01
Hardness (as mg/ℓ $CaCO_3$)	187.95	2.14	6.55

Note: ND - not detected
- value being checked

being developed at the U.S. Geological Survey, Central Region Research Center. The HST code was received just before the end of the reporting period. Plans call for its compilation and application on the University of Minnesota CRAY vector processor.

A new model grid has been designed for use with the SWIP code for long-term test simulations. The new grid is 31 blocks x 26 blocks x 6 blocks; four new grid blocks have been added to account for the location of monitoring well AM4. More lateral grid blocks may be needed if model simulations indicate that heat is flowing beyond the lateral model boundaries. A new flux rate is being determined at the model boundary by use of the analytical flow-net analysis method.

Residual heat from short-term testing will be determined by simulating the inactive period from the end of short-term test cycle 4 to the start of injection for the long-term test cycle using the short-term test model. Flow and temperature data from the field test will be used in the model to predict performance of the first long-term test.

The recovery phase of the long-term test cycle will begin April 2, 1985, and will continue until the end of May. The peak temperature of the recovered water is expected to be 93°C (200°F).

3.1.2 Parisian Department Store Chill ATES Monitoring

Energy performance monitoring of a chill ATES system at the Parisian Department Store at the University Mall in Tuscaloosa, Alabama, was initiated in the fall of 1982. Operational and monitoring system problems made it impossible to accurately determine the performance during the first year of monitored operation. The system was modified prior to and during the second year of operation to try to determine its energy performance. It was not possible to install monitoring wells. Therefore, the limited data gathered for operation of the store cooling system, augmented by periodic manual measurements, was the only information available for determining system performance. During the 1983-84 winter, 59 million liters (15.6 million gal) of chilled water possessing 826,000 kWht (2.82×10^9 Btu) of cooling energy were injected into the water table aquifer at the Parisian site. During the following summer, 127 million liters (33.7 million gal) of groundwater were recovered having 228,000 kWht (777 million Btu) of chill energy. Thus, although more than twice as much groundwater was recovered as was injected, the chill energy recovery totaled less than 28% of that injected.

The relatively poor performance of the system is attributed to control and system leakage problems that resulted in inadvertent mixing of ambient and chilled groundwaters. Despite the low storage performance, the store's cooling system can utilize the installed ATES system for simple groundwater cooling even when the groundwater temperature is at the natural temperature of 19°C (67°F). Such use reduces auxiliary chiller operation required for building air conditioning, thus reducing summer electric energy usage and demand. It is not known whether cost savings associated with the system as it currently operates are sufficient to provide payback on the capital investment required for installation of the ATES system.

Monitoring at the Parisian site was discontinued in September 1984 for three reasons: the relatively poor performance of the system, the inability to install monitoring wells to determine system geohydrologic behavior, and the lack of sufficient funds for continued work at this site.

3.1.3 University of Alabama Student Recreation Center Chill ATES Monitoring

University of Alabama researchers are monitoring an operating chill ATES system installed at the university's Student Recreation Center in Tuscaloosa. The objectives of this effort are

- to characterize this ATES system and its performance through analysis of geohydrothermal flow field data and energy flow data, respectively
- to estimate system economics in terms of life cycle costs and simple payback period.

The system being studied consists of cooling coils, cooling tower, wells, and the aquifer storage system. These elements are portrayed schematically in Figure 3.3. System operation is based on the direct cooling concept, in which water is chilled in the cooling tower during cold periods, then stored in an aquifer for later recovery as needed for air conditioning.

The overall system operates between 2°C (36°F) and 16°C (60°F). The cooling tower operates whenever the wet-bulb temperature drops below 7°C (45°F). Cooling tower operation is related to weather only, and is independent of heating load.

Access to the confined water table aquifer is provided by wells drilled between the surface and the aquifer base. Three "warm" wells and three "cold" wells comprise the aquifer system, as shown in Figure 3.4. Each well contains a submersible three-stage pump and return riser. Warm well pump capacity is

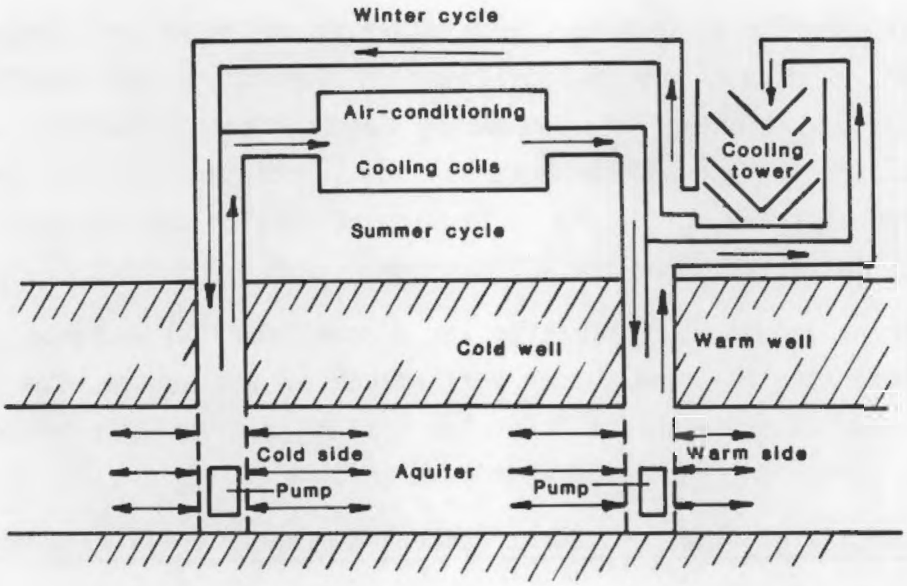


FIGURE 3.3. Chill ATES System Schematic

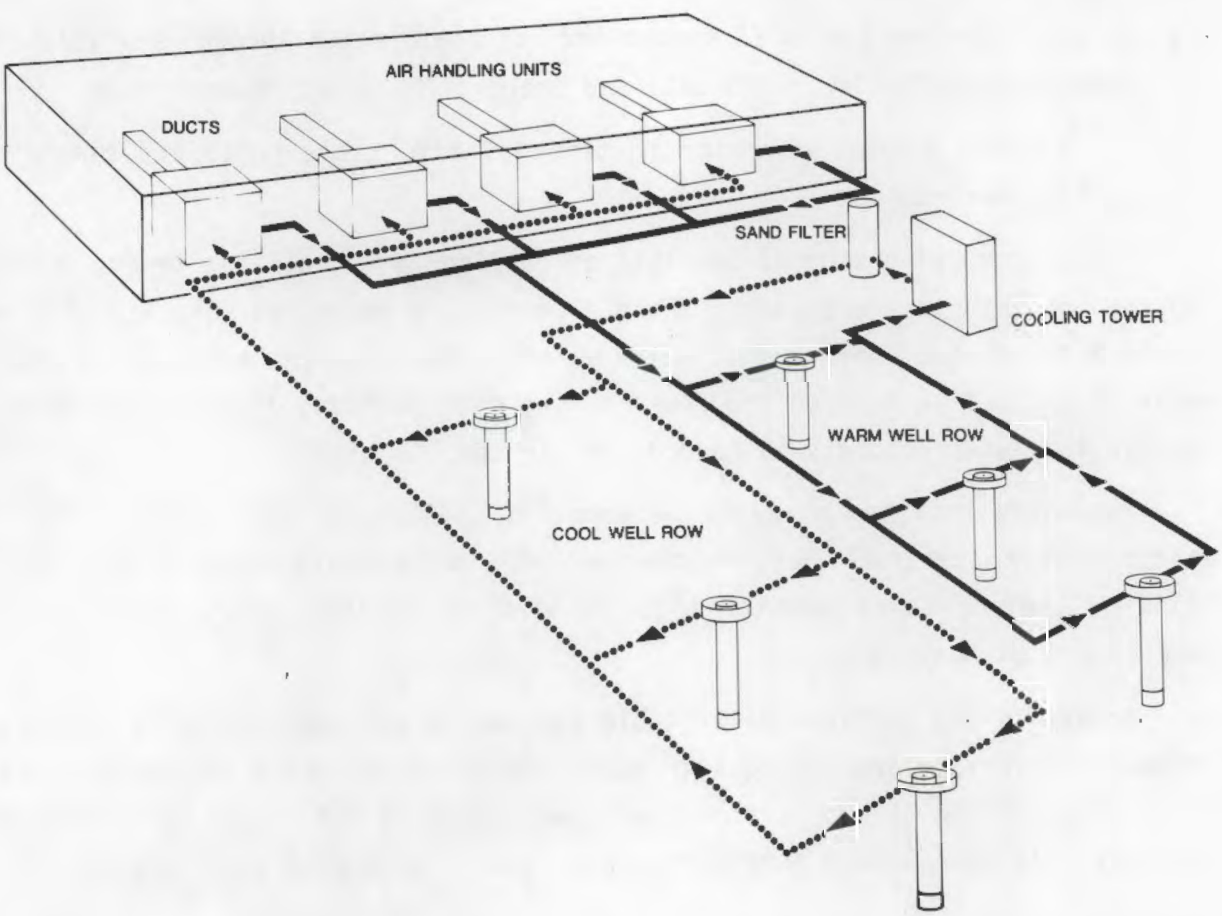


FIGURE 3.4. Schematic of the University Recreation Building Chill ATES System

568 ℓ/min (150 gpm) at 43-m (140-ft) head, and cold well capacity is 454 ℓ/min (120 gpm) at 61-m (200-ft) head. The cooling tower capacity is 1703 ℓ/min (450 gpm) of water from 13°C (56°F) to 7°C (45°F) with 4°C (40°F) wet-bulb ambient temperature. The wells are 27 to 30 m (90 to 100 ft) deep, use 2.5-cm (1-in.) PVC sand screen, are packed with gravel in the saturated zone, cased with solid PVC casing, and are grouted with concrete to the surface.

Water is injected into one well and moves toward the next well from which an equivalent amount of water is withdrawn. In this system there is essentially zero volume use of water, except during winter cooling when some evaporation occurs. This aquifer system is designed for 139,000 ton-hours per year of thermal storage.

The system began operation in late 1982 following construction of the Student Recreation Center facility. Some chilling of water took place during the 1982-83 winter. The system successfully met essentially 100% of the 62,000-ft^2 facility's air conditioning needs during the summers of 1983 and 1984.

The monitoring effort began in late 1984 with construction of 15 monitoring wells located within the ATES system, as shown in Figure 3.5. These comprise three background head monitoring wells, three additional head monitoring wells, and nine temperature monitoring wells. All 15 wells are cased with 5-cm (2-in.) PVC pipe. Each of the six head wells is fitted with a sand screen near the bottom.

These monitoring wells will be used in conjunction with monitoring of the "warm" and "cold" wells and the cooling tower to collect various sets of data:

- core samples drilled from the monitoring wells
- water head measurements
- water temperature
- water flow injection and recovery rates with temperature
- power input (pumps and cooling tower fans).

These data will be used to define and characterize the aquifer, determine natural flow, provide three-dimensional temperature distributions over time, and compute energy consumption. From these analyses, aquifer performance and

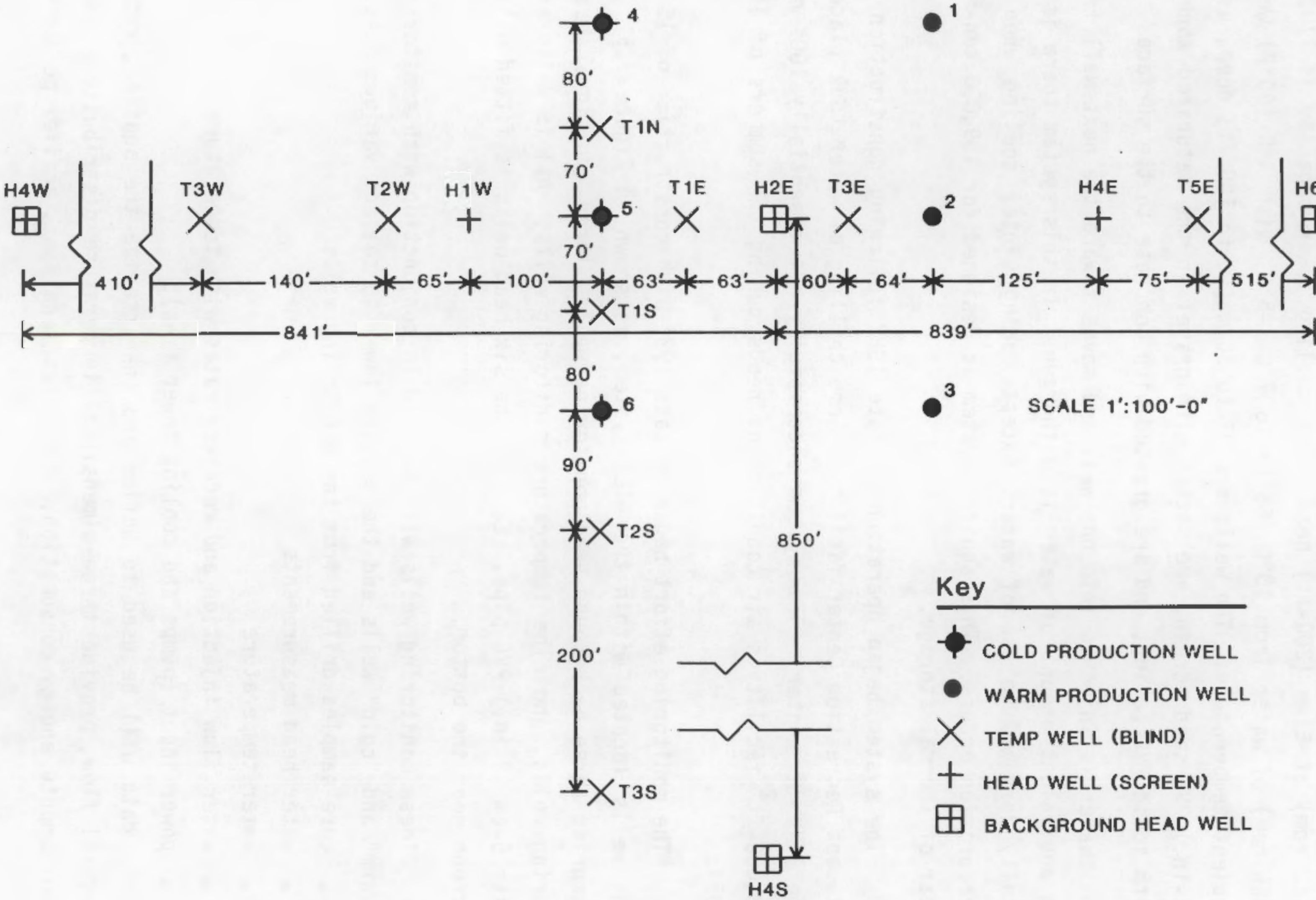


FIGURE 3.5. Monitoring Well Locations

energy recovery will be determined, as will air conditioning system performance.

During this reporting period, sediment samples collected during the construction of six production wells were analyzed. In December, sediment samples were collected from the monitoring wells and subsequently analyzed. From those two data sets, a sedimentary framework report will be prepared for use in describing the aquifer and relating the input and output parameters of the stored water to the aquifer's sediment characteristics.

The equipment necessary for calibrating flow rates and temperatures was constructed in the laboratory. Following testing, it will be utilized in the field.

At the close of the reporting period, most computer equipment for logging and evaluating test data had been received. A single exception is the channel expansion boards. The programs for operating the monitoring system had been completed and satisfactorily tested. The underground conduits for connecting the thermistors in the production wells with the computer were installed. Thermocouples were installed in the six production wells. Computer monitoring of the cooling tower, the building, and the six production wells is expected to begin in May 1985.

Water temperatures were measured in the monitoring wells routinely twice each week throughout March and April. Water levels in the head wells have also been taken twice each week.

3.1.4 Laboratory Testing and Field Analyses

Studies of physicochemical processes occurring at the St. Paul FTF were conducted using a combination of three techniques: 1) laboratory-scale flow tests at elevated pressure and temperature on core samples from the reservoir formation, 2) onsite core flooding and membrane filter tests performed in conjunction with cycling, and 3) geochemical analysis of chemical reactions in the aquifer system. Closely integrated studies are being performed at the University of Minnesota and at PNL.

Laboratory studies in 1984 concentrated on determining the effect of ion-exchange softening of groundwater on the properties, especially permeability, of aquifer core samples. Laboratory tests using representative unsoftened groundwater had indicated significant alteration of core properties. Permeabilities were observed to decrease as fluid temperature increased, and dissolution of dolomite and silicate cementing agents was evident from scanning electron micrographs. Similar effects were observed when softened water was used. One of the major differences between laboratory experiments and field conditions is the large amount of fluid circulated through laboratory cores compared to that expected in the field. This may be one of the main reasons why no degradation was observed at the field test site during short-cycle tests.

Membrane filter tests and core flooding tests conducted at the St. Paul FTF with the Field Injectivity Test Stand indicate improved injectability of groundwater during successive short (24-day) cycles of injection, storage, and recovery. Improved injectability (substantially lower particle content) is seen in Figure 3.6 as an increase in the fluid volume passed through 10-μm filters during the same time periods at similar temperatures and differential pressures (Blair, Deutsch, and Mitchell 1985). These results indicate that ATES operations at the St. Paul FTF have experienced reduced suspended solids and otherwise favorable injectability characteristics.

Results of core flooding tests conducted in the same Field Injectivity Test Stand demonstrated that several thousand pore volumes of fluid in the 50°C (122°F) to 90°C (194°F) range can be passed through representative core samples with no significant loss in permeability. However, examination of one core sample after it was subjected to a flow of approximately 25,000 pore volumes showed that a substantial portion of the cementing agents was dissolved. Thus, while there has been no degradation in the hydrologic performance of the St. Paul FTF, it is likely that mineralogic, mechanical, and structural changes are occurring in the fabric of the storage aquifers in the immediate vicinity of the injection well. The degree and significance of the changes, while probably quite small, remain undetermined.

3.1.5 Numerical Modeling of ATES

Numerical modeling efforts were funded in several different areas during the period from April 1984 through March 1985. Researchers at Lawrence Berkeley Laboratory (LBL) conducted two studies. One involved simulation of

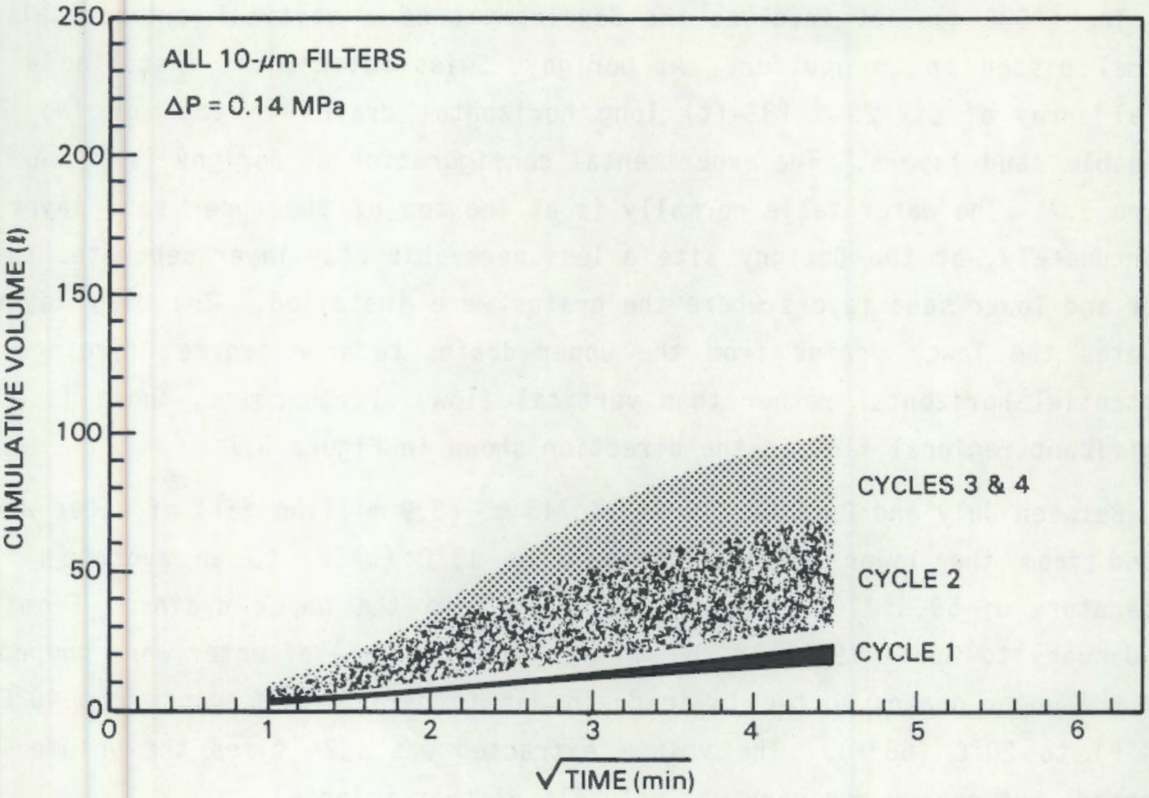


FIGURE 3.6. Cumulative Throughput Through 10-μm Filters Versus $\sqrt{Time}$ for Fluids Reinjected During Heat Recovery

the SPEOS project at Dorigny near Lausanne, Switzerland; the other involved analysis of the potential for utilizing resistivity to monitor the location and movement of thermal fronts at ATES sites. The latter project was cofunded with the Basic Energy Sciences Office within DOE. PNL researchers provided hydrologic flow field predictions and advice on a proposed chill ATES project in Tuscaloosa, Alabama. Further modifications were also made to the simple aquifer thermal energy storage system (ATESS) model to incorporate more realistic hydrothermal behavior.

Lawrence Berkeley Laboratory utilized the PT computer model to simulate the behavior of the SPEOS concept, as implemented at the Dorigny site. This simulation provided insight into the site's performance and showed a potential for higher recovery efficiencies.

The SPEOS concept involves the development of a vertical cylindrical thermal piston in an aquifer. At Dorigny, Swiss researchers installed a radial array of six 25-m (82-ft) long horizontal drains in each of two permeable sand layers. The experimental configuration at Dorigny is shown in Figure 3.7. The water table normally is at the top of the upper sand layer. Unfortunately, at the Dorigny site a less permeable clay layer separates the upper and lower sand layers where the drains were installed. The clay layer isolates the lower drains from the upper drains to some degree, forcing substantial horizontal rather than vertical flow. Furthermore, there is a significant regional flow in the direction shown in Figure 3.7.

Between July and December 1982, 14,743 m^3 (3.9 million gal) of water were pumped from the lower drains, heated from 12°C (54°F) to an average temperature of 59.3°C (139°F), and injected into the upper drains. From mid-January to April 1983, 18,280 m^3 (4.8 million gal) of water were pumped from the upper drains to the lower drains at temperatures ranging from 40°C (104°F) to 20°C (68°F). The volume extracted was 1.24 times the volume injected, but energy recovery was only 41% of that injected.

Simulations using PT provided considerable insight into the performance at the site and the potential for higher recovery efficiencies. The most significant single factor affecting recovery was found to be the large aspect ratio (radius divided by aquifer thickness) of the actual storage zone. The high aspect ratio was a direct result of having the less permeable clay layer between the more permeable sand layers surrounding the drains. Efforts at the site to install vertical drains to increase flow across the clay layer may effectively reduce aspect ratios, thereby improving energy recovery. Regional flow was found to have a smaller effect than aspect ratio; however, measures to control hydraulic gradient near the storage zone, such as bypassing or selective injection and production from gradient control wells, might improve performance. Further testing at the site could aid in evaluating these measures.

Researchers from LBL also explored the use of resistivity measurements for monitoring the location of the thermal front in ATES. Calculations were performed to show the feasibility of resistivity monitoring and to determine

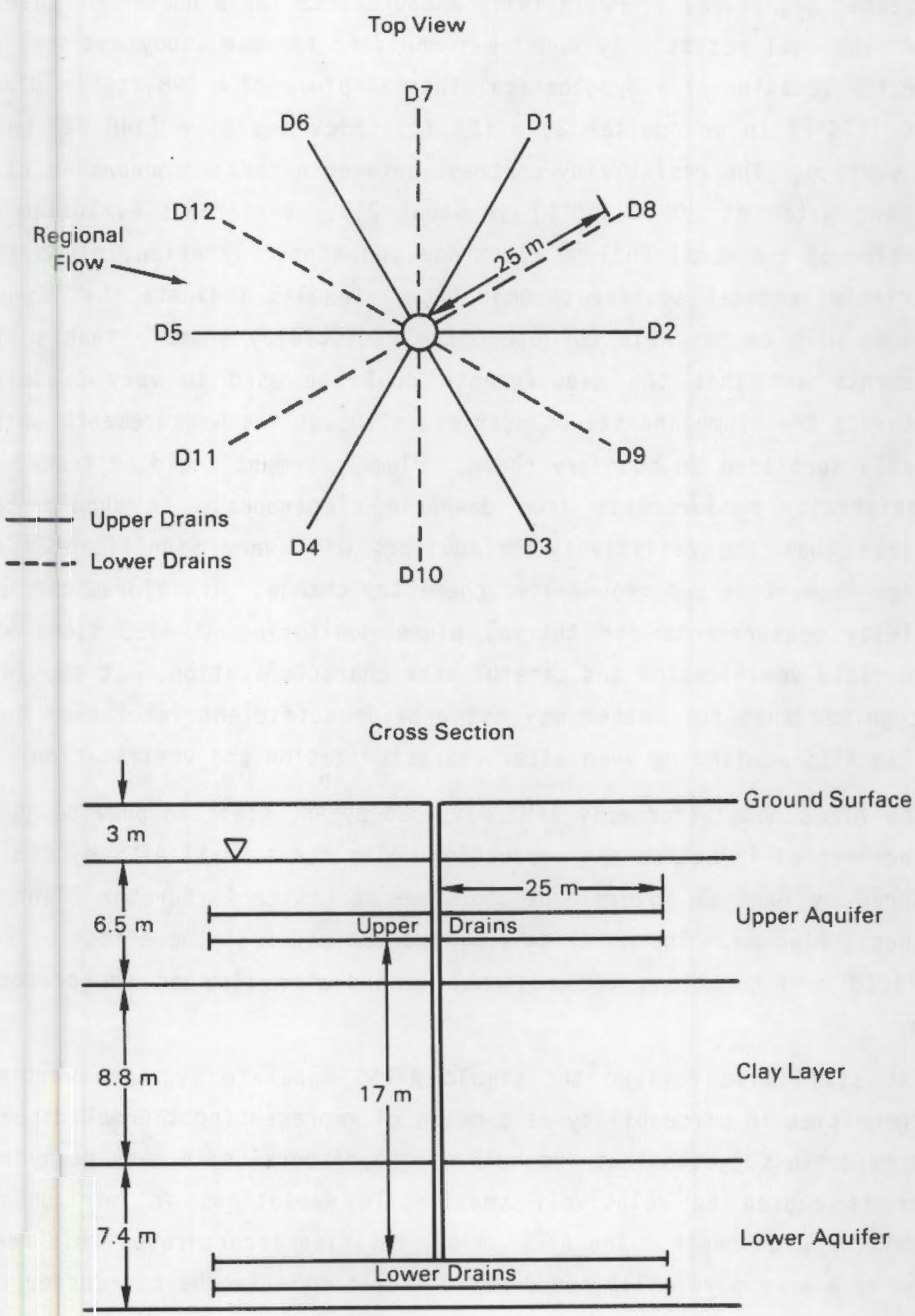


FIGURE 3.7. Schematic Diagram of the SPEOS Experiment

the expected magnitudes of resistivity measurements for a number of cases. A three-dimensional resistivity model was modified for the study and applied to monitor the location of a hypothetical thermal plume 30 m (98 ft) in diameter at 80°C (176°F) in an aquifer 25 m (82 ft) thick and 45 m (148 ft) below ground surface. The resistivity contrast between natural groundwater at 20°C (68°F) and water at 80°C (176°F) is about 2.3. Variations evaluated by application of the model include electrode and sensor location, plume shape, and variable vertical aquifer peremability. Results indicate that downhole electrodes were better able to detect the resistivity anomaly than surface measurements and that the measurements could be used to very crudely characterize the plume and its boundaries, although the measurements were not especially sensitive to boundary shape. Plume movement could be traced using the resistivity measurements from downhole electrodes. It should be emphasized that the resistivity in aquifers will vary significantly as formation properties and groundwater chemistry change. Therefore, the use of resistivity measurements for thermal plume monitoring at ATES sites will require field verification and careful site characterization. It should also be recognized that the method may not provide sufficient resolution to be useful in ATES monitoring even after characterization and verification.

The ATESS model (formerly AFM) was used by PNL staff to provide guidance for placement of injection and production wells for a chill ATES system being considered by General Motors (GM) for the Rochester Carburetor Plant in Tuscaloosa, Alabama. The modeling provided estimates of the effect of various well field configurations and regional groundwater flow on the proposed system.

PNL staff also revised the simple ATESS model to simulate vertical inhomogeneities in permeability as a means of representing thermal dispersion. Recent evidence suggests that the bulk of the dispersion in many geohydrologic systems is caused by relatively small-scale variations in horizontal permeability with depth. The ATESS model revision incorporates this new data to provide a more physically sound method for simulating heat transfer in ATES systems.

3.2 STES TECHNOLOGY ASSESSMENT AND DEVELOPMENT

As originally conceived, the STES Technology Assessment and Development (STES-TAD) studies were intended to provide assessment of the economic, institutional, and legal aspects of all STES concepts (including ATES), and to assess and develop nonaquifer STES concepts. This portion of the STES Program has received relatively little funding. In FY 1984-85, STES-TAD studies received less than 10% of the total STES budget. No funding was available for economic, legal, and institutional studies during the reporting period. The assessment, and especially the development, of some STES concepts have been funded. The concepts that have received support include solar/STES systems studies and use of zeolites for sublimation of STES ice. These efforts are discussed below.

3.2.1 STES in Caverns at Ely, Minnesota

In 1983-84 a study of STES using an abandoned mine at Ely, Minnesota, was cofunded with the Minnesota Geological Survey. The positive results of that study led a local entrepreneurial group to begin development of a mine water source heat pump system. Recently, the City of Ely received a state grant to study a similar system, which would ultimately lead to STES with solar or waste incineration as the seasonal heat source. Modest funds have been set aside to monitor the operation of either system at this site. Neither system became operational during the reporting period; therefore, there was no DOE-funded activity on this project.

3.2.2 Analyses of Solar/STES Systems

Argonne National Laboratory (ANL) conducted studies of solar with STES supported by both the Energy Storage Division (through PNL) and the Solar Thermal Division at DOE. These studies have been directed at establishing the technical and economic bases for solar/STES systems. One significant element of the studies has been international cooperation on Task VII (Central Solar Heating Plants with Seasonal Storage) of the International Energy Agency (IEA) Solar Heating and Cooling Programme. One of the studies jointly funded through PNL has been an assessment of central solar heating plants with seasonal storage (CSHPSS) systems in New England. This study grew out of an earlier investigation of a solar heating system utilizing available tankage at the Charlestown Naval Yard, a historical park maintained by the National Park Service, as the STES element. (The National Park Service has indicated its interest in cofunding the necessary engineering feasibility study of such a system when funding is available.)

The most expensive part of a solar space heating system is the collector. Meeting winter heating needs in northern climates is particularly costly because solar insolation is at its lowest when demand is at its highest. Hence, a large collection area is needed to meet winter heating needs. During the summer most of this collection area goes unused. This mismatch between seasonal demand and availability is what STES is designed to resolve. Use of STES dramatically reduces collection area requirements, making solar space heating systems more cost-effective.

The results of the New England solar/STES assessment were encouraging. Because of the expected paucity of suitable aquifers, rock mass thermal storage using multiple boreholes was evaluated as the preferred storage option. Cost estimates were developed from earlier IEA assumptions and confirmed or altered following contact with local vendors. A base case economic scenario was developed and applied to a matrix of design variations. It was concluded that such systems would be cost-effective now in New England. The economic promise of the systems was found to vary with the economic assumptions. Unfavorable economic conditions meant loss of economic advantage for the solar/STES systems relative to conventional technology. The addition of current Federal Energy Tax Credits and favorable funding alternatives (such as tax exempt municipal bonds) improved the cost-effectiveness of the solar/STES systems. The major uncertainties in the assessment were the collector cost and the suitability of the local geology for rock borehole STES. The geology becomes a major issue when there is significant secondary regional flow through fractures within the storage zone. Thus, site geologic suitability is an important factor requiring early assessment. A final report on this study is in preparation.

3.2.3 Zeolite-Augmented Ice Storage

The generation of ice during winter to provide summer air conditioning has been investigated and appears to be a cost-effective option only in the extreme northern regions of the country. One method to reduce the amount of ice required to meet the summer cooling load is to use the heat of sublimation rather than merely the heat of fusion to provide cooling. This would increase the amount of cooling per pound of ice by a factor of eight. In 1983 the New Mexico Solar Energy Institute (NMSEI) was contracted to construct and test a system that would utilize zeolites as a water vapor adsorber combined with a solar collector and evaporative cooling units for system heating and auxiliary cooling.

Testing was conducted primarily in the late winter and spring of 1984. The system and results of that testing are summarized in the UES Program Summary covering the period from April 1983 through March 1984 (Kannberg 1984). Since that time the final report on this work has been published and a related Master's thesis has been prepared (not funded by PNL) addressing the potential for utilizing other adsorbents (Humphrey 1985).

As noted in the last UES Annual Summary (Kannberg 1984), the testing at NMSEI has proved the concept to be feasible, but significant technical and economic issues are evident. The system, as configured for the testing, had substantial parasitic energy requirements. These requirements might be greatly reduced if other adsorbents were used or developed. Because water vapor flows at low pressure in the system, high vapor flow rates are necessary. However, these high flow rates were not a limiting factor in the testing. Substantial improvements in system performance are possible from both improved system design and the use of alternative or improved adsorbents.

No additional study has been undertaken since the completion of the final project report (Redman 1985). However, a workshop on utilization of adsorbents in systems providing chill for air conditioning is being considered.

3.3 INTERNATIONAL STES ACTIVITIES

Seasonal thermal energy storage is being studied in many European and Scandinavian countries, as well as in North America. Several of these nations have major commercial demonstration projects installed, under construction, or on the drawing boards. Many of these projects are represented in one or the other of two IEA programmes involving STES in which DOE participates.

Six types of STES are being investigated by IEA participants under Task VII, "Central Solar Heating Plants with Seasonal Storage (CSHPSS)", as part of the Solar Heating and Cooling Programme. These include storage in tanks, pits, caverns, aquifers, earth, and rock. Active projects are underway in Canada, Denmark, France, Germany, Sweden, Switzerland, and The Netherlands. The choice of storage type is strongly influenced by the geology characteristic of the country. Thus, Swedish projects have concentrated primarily on rock and cavern storage, although aquifer storage is also being investigated. West Germany has concentrated on pit and tank STES, and The Netherlands is exploring earth STES. This does not mean that other types of STES are not possible; rather, conditions are not widely suited for all types. (A recent study indicated that 18% of the annual Swedish heating requirements could be met with aquifer STES.) All of these storage modes show promise for particular terranes and economic situations.

Some of the projects already are, or soon will be, supplying energy to sizable loads. At Lulea, Sweden, preliminary studies of rock thermal storage were completed in 1981. A system for supplying seasonally stored solar energy to a university building went into operation in the summer of 1983. The STES system will store about 2 GWh of energy and is expected to have a storage efficiency of 60%. Beginning last winter at Lyckebo, Sweden, solar heat stored in a 100,000-m^3 (3,530,000 ft^3) water-filled uninsulated rock cavern will supply heat to 550 houses through a local district heating network. At Lambohov, Sweden, solar/STES with heat pumps will supply heat to 55 terrace homes from a 10,000-m^3 (353,000 ft^3) excavated pit. At Studsvik, Sweden, a 10,000-m^3 (353,000-ft^3) pit STES system provides year-round heating to a nearby office building. The Studsvik facility is unique because the floating insulated lid of the storage pit is mounted with compound parabolic solar collectors and rotates to track the sun. After several years of study, an earth storage system is being installed at Groningen, The Netherlands, for heating 100 solar houses. Canada has investigated the use of aquifers for both heat and chill storage and has installed a solar heat storage system in a Government of Canada building in Scarborough near Toronto. Canadian researchers have also been active in developing ice storage concepts and plans to commercially implement the "Fabrikaglace" concept of ice storage at two

Canadian sites. Numerous other pilot projects and demonstrations are underway throughout the world. Researchers in India, Poland, Peoples Republic of China, and Japan, as well as Europe, Scandinavia and North America, are studying STES systems.

The U.S. is participating in another IEA effort, Task III, "Aquifer Storage Demonstration Plant in Lausanne-Dorigny, and Associated Projects", under the Energy Conservation Through Energy Storage Programme. The U.S. is providing information on the U.S. ATES projects in exchange for data concerning the performance of the Danish Horsholm project, and the Swiss SPEOS (Dorigny) project. The Horsholm project is of special interest because it is an ATES system integrated into a district heating system on a commercial basis, and because it uses a five spot well configuration (as opposed to the doublet configuration selected for study in this country). Data exchange from all of these projects enriches the programs of all the countries. It is interesting to note that both Switzerland and Denmark have major demonstration projects in other types of STES systems: a 3500-m^3 (123,550-ft^3) solar/earth STES system near Vaulruz, Switzerland, and a 49,400-m^3 (1,743,820-ft^3) excavated pit STES system at Hjortekear, Denmark.

There is considerable international activity in STES. The DOE is a participant in that activity, sharing information on the performance and problems of the various projects and technologies.

REFERENCES

Blair, S. C., W. J. Deutsch and P. J. Mitchell. 1985. Permeability, Geochemical, and Water Quality Tests in Support of an Aquifer Thermal Energy Storage Site in Minnesota. PNL-5438. Pacific Northwest Laboratory, Richland, Washington.

Humphrey, M. A. 1985. Comparison of Water Vapor Adsorption at Room Temperature of Silica, Alumina, and Silica-Alumina Precipitates. M.S. Thesis, New Mexico State University, Las Cruces, New Mexico.

Kannberg, L. D. 1984. Underground Energy Storage Program 1983 Annual Summary. PNL-5127. Pacific Northwest Laboratory, Richland, Washington.

Kannberg, L. D., et al. 1981. Annual Report for 1980 - Compressed Air Technology Program. PNL-3804, Pacific Northwest Laboratory, Richland, Washington.

Kannberg, L. D., et al. 1982. Annual Report for 1981 - Compressed Air Technology Program. PNL-4281, Volumes I and II, Pacific Northwest Laboratory, Richland, Washington.

Kannberg, L. D., et al. 1983. Underground Energy Storage Program 1982 Annual Report. PNL-4735, Pacific Northwest Laboratory, Richland, Washington.

Kreid, D. K., and M. A. McKinnon. 1978. FY-1977 Progress Report Compressed Air Energy Storage Advanced System Analysis. PNL-2464, Pacific Northwest Laboratory, Richland, Washington.

Loscutoff, W. V., et al. 1979. Pacific Northwest Laboratory Annual Report for 1978 to the DOE Division of Energy Storage Systems - Compressed Air Energy Storage Technology Program. PNL-2935, Pacific Northwest Laboratory, Richland, Washington.

Loscutoff, W. V., et al. 1980. Compressed Air Energy Storage Technology Program Annual Report for 1979. PNL-3395, Pacific Northwest Laboratory, Richland, Washington.

Minor, J. E. 1980. Seasonal Thermal Energy Storage Program Progress Report April 1979 - December 1979. PNL-3322, Pacific Northwest Laboratory, Richland, Washington.

Minor, J. E. 1981. Seasonal Thermal Energy Storage Program Progress Report January 1980 - December 1980. PNL-3746, Pacific Northwest Laboratory, Richland, Washington.

Redman, C. M. 1985. Experimental Testing of Cooling by Low Pressure Adsorption in a Zeolite. PNL-5365, Pacific Northwest Laboratory, Richland, Washington.

Smith, G. C., et al. 1978. FY-1977 Progress Report - Stability and Design Criteria Studies for Compressed Air Energy Storage Reservoirs. PNL-2443, Pacific Northwest Laboratory, Richland, Washington.

DISTRIBUTION

No of Copies

OFFSITE

US Department of Energy
Attn: J. Brogan
Office of Energy Systems Res.
Forrestal Bldg, CE-141 5E-052
Washington, DC 20585

US Department of Energy
Attn: I. Gyuk
Office of Energy Systems Res.
Forrestal Bldg, CE-141 5E-052
Washington, DC 20585

US Department of Energy
Attn: R. Shivers
Office of Energy Systems Res.
Forrestal Bldg, CE-141 5E-052
Washington, DC 20585

US Department of Energy
Attn: Director, Policy and Planning
Office of Conservation and Solar Applications
Washington, DC 20545

30 DOE Technical Information Center
U.S. Department of Energy
P.O. Box 62
Oak Ridge, TN 37830

Argonne National Laboratory
Solar Thermal Storage Program
Attn: A. Michaels
Building 362
9700 S. Cass Avenue
Argonne, IL 60439

Auburn University
Attn: F. J. Molz
School of Engineering
Auburn, AL 36830

No of Copies

GeoTrans Inc.
Attn: J. W. Mercer
PO Box 2550
Reston, VA 22090

Walter Hausz
4520 Via Vistosa
Santa Barbara, CA 93110

Lawrence Berkeley Laboratory
Attn: C. F. Tsang
University of California
Bldg. 90, Room 1012-H
1 Cyclotron Road
Berkeley, CA 94720

Lawrence Livermore Laboratory
Attn: J. Yow
PO Box 808
Mail Stop L-202
Livermore, CA 94550

Lawrence Livermore Laboratory
Attn: Tech. Info. Dept, L-3
University of California
PO Box 808
Livermore, CA 94550

Charles F. Meyer
1141 Cima Linda Lane
Santa Barbara, CA 93108

Minnesota Geological Survey
Attn: M. Hoyer
2642 University Avenue
St. Paul, MN 55114-1057

Minnesota Geological Survey
Attn: M. Walton
2642 University Avenue
St. Paul, MN 55114-1057

No of Copies

New York State Energy
Research & Development
Agency
Attn: Director
Rockefeller Plaza
Albany, NY 12223

New York State Energy
Research & Development
Agency
Attn: G. Walmet
Rockefeller Plaza
Albany, NY 12223

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

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

Charles Redman
4500 Panorama
Las Cruces, NM 88001

Rocket Research
Attn: L. B. Katter
York Center
Redmond, WA 98052

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

Sandia Laboratories
Technical Library Div. 3141
Albuquerque, NM 87185

No of Copies

Sandia Laboratories
Attn: R. O. Woods
Organization 4715
Albuquerque, NM 87115

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

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

Tennessee Valley Authority
Attn: W. Waldrop
Asst. Branch Chief
Water Systems Develop. Branch
Division of Water Management
PO Drawer E
Norris, TN 37828

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

University of Minnesota
Attn: S. Richards
Physical Plant Operations
University of Minnesota
200 Shops Building
319 15th Avenue S.E.
Minneapolis, MN 55455

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

No of
Copies

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

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

FOREIGN

Bengt Hidemark Gosta Danielson Arkitekter SAR
Attn: A. Boysen
Jarntorget 78
S-11 29 Stockholm
Sweden

Public Works of Canada
Attn: E. L. Morofsky
C456 Sir Charles Tupper Bldg.
Riverside Dr. and Heron Rd.
Ottawa, Ontario
K1A 0M2 Canada

No of
Copies

ONSITE

DOE Richland Operations Off.

H. E. Ransom/D. R. Segna

35 Pacific Northwest Laboratory

L. D. Kannberg (25)
P. J. Mitchell
J. R. Raymond
L. Vail
Technical Information (5)
Publishing Coordination (2)