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Underground Energy Storage Program

1983 Annual Summary

June 1984

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

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UNDERGROUND ENERGY STORAGE PROGRAM

1983 ANNUAL SUMMARY

L. D. Kannberg

June 1984

Prepared for
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Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This is the 1983 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 extending from April 1983 through March 1984.

The report summarizes the activities and notable progress toward program objectives in both Seasonal Thermal Energy Storage (STES) and Compressed Air Energy Storage (CAES). 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 the STES and CAES technologies.

L. D. Kannberg, Manager
Underground Energy Storage Program

ACKNOWLEDGMENTS

Progress achieved during the April 1983 through March 1984 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; 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 and engineers include S. C. Blair, J. R. Raymond, L. Vail, R. D. Allen, T. J. Doherty, and R. L. Erikson.

D. Segna, U.S. Department of Energy, Richland Operations Office and I. Gyuk, U.S. Department of Energy, Washington, D.C. Headquarters 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 1983 through March 1984 are briefly described. Primary activities in seasonal thermal energy storage (STES) involved field testing of high temperature (>100°C) aquifer thermal energy storage (ATES) at St. Paul, laboratory studies of geochemical issues associated with high temperature ATES, monitoring of a chill ATES facility in Tuscaloosa, studies of STES in abandoned mines, and STES linked with solar energy collection. The scope of international activities in STES is briefly discussed. Activities in compressed air energy storage (CAES) were confined to monitoring and reviewing technical progress at the Pittsfield Aquifer Test (PAT) in support of the Electric Power Research Institute's PAT Technical Review Committee.

Four short cycles of ATES testing have been completed at the St. Paul Field Test Facility (FTF). The last three cycles were completed during the reporting period. Results of the tests are promising. A fluid volume (equal to that injected) was recovered after injection at successively higher temperatures. 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. Calcium carbonate precipitation was controlled by use of a specially constructed reactor bed installed in the surface facilities. Longer-term tests are planned for initiation in the summer of 1984.

Laboratory testing has shown that the intrinsic permeability of sandstone core will be reduced as temperature is increased, although such behavior has not been obvious during testing at St. Paul. Examination of St. Paul FTF filters indicates that the injectability of the water improves with successive cycles. Geochemical models based on laboratory-derived reaction rate coefficients were reasonably accurate in predicting important groundwater chemistry changes, although the geochemical data base for many minerals is very incomplete and concentrations of some groundwater chemical constituents were unpredictable.

Development of two simple numerical models was completed during the reporting period, and the sophisticated PT model was used to simulate testing at the Mobile Field Test Facility. One simple model (UCATES) is applicable to unconfined ATES but is limited because of its relatively crude boundary heat transfer simulation. The other model (AFM) is applicable to multiple-well confined ATES systems. These models were tested against available closed-form solutions but have not been verified against field data. The PT code was applied by Lawrence Berkeley Laboratory to the third cycle test at the Mobile FTF. Predicted recovery efficiency agreed well with field results but poorer agreement was obtained for recovery temperature history.

Monitoring of a chill ATES facility at the Parisian Department Store has been frustrated by numerous lapses in operating system controls and in data acquisition. Limited corrective measures have been taken and further monitoring is underway. Despite these monitoring and control problems the system has provided a substantial amount of cooling during the summer, replacing one of the two conventional chillers.

A preliminary study of STES in abandoned mine caverns at Ely, Minnesota, was completed and initial steps are underway to utilize the thermal energy currently in the mine for heat pumping. Eventually solar or waste heat may be used to charge the mine with warm water for STES. The stored heat would be used with a heat pump to supply heat to the local community college and possibly a district heating system for the town of Ely. Such a system is now being carefully studied by the city under a state energy grant.

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 preliminary study of clathrate hydrates for use independently or in conjunction with conventional ice STES was completed by Argonne National Laboratory. Several candidate clathrate hydrates were identified; however, relatively high material and tankage costs indicate that their use for STES is probably uneconomic for the foreseeable future. Additional study of clathrate hydrates, primarily for diurnal thermal storage, is being sponsored by Oak Ridge National Laboratory.

Studies of STES with solar energy collection for district heating were supported. These studies concentrated on using abandoned underground tanks for STES at the Charlestown, Boston Navy Yard Historical Park. 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 researchers, program and DOE staff participated in the successful International Conference on Subsurface Heat Storage in Theory and Practice, held in Stockholm, Sweden, in June 1983. The conference was organized by the Swedish Building Research Council in cooperation with DOE and the National Research Council of Canada. Wide international interest in STES technology was evidenced at this conference. 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.

Pacific Northwest Laboratory monitored the progress of the Pittsfield Aquifer Test of CAES on behalf of DOE. The field test had been transferred from DOE sponsorship to the Electric Power Research Institute in February 1983. In cooperation with DOE, EPRI will report detailed results of the test as well as the final porous media CAES reservoir stability criteria at a later date.

CONTENTS

PREFACE . . . iii

ACKNOWLEDGMENTS. . . . v

SUMMARY . . . vii

FIGURES . . . xiii

TABLES . . . xiv

1.0 INTRODUCTION . . . 1.1

2.0 UNDERGROUND ENERGY STORAGE PROGRAM . . . 2.0

2.1 APPROACH . . . 2.1

2.2 HISTORICAL SCOPE AND MILESTONES . . . 2.3

2.3 RESOURCE REQUIREMENTS . . . 2.6

3.0 SEASONAL THERMAL ENERGY STORAGE . . . 3.1

3.1 ATES TECHNOLOGY STUDIES . . . 3.2

3.1.1 St. Paul Field Testing . . . 3.2

3.1.2 Parisian Department Store Chill ATES Monitoring . . . 3.6

3.1.3 Laboratory Testing and Field Analyses . . . 3.8

3.1.4 Numerical Modeling of ATES . . . 3.11

3.2 STES TECHNOLOGY ASSESSMENT AND DEVELOPMENT . . . 3.13

3.2.1 STES in Caverns at Ely, Minnesota . . . 3.13

3.2.2 Solar/STES at the Charlestown, Boston Navy Yard . . . 3.16

3.2.3 Passive Chill STES with Clathrates . . . 3.17

3.2.4 Zeolite-Augmented Ice Storage . . . 3.19

3.3 INTERNATIONAL STES ACTIVITIES . . . 3.21

4.0 COMPRESSED AIR ENERGY STORAGE . . . 4.1

REFERENCES . . . R.1

FIGURES

2.1 Department of Energy Programs to Pursue Development of Underground Energy Storage 2.2

2.2 Department of Energy Seasonal Thermal Energy Storage Program History 2.4

2.3 Department of Energy Compressed Air Energy Storage Research History 2.5

2.4 Underground Energy Storage Program Structure 2.7

2.5 Major Department of Energy Milestones 2.8

2.6 Funding History of the Underground Energy Storage Program . . 2.9

3.1 Test Cycles I-IV - Flow Rates and Temperatures of Heated Water Injected and Recovered, Plotted Against Time 3.5

3.2 Recovery Temperatures Versus Time for Test Cycles I Through IV 3.6

3.3 Calcite Precipitation as a Function of Temperature at the St. Paul FTF 3.8

3.4 Permeability Versus Temperature for High Temperature Test 3.9

3.5 Production and Rejection Temperatures Versus Time for the Third Cycle 3.12

3.6 The Pit (Miner's Lake) and Principal Mine Shafts North of Ely, Minnesota 3.14

3.7 Isometric Drawing Showing Cross Sections Through the Principal Workings in the Thickest Part of the Ore Body. . . . 3.15

3.8 Solar Zeolite-Augmented Ice STES Test Schematic 3.20

TABLES

3.1 Key Parameters for the Short-Term Cycles at the University of Minnesota ATES Field Test Facility 3.4

3.2 Energy Performance Data for the Parisian ATES Chill System . . 3.7

3.3 Candidate Congruent Clathrate Hydrates for STES 3.19

3.4 Summary of Energy Flows for Zeolite-Augmented Ice STES . . . 3.21

UNDERGROUND ENERGY STORAGE PROGRAM
1983 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 entrepreneurial 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 (STES) 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 United States. Many potential energy sources exist for use in an aquifer thermal energy storage 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 to over 250°C are available for heating. Potential energy uses include individual- or district-scale space heating, industrial or institutional plant heating, and heat for processing/manufacturing. Recent studies and small-scale field experiments have reported energy recovery ratios above 60% for seasonal storage and 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.

Compressed air energy storage (CAES) is a technique for supplying electric power to meet peak load requirements of electric utility systems. It incorporates a modified state-of-the-art gas turbine and an underground reservoir--an aquifer, a salt cavity, or a mined hard rock cavern. The compressor and turbine sections of the gas turbine are alternately coupled to a motor/generator. During nocturnal and weekend off-peak periods, low-cost power from base load plants using coal or nuclear fuels would be used to drive motors to compress air, which would be stored in the underground cavern. During the subsequent diurnal peak-load periods, the compressed air would be withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. This concept reduces the consumption of premium fuels by more than 60% for conventional combustion turbine systems. Some advanced CAES concepts would require no petroleum fuels.

In 1975, the Pacific Northwest Laboratory (PNL) was selected as DOE's lead laboratory in researching and developing CAES technology. Comparable efforts in the STES area 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.

This report documents the work performed and progress made toward resolving and eliminating technical and economic barriers associated with the STES and CAES technologies. The reporting period extends from April 1983 to March 1984. Work performed prior to April 1983 was documented in previous annual reports (Smith et al. 1978; Kreid and McKinnon 1978; Loscutoff et al. 1979; Loscutoff et al. 1980; Kannberg et al. 1981; Minor 1980; Minor 1981; Kannberg et al. 1982; Kannberg et al. 1983). 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. In Section 4.0, CAES efforts are similarly described.

2.0 UNDERGROUND ENERGY STORAGE PROGRAM

The U.S. Department of Energy (DOE), operating through its Pacific Northwest Laboratory (PNL), established a program to encourage the timely implementation of underground energy storage 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.

Pacific Northwest Laboratory, operated for DOE by Battelle Memorial Institute, was selected as lead laboratory to investigate two concepts--STES and CAES--having strong potential for contributing to this goal. The lead laboratory assignment included responsibility for development and management of programs in both 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 Underground Energy Storage (UES) Program.

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.

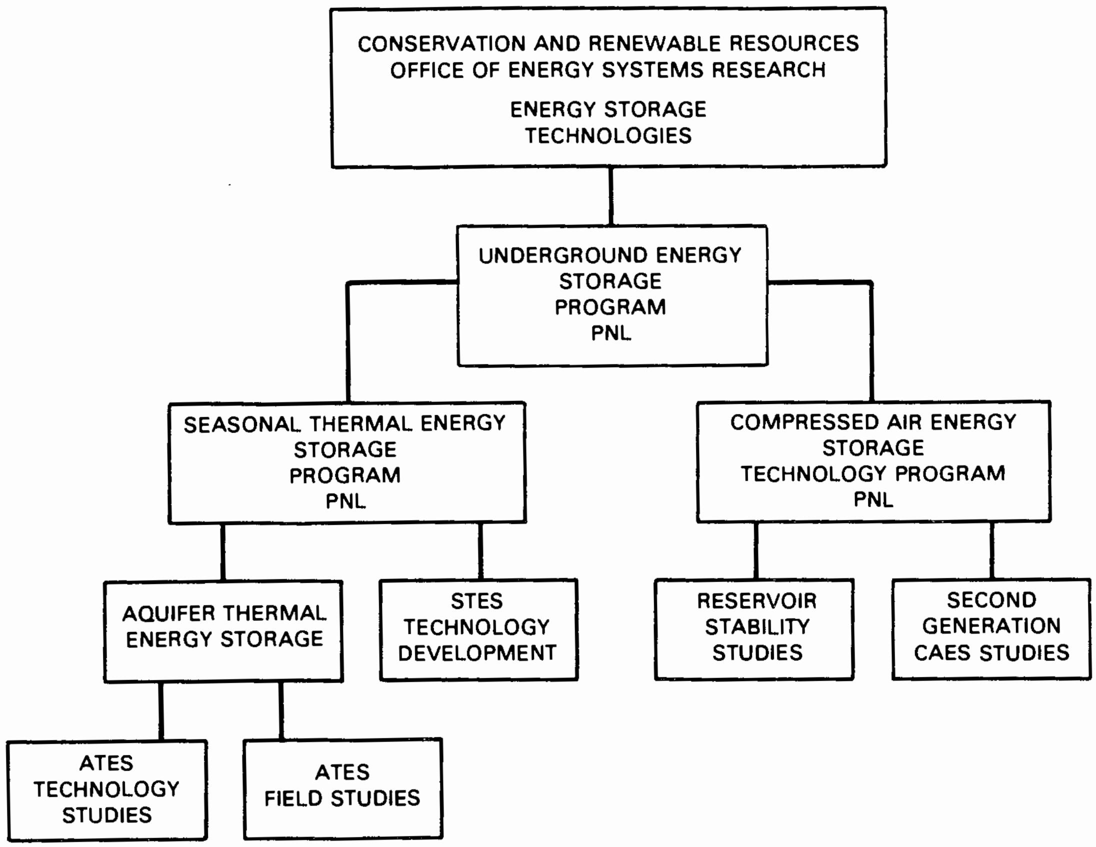

FIGURE 2.1. Department of Energy Programs to Pursue Development of Underground Energy Storage

- 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.
- The economic character of STES methods has not been well characterized 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 not typically 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. Aquifer thermal energy storage (ATES) therefore became the prime technology for study in the STES Program.

For conventional CAES systems, a key factor was long-term underground reservoir stability. To provide the utilities with a high degree of confidence in the CAES concept, it was necessary to pursue a comprehensive technology research and development program to establish guidelines for CAES reservoir design. Another potential deterrent to CAES technology commercialization is the dependence of CAES plants on petroleum fuels. Thus, it was necessary to identify and examine second-generation CAES concepts, which are less reliant on petroleum fuels.

2.2 HISTORICAL SCOPE AND MILESTONES

The historical scope of the DOE-sponsored STES and CAES studies is shown in Figures 2.2 and 2.3, respectively. 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 program 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.

In 1975, DOE-sponsored studies in CAES began. A well-defined program was initiated to establish reservoir stability criteria and develop second-generation CAES systems. The reservoir stability studies received the bulk of

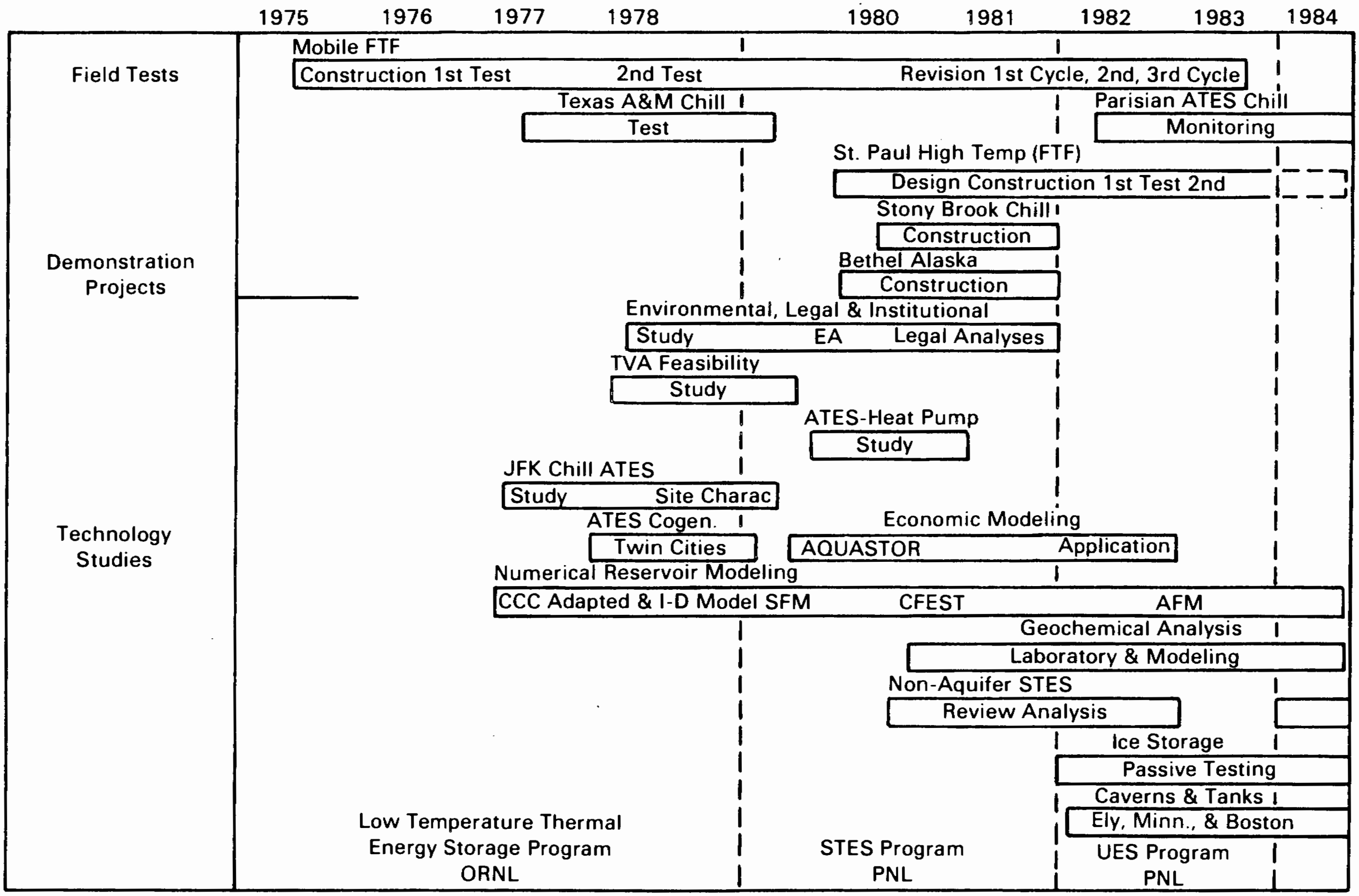

FIGURE 2.2. Department of Energy Seasonal Thermal Energy Storage Program History

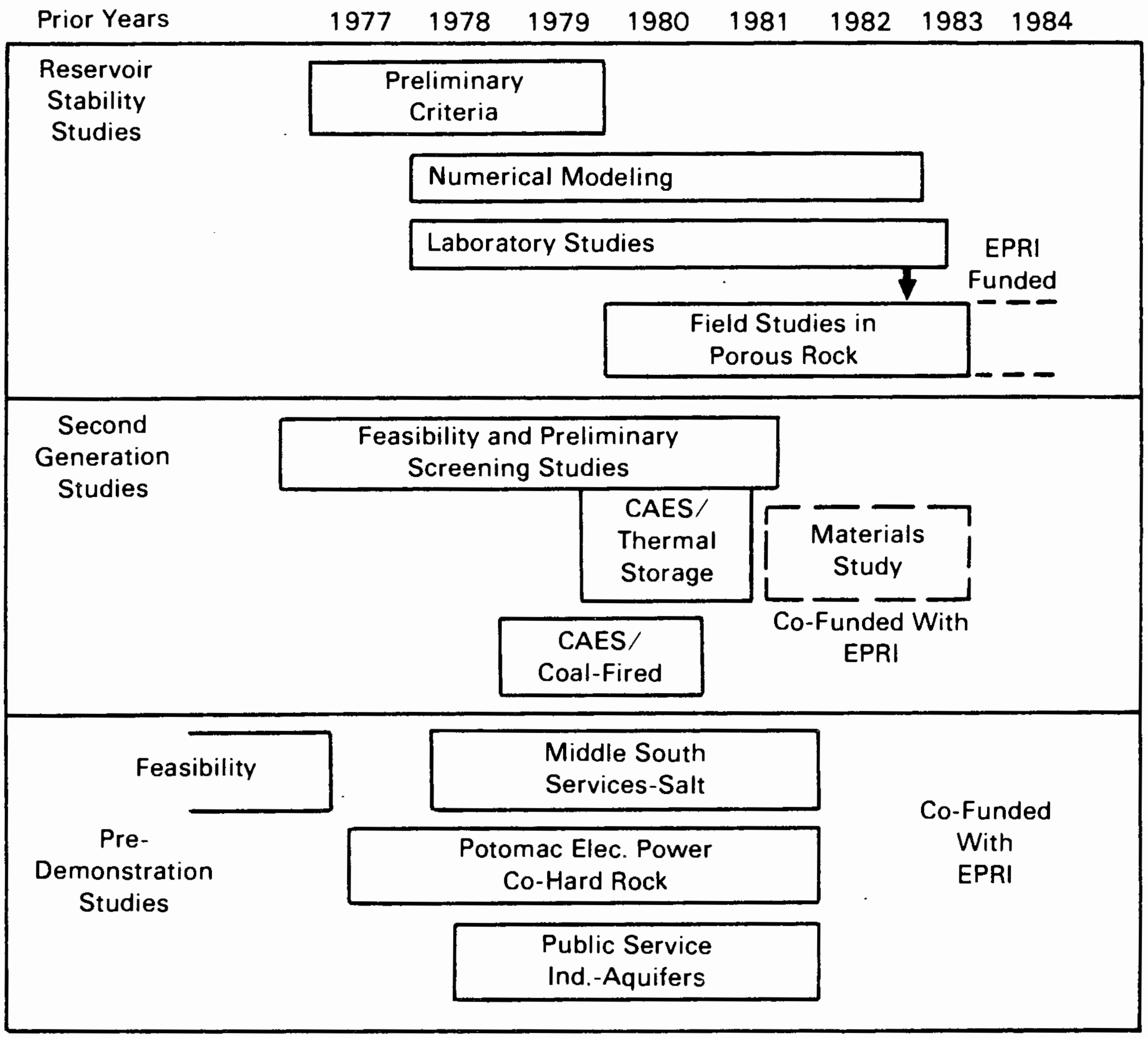

FIGURE 2.3. Department of Energy Compressed Air Energy Storage Research History

the support because of the timely need to develop such criteria. Reservoir stability studies included numerical modeling, laboratory studies, and, for porous media, field testing. Second-generation CAES studies included preliminary concept screening, conceptual design, and study of critical components. Virtually all DOE-sponsored CAES research was closed out prior to this reporting period. More detail on both CAES and STES projects conducted in preceding years can be found in earlier program annual reports.

The major UES projects conducted in 1983 are indicated in Figure 2.4. It is the policy of the Energy Storage Technologies Division of DOE to select the few critical milestones for tracking progress in the various programs. These milestones for the UES Program are shown in Figure 2.5. Only two major DOE milestones were encountered during the reporting period. The transfer of the CAES Pittsfield Aquifer Field Test to EPRI took place 1 month ahead of the milestone date when DOE funding for the work expired. The completion of short-term cycles at St. Paul occurred 3 months later than the milestone date due to operating equipment malfunctions and the addition of another short cycle to the planned testing schedule.

2.3 RESOURCE REQUIREMENTS

The historical funding requirements for STES and CAES are shown in Figure 2.6. Historically, funding has been substantially higher than current levels. The current scope of activities stresses elimination of CAES R&D, more cost-sharing in STES field activities, and reduced investigation of STES economics, system behavior, and new STES concepts.

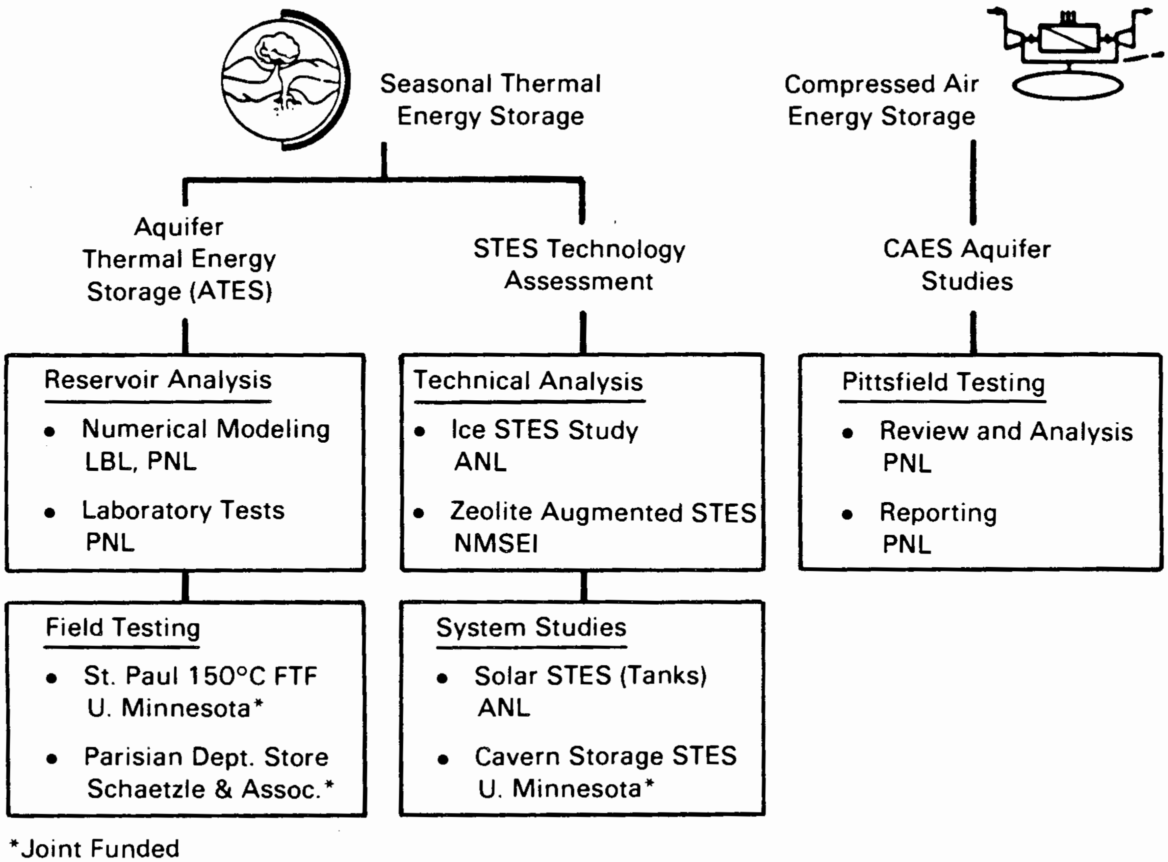

FIGURE 2.4. Underground Energy Storage Program Structure

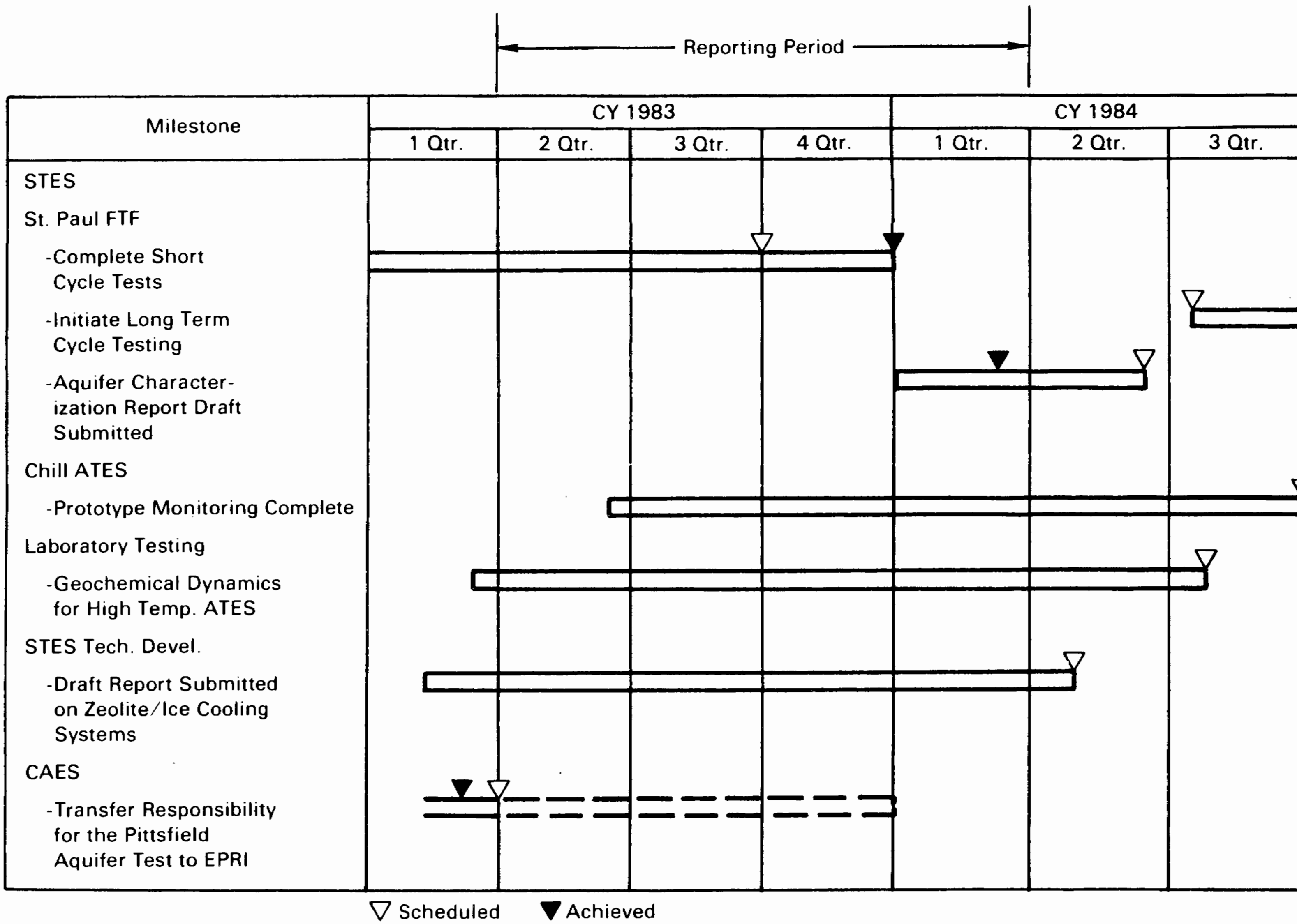

FIGURE 2.5. Major Department of Energy Milestones

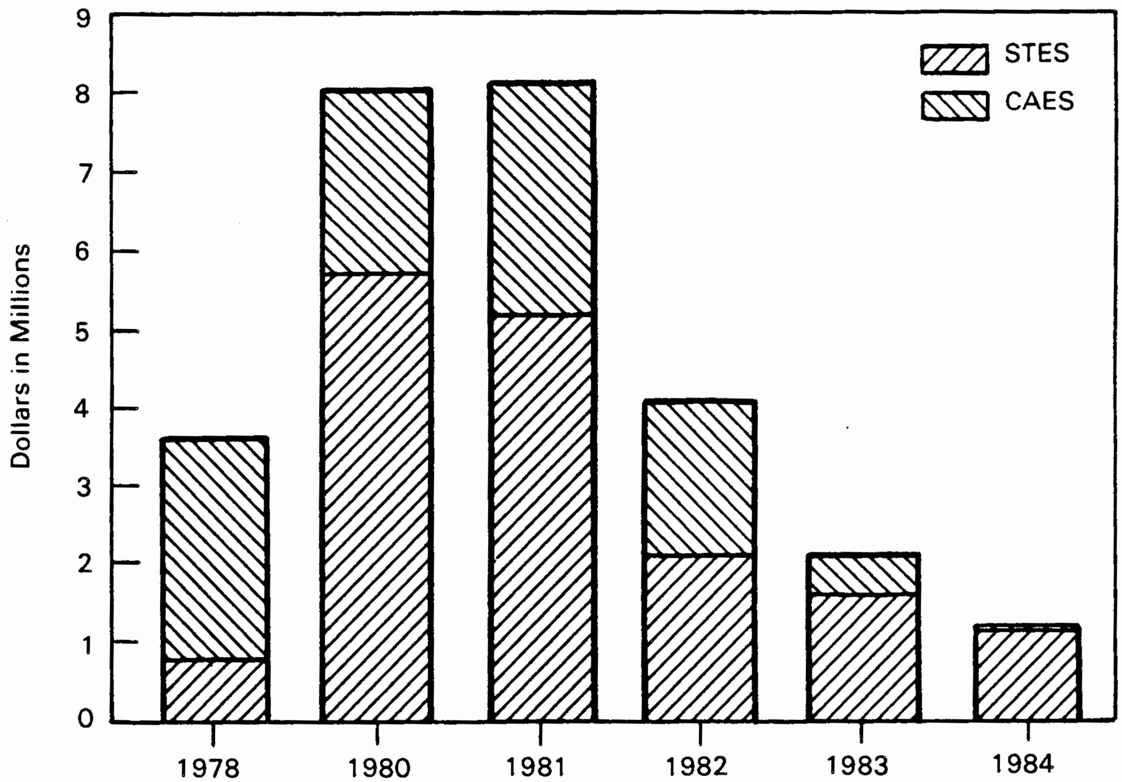

FIGURE 2.6. Funding History of the Underground Energy Storage Program

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, although the current projects include private parties 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, DOE-sponsored study of high temperature ATES (over 100°C) 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 all other STES concepts and economic analyses of all STES technologies. In the last 2 years the economic analysis element has been reduced to a very small effort.

The major activities of the STES Program are illustrated in Figure 2.4. 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 technical 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 65% of all STES funding in FY 1984. As such, field test activities will be discussed at greater length than other activities.

3.1.1 St. Paul Field Testing

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. Four short-term test cycles of heated water injection have been completed at the St. Paul FTF. The first two test cycles were delayed by calcium carbonate precipitation and pump shaft bearing failures, respectively. The remaining two test cycles were completed without incident. Completion of the short-term cycles marks the completion of the first phase of testing planned at the St. Paul site.

The first injection test with hot water (85°C) was started in May 1982 and was terminated after about 50 hours due to severe plugging by calcium carbonate precipitation in the well and heat exchangers. Backflushing the well was aborted when pump shaft bearings (synthetic rubber) failed in the hot water. A long delay ensued, during which a means of handling the carbonate precipitation problem was developed, the pump bearings were replaced, and the injection (production) well was restored by acid treatment.

Host aquifer water quality is very good at the St. Paul site, with about 230 ppm of dissolved solids (mostly Ca and Mg bicarbonate). However, when the water is heated, these solids, which display retrograde solubility (solubility decreases with increasing temperature), precipitate as scale on all available surfaces. While the potential for scaling was recognized early in the project, the magnitude was not. Subsequent calculations indicate that operation of the St. Paul FTF as designed could cause precipitation of over 175 kg of $CaCO_3$ daily.

Minnesota state regulations require a variance for injection of groundwater (or any other material) into aquifers. The permit obtained for the St. Paul project expressly prohibited the addition of chemicals to waters injected into the aquifer. This precluded use of conventional ion exchange water softening to control $CaCO_3$ precipitation. Therefore, water softening was accomplished without ion exchange by pumping the heated supersaturated ($CaCO_3$) water through a limestone reactor bed wherein calcium carbonate precipitated, bringing it substantially closer to chemical equilibrium. This precipitation in the heat exchanger and in the reactor bed necessitated frequent cleaning and replacement. No reduction in reservoir performance was observed during testing when the reactors were in use. Utilization of such a reactor bed was expedient for short-term test cycles but is not suitable for long-term operation.

The first short-cycle injection test was completed in December 1982. Key parameters of this and subsequent cycles are given in Table 3.1. In May 1983, the second short cycle injection was completed. After 10 days of storage, recovery was initiated. The bearings on the line shaft turbine failed as temperatures reached 80°C. After 90 days of delay, redesign, and installation of the line shaft bearing assemblies, fluid recovery was completed. The long storage period had reduced the energy storage efficiency substantially to 46%. The third and fourth cycles were completed in the fall of 1983 without incident. The temperatures of injection and recovery were increased each cycle. Figure 3.1 shows the injection and recovery flows and temperatures for Cycles I through IV (Walton et al. 1984). Figure 3.2 shows the recovery temperature histories for all of the four cycles (Walton et al. 1984).

Several features make the results of the St. Paul testing very promising for ATES. Relatively good recovery efficiencies have been obtained, even though

- relatively small volumes were injected (even considering the short storage periods)
- injection occurred into two primary hydraulic zones, which were widely separated

- the injection temperature was raised each time, minimizing the effectiveness of previous cycle preheating of the aquifer.

TABLE 3.1. Key Parameters for the Short-Term Test Cycles at the University of Minnesota ATES Field Test Facility

	Flow Rate (ℓ sec^{-1})	Mean Temperature (°C)	Volume Pumped (10^3 m^3)	Duration (Days)	Energy Recovery Factor[b]
Cycle I					
Injection	18.4	89.4	8.3	5.2	
Storage				13	0.59
Recovery	18.1	59.3	8.1	5.2/6	
Cycle II					
Injection	17.6	97.4	12.2	8[a]	
Storage				90	0.46
Recovery	17.8	55.2	12.3	8	
Cycle III					
Injection	18.3	106.1	12.2	7.7[a]	
Storage				9.7	0.62
Recovery	17.8	81.1	11.8	7.7	
Cycle IV					
Injection	17.9	114.8	11.9	7.7[a]	
Storage				10.1	0.58
Recovery	17.8	89.1	11.9	7.7	

(a) Net injection time (i.e., periods of maintenance not included).
(b) Thermal energy recovered above supply well temperatures divided by heat added during injection.

Longer-term tests are now being planned for St. Paul. These tests will involve 45 to 60 days each of injection, storage, and recovery, respectively (as compared to the 8 days of injection, storage, and recovery utilized in the short cycles). This is a five- to eightfold increase in the duration of the cycles. The application for a permit to conduct the longer-term tests that has been submitted to the Minnesota Pollution Control Agency includes a request for utilization of ion exchange water softening for control of calcium

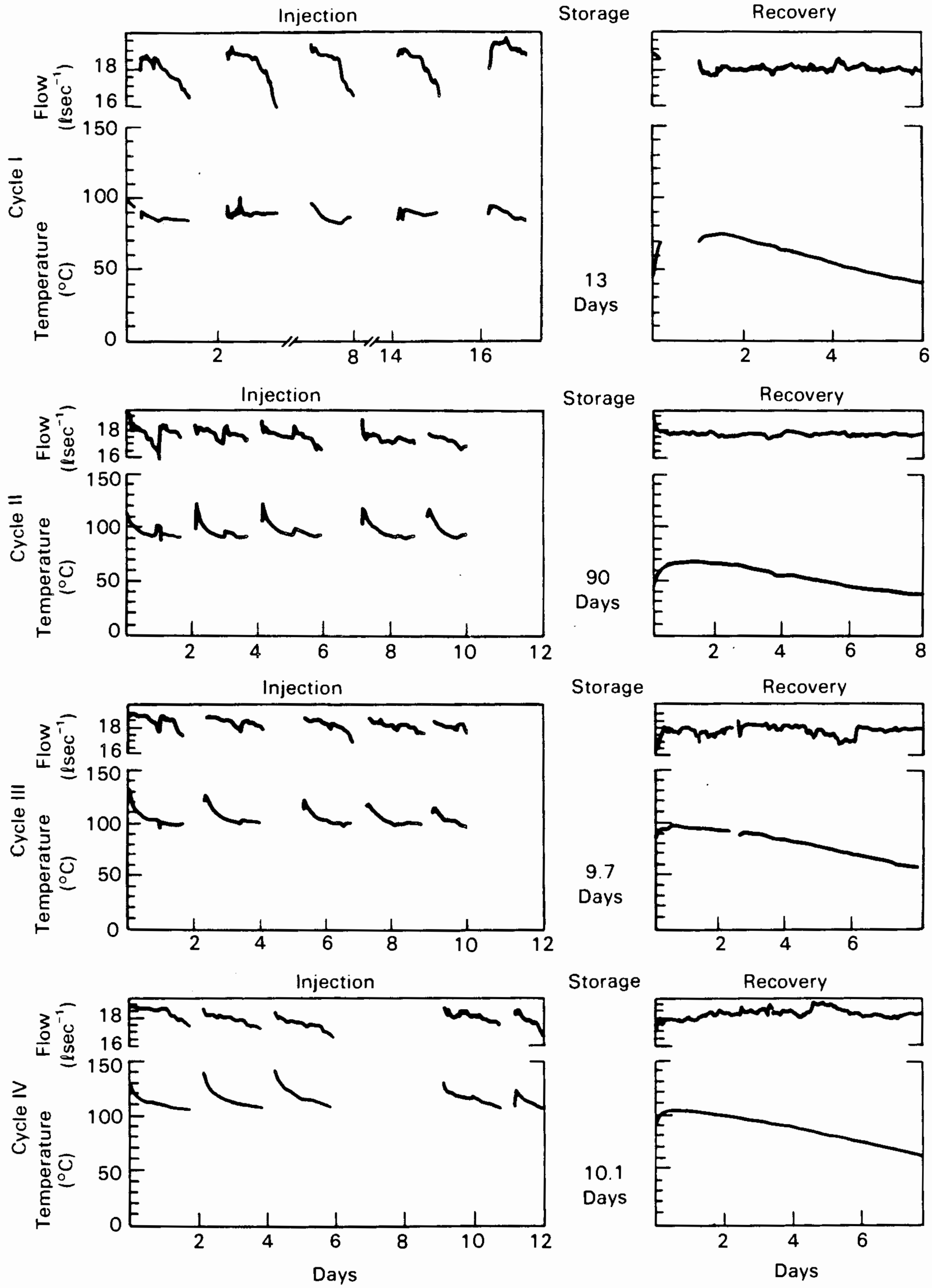

FIGURE 3.1. Test Cycles I-IV - Flow Rates and Temperatures of Heated Water Injected and Recovered, Plotted Against Time (Ordinate Scales for Recovery are the Same as Those for Injection)

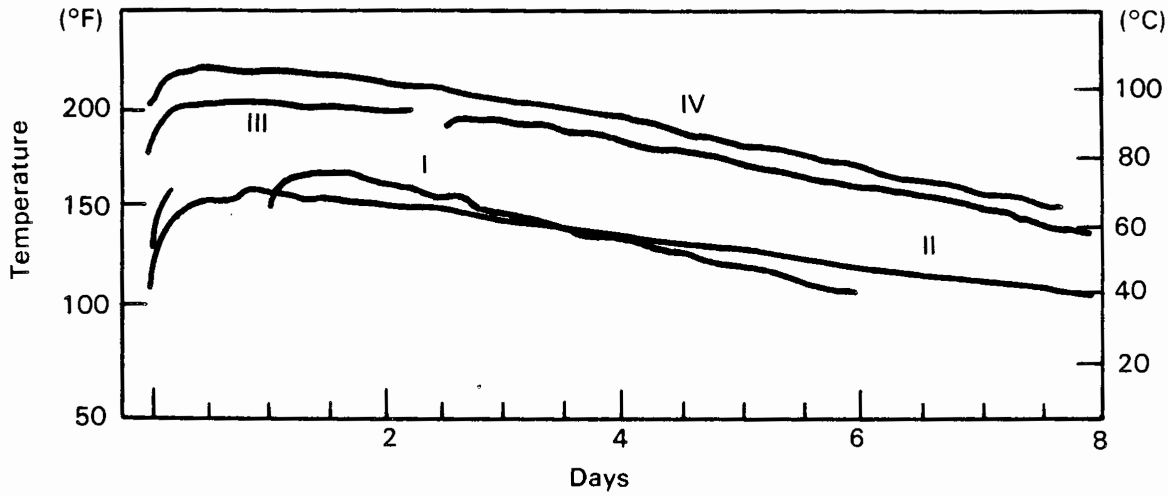

FIGURE 3.2. Recovery Temperatures Versus Time for Test Cycles I through IV

carbonate precipitation. If granted, this will allow the investigation of a popular calcium carbonate precipitation control technique at an ATES test facility. It will also allow assessment of reservoir geochemical reactions when ion exchange is used.

3.1.2 Parisian Department Store Chill ATES Monitoring

Schaetzle & Associates were contracted by PNL to monitor the energy performance of an ATES chill system installed by the contractor for air conditioning the Parisian Department Store in University Mall, Tuscaloosa, Alabama. The system uses a cooling tower during cold weather, below 47°F wet bulb temperature, to chill groundwater to an average 43°F. The cold water is stored in an unconfined aquifer and recovered as required for air conditioning on an annual basis. This contract provided for energy performance monitoring only. No reservoir in situ monitoring was conducted.

The store's temperature control system uses outside air for cooling, if the outside air temperature is sufficiently low, to hold the store at 70°F. If the temperature rises to 72°F, the aquifer system is activated. At 74°F the backup commercial chillers are started. The ATES system was not operational the first summer (1981) after the store opened and all cooling was performed with the commercial chillers.

Data for the several phases of annual operation of the ATES chill storage system are given in Table 3.2. Chill charging was started in the fall of 1981. Problems with overflowing wells and frozen pipes resulted in loss of operation in December and January. Chill charging was conducted from February through April. Energy recovery was started in May and was used the rest of the summer to precool the air before it entered the backup unit. In this capacity 40 tons of cooling were provided from groundwater pumped from the storage well.

TABLE 3.2. Energy Performance Data for the Parisian ATES Chill System

Mode	Operating Period	Volume Stored 10^6 gal	Electrical Energy 10^6 Btu	Chill Energy 10^6 Btu
Recovery	5/82 - 10/82	19.3	86.7	750
Charging	1/83 - 4/83	12	233	2018
Recovery	7/83 - 8/83[(a)]	6.6	30	273
Charging[(b)]	11/83 - 4/84	174 gpm	30.6 kW	1.5 x 10^6 Btu/hr

(a) Available data limited to the period prior to August 16, 1983.
(b) Data compilation incomplete. Only rate information available.

Delays in the repair to both the air conditioning and ATES system during the fall of 1982 resulted in the delay of initiating chill charging until January 1983. Additional system control problems and a warm winter further contributed to limiting the amount of chill entered into storage. Orifice installation and safety system leaks prevented initiation of chill storage recovery until July 12, 1983. Recovery temperatures were considerably warmer than anticipated and the operation of the aquifer storage system was again limited to precooling of air.

Injection well workover in the fall of 1983 resulted in a considerable increase in the performance of the wells. The system has operated well during the 1983-84 winter chill charging period and good performance is anticipated during the summer recovery.

It is interesting to note that a similar system installed at the University of Alabama has operated through its first year without problems and provided all the cooling to the University Recreation Building for which it was designed.

3.1.3 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) on-site core flooding and membrane filter tests performed in conjunction with the short-term cycling, and 3) geochemical analysis and modeling of chemical reactions in the aquifer system. Closely integrated studies are being performed at the University of Minnesota and at PNL. The importance of geochemical study was amply demonstrated by the $CaCO_3$ precipitation problem at St. Paul, a problem that is expected to be common to many sites. The magnitude of $CaCO_3$ precipitate at St. Paul as a function of temperature is illustrated in Figure 3.3.

Laboratory studies have concentrated on determining the effect of increased groundwater temperature on the permeability of aquifer core samples. Early data indicated that the permeability of sandstone aquifer core is reduced dramatically when heated groundwater is pumped through the samples.

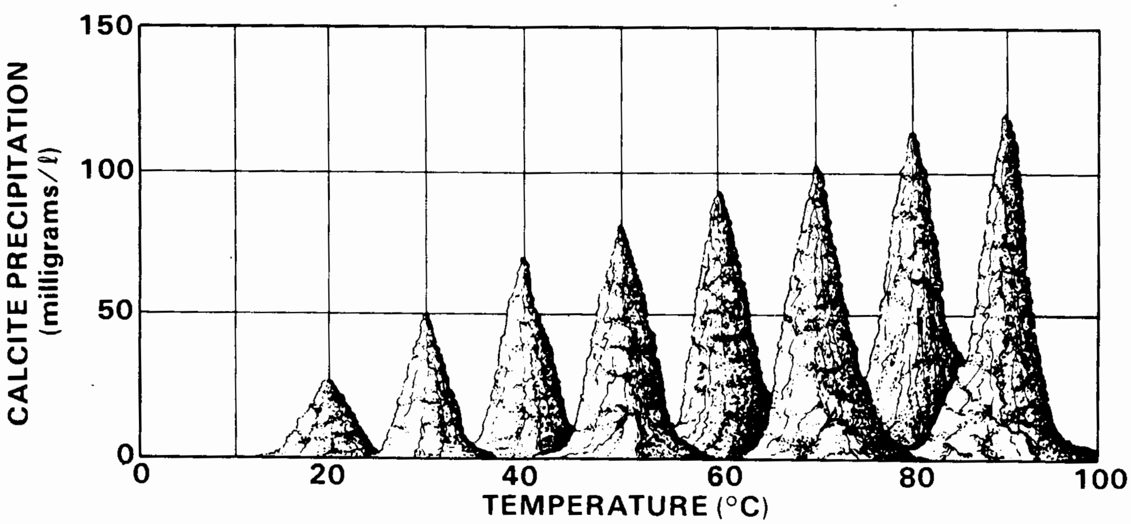

FIGURE 3.3. Calcite Precipitation as a Function of Temperature at the St. Paul FTF

The validity of these data was questioned when it was discovered that mechanical/chemical changes in the testing apparatus could have a significant effect on sample permeability (Stottlemyre, Cooley and Banik 1981). Recent laboratory tests on Ironton-Galesville core conducted under stringent conditions still indicated that permeability decreased significantly as temperature was increased. Such data are illustrated in Figure 3.4. However, the role of this phenomenon is uncertain because it may be confined to the more consolidated, less permeable portions of the Ironton-Galesville formation obtained from the St. Paul FTF site. Dissolution of the dolomite and silicate cementing agents was observed; this, as well as accompanying changes in mechanical properties, may occur in the host aquifer at St. Paul. Additional tests at ambient temperature to evaluate the effect of particle migration under conditions of reversed flow indicated that this process will not significantly impair formation permeability at the St. Paul site. This may indicate a lower limit to any deleterious effects of ATES in such aquifers. Although the roles of the various physicochemical process are not well characterized, it is important to note that no significant reduction in aquifer permeability has been observed during short-cycle testing at St. Paul.

Membrane filter tests and core flooding tests conducted in the Field Injectivity Test Stand (FITS) installed at the St. Paul FTF indicate that the

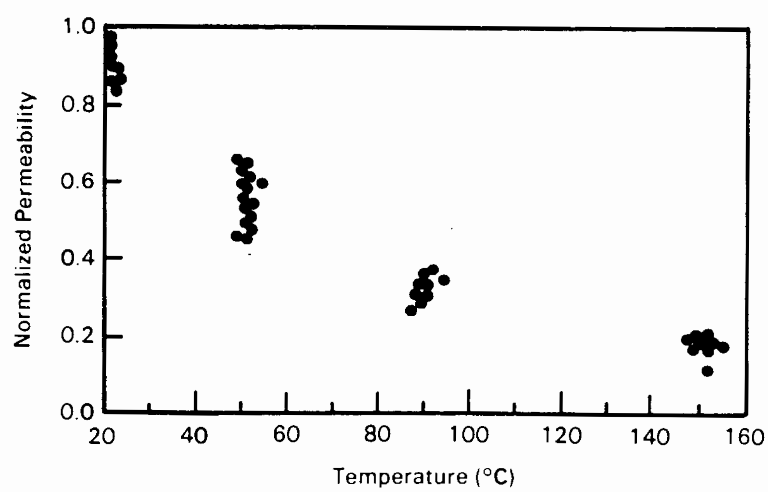

FIGURE 3.4. Permeability Versus Temperature for High Temperature Test (Blair, Deutsch and Kannberg 1984)

water quality improves with successive cycles, in terms of both hardness of recovered water and the core or filter plugging capability (i.e., injectability).

A series of batch laboratory tests was run at both PNL and the University of Minnesota using aquifer materials and typical injection waters at the St. Paul site. These tests concentrated on the evaluation of geochemical reactions and reaction rates. The materials most important in the experiments were Ca, Mg, and silica (SiO_2). The solid/fluid interactions behaved as anticipated, with $CaCO_3$ precipitating during heating and silica going into solution at detectable rates at temperatures above 110°C. In PNL tests at 150°C, Si and Mg reached minimum values after 5 to 10 hours. (It should be noted that the fluid to solid volume ratio is much higher in these tests than is typical of the reservoir.) Similar tests at the University of Minnesota resulted in determination of reaction rates indicating that, at temperatures above 110°C, the injected groundwater would become saturated with quartz (silica) during the short-term storage periods.

Water quality monitoring of the short-term tests was conducted by University of Minnesota researchers. As noted in Walton et al. (1984),

> Alkalinity and Ca concentrations and pH values of withdrawal waters followed a pattern in all short-term ATES tests that was consistent with quartz dissolution in all tests. Magnesium concentrations were lower in withdrawal waters than in injection waters, which implies precipitation of a magnesium-containing mineral. Potassium concentrations, on the other hand, increased during hot water storage, probably because of ion exchange. Sodium, sulfate, and fluoride were expected to be conservative and they were conservative in some tests. Chloride was expected to be conservative too, but chloride concentrations were consistently higher in withdrawal waters than in injection waters.
>
> A model assuming chemical equilibrium between quartz, calcite, and injection waters at withdrawal water temperatures showed good agreement between computations and actual analyses.

The use of models is very valuable in predicting geochemical reactions. However, the models are severely handicapped by the lack of data on the kinetics of geochemical reactions of interest for ATES, particularly at higher temperatures.

3.1.4 Numerical Modeling of ATES

Aquifer thermal energy storage numerical model development and utilization has been sponsored during the reporting period at a low level. Model analysis of the final Mobile, Alabama, field test cycle was completed by Lawrence Berkeley Laboratory (LBL) utilizing their sophisticated 3-dimensional model, PT, in an axisymmetric mode. The simple confined aquifer areal flow model (AFM) was completed at PNL and tested against closed-form analytic solutions with good agreement. The UCATES code, a limited simple model for unconfined ATES simulation, was completed and partially verified against analytic solutions.

Lawrence Berkeley Laboratory used PT to simulate the planned third cycle test at Mobile, Alabama. Comparison between the simulation and the actual system performance is shown in Figure 3.5. The third cycle test was conducted at the Mobile FTF in an attempt to optimize recovery at a site where buoyancy plagued efforts to gain high energy recovery efficiency at high temperatures. The field test employed injection in the top half of the aquifer and dual recovery from the bottom and top of the aquifer. Fluid recovered from the top of the aquifer was considered the production fluid and that taken from the bottom portion of the aquifer the rejection fluid. It was hoped that, by utilizing such an injection and recovery scheme, the effects of buoyancy could be mitigated. The simulation predicted a recovery ratio of 44%, agreeing well with the value of 42% obtained from the field test. However, typical of earlier comparisons of code predictions and field results, the predicted temperatures start higher and end lower than the field results. The predicted rejection fluid temperatures are consistently lower than those observed in the field. These results indicate that buoyancy flow may be overpredicted in the model.

The philosophy behind the development of the AFM model was to extend the computational scheme developed for the Steady Flow Model (developed by researchers at the Lund Institute in Sweden and LBL) from an axisymmetric single well to an areal, multiple well model. It was further desired to integrate this with simple operations equipment, such as a heat exchanger or

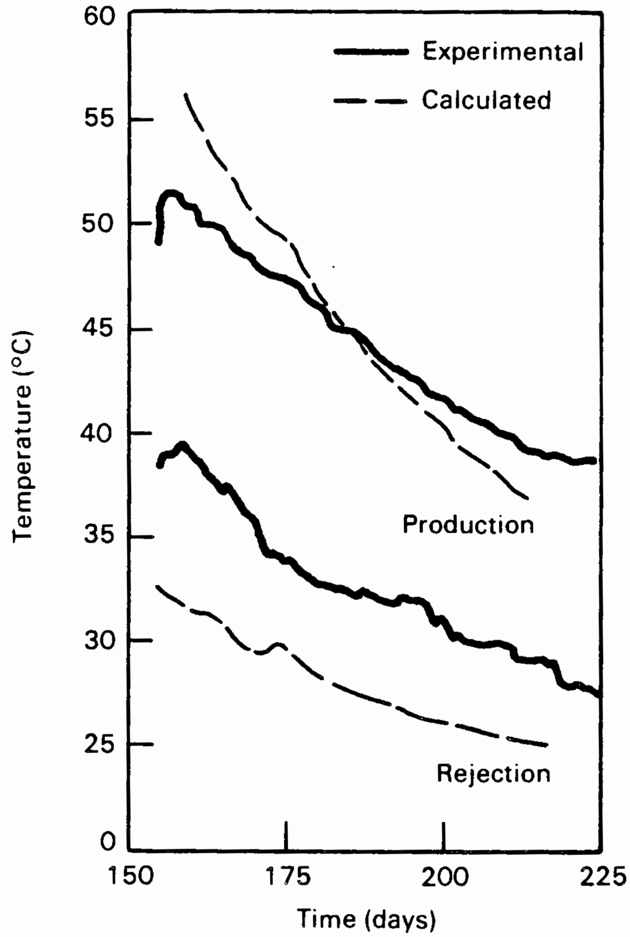

FIGURE 3.5. Production and Rejection Temperatures Versus Time for the Third Cycle

heat pump, thus providing a means to investigate various operational strategies and determine their impact on reservoir response and, ultimately, storage economics. The development of the model was completed and verified against available closed-form ATES solutions during the reporting period. While the agreement was good, no test against field data has yet been conducted and no parametric analyses of operational strategies have been performed. The model has been converted to a microcomputer and documentation is in preparation.

Prior to development of the UCATES model at the University of Minnesota, no model was available for simulating ATES in unconfined aquifers (such as that being utilized for the Parisian Department Store chill ATES system). During the reporting period, the University of Minnesota completed development and limited initial testing of the UCATES code, and a draft final report has been prepared. The model utilizes a very simple overburden heat transfer scheme, which significantly limits the applicability of the model. This portion of the model can be modified in the future to incorporate a more sophisticated and correct treatment of the overburden heat transfer.

Development and application of ATES numerical models has been given a lower priority than high temperature field testing, laboratory investigation of geochemical issues, and, most important, technology transfer and assistance to private and public implementation of ATES. As such, it is not expected that any significant numerical modeling development activities will be sponsored in the near future.

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 non-ATES STES concepts. This portion of the STES Program has received relatively little funding. In FY 1983-84 STES-TAD studies received slightly over 10% of the total STES budget. Essentially no economic, legal, and institutional studies were funded during the reporting period. The assessment, and especially the development, of some STES concepts has been funded and is summarized in the following discussion. The concepts that have received support include STES in caverns, solar/STES systems studies, ice STES, and use of zeolites for sublimation of STES ice.

3.2.1 STES in Caverns at Ely, Minnesota

In 1982 a project was started to assess the STES potential of abandoned iron ore mines at Ely, Minnesota. The assessment was performed by and cost-shared with the Minnesota Geological Survey. Most of the work was completed and reported in the last annual report (Kannberg et al. 1983).

The activities during this reporting period involved assembling the information gained from review of old mine working drawings, temperature and chemistry profiling of the mine shafts, and evaluation of the mine for STES. A map of the mine location is shown in Figure 3.6. An isometric drawing of the mine workings is shown in Figure 3.7. It is estimated that the mine workings contain 16.2 to 17 million m^3 of water that could be used for storage. Profiles of the mine had found three thermo-chemo-clines with warmer, more saline water being found at deeper points in the shafts. Pump testing indicated excellent hydraulic communication among the various shafts. The surface lake (Miner's lake) was more poorly hydraulically connected to the mine workings, although water from the lake was observed to infiltrate into the mine workings. Mine shaft waters at greater depths were above 10°C, indicating the existence of a significant body of water that could be used for heat pumping. It was further noted that the mine workings would make an excellent STES reservoir once the current resource was exhausted. A brief study of the miner's lake indicated that it could supply a large amount of summer solar-heated water for charging the mine when used as a STES system. (Surface water to a depth of 3.7 m in the lake was over 20°C when measured in June 1982).

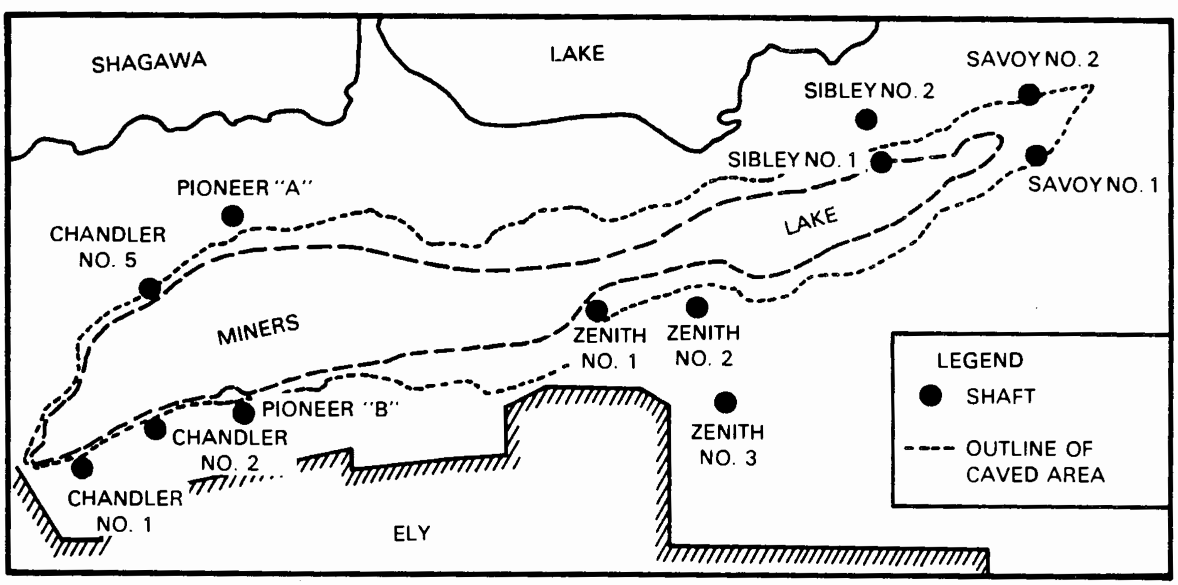

FIGURE 3.6. The Pit (Miner's Lake) and Principal Mine Shafts North of Ely, Minnesota

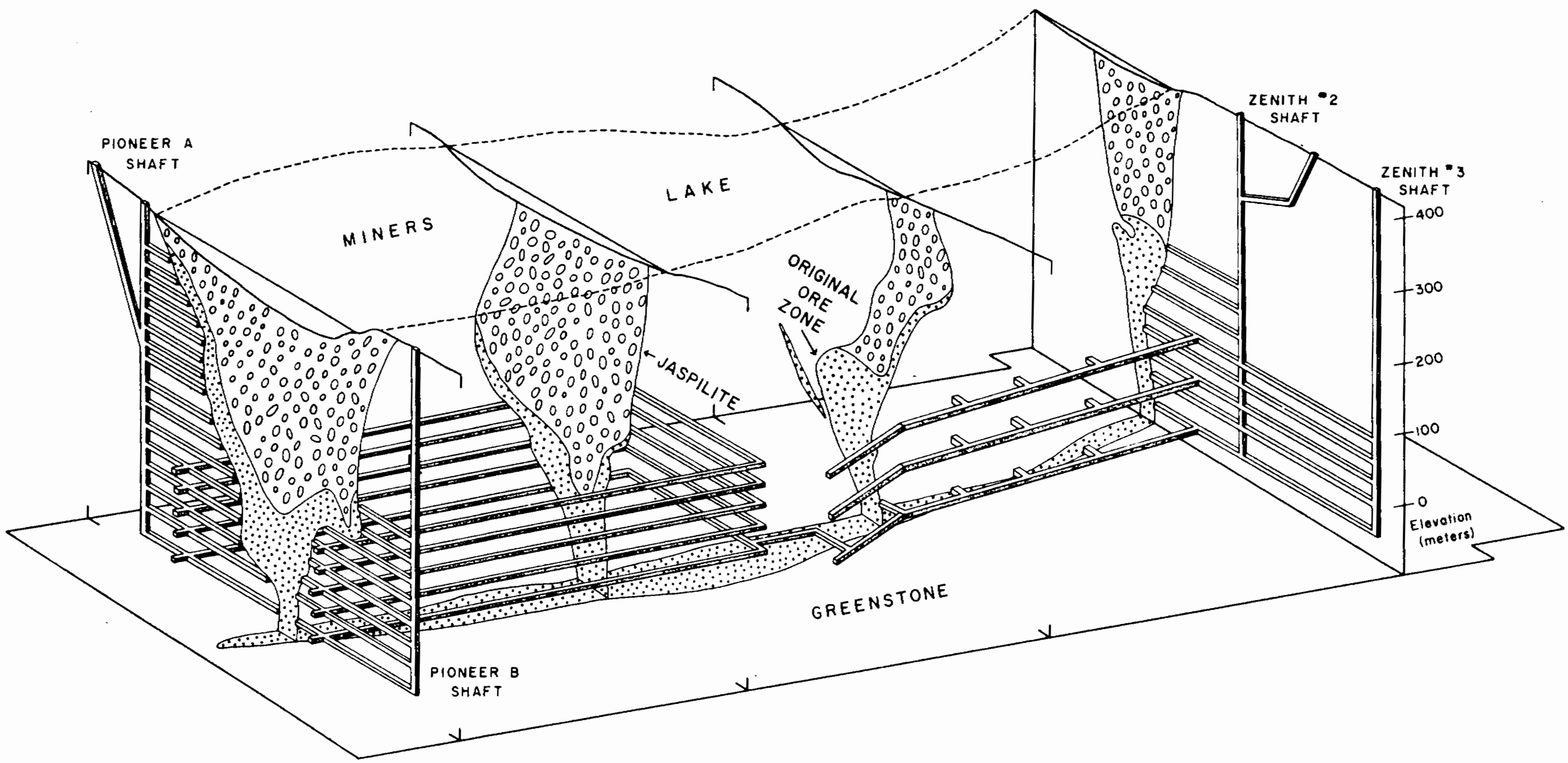

FIGURE 3.7. Isometric Drawing Showing Cross Sections Through the Principal Workings in the Thickest Part of the Ore Body

Two local entrepreneurs, Andy Hill and Douglas Barr, formed Zenith Properties, Inc., to take advantage of the mine potential. They have constructed a passive solar greenhouse near the mine openings and plan to use mine waters initially for winter heating of the greenhouse using a heat pump. Plans call for connection to the local community college in the near future for supplying winter heating. Furthermore, the city of Ely is studying installation of a district heating system that could utilize the mine works for STES.

The potential for utilization of mines in Minnesota has attracted considerable attention from state lawmakers and industry. There are numerous abandoned mines in the north central U.S. and other parts of the country, which might be utilized for STES. Such use is particularly attractive to Ely and other minehead communities that have suffered loss of mine-related business and population.

3.2.2 Solar/STES at the Charlestown, Boston Navy Yard

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.

Argonne National Laboratory (ANL) serves as the coordinator for DOE participation in an International Energy Agency effort entitled "Central Solar Heating Plants with Seasonal Storage" under the Solar Heating and Cooling Programme. Pacific Northwest Laboratory supports their activities with input from PNL as well as by funding ANL and their subcontractors to study the storage portion of solar STES projects. One of the projects to which PNL contributed was the investigation of a solar district heating system using STES for the Charlestown, Boston Navy Yard National Historical Park. A preliminary study of this system was completed and reported last year. During the reporting period Dwayne Breger and Allan Michaels have investigated the use of heat pumps in the system and provided additional input to other IEA participants on this topic.

Results from the MINSUN computer code, created and used internationally for analyzing solar/STES systems, indicate a definite performance and economic improvement for all collector types by including the heat pump. Flat plate collectors showed substantially greater improvement due to their more pronounced increase in efficiency at the lower inlet temperatures. With the heat pump, all three collectors provide comparable performance, and the flat plates were chosen as the design system due to their lower cost.

A design system of 2300 m^2 flat plate collectors with heat pump was selected. The system provides a solar fraction of 50% for the 2167-MWh annual heat and domestic hot water load. This relatively low seasonal solar fraction results from the constraint imposed by the fixed volume of the existing water tanks. The annualized cost of the solar energy supplied is $66.60/MWh, which is competitive with the conventional heating alternative with a heating cost of $0.05/kWh.

The National Park Service is interested in undertaking additional architect/engineer studies of such a solar/STES system. Plans call for cofunding more detailed studies of the system in late 1984.

3.2.3 Passive Chill STES with Clathrates

Air conditioning is a major consumer of energy in the U.S., so much so that many utilities, even in the Northeast, experience their peak electric demand in the summer. The storage of winter chill to meet air conditioning demands in the summer has already been briefly discussed with reference to chill ATES at the Parisian Department Store. But other types of chill storage, in particular ice storage, are also attractive. Ice storage was used extensively for cooling until the advent of vapor compression refrigeration systems. Ice storage is being revived for diurnal cooling of commercial buildings where utilities have time-of-day rates. Several seasonal ice storage systems are being attempted, including a snow generation and storage project at a Prudential Insurance Company building in New Jersey and an ice generation and storage system in Quebec sponsored by the Canadian government.

Preliminary economic studies indicated that ice STES would be one of the most economic chill storage methods. Pacific Northwest Laboratory sponsored studies of passive heat pipe ice generation studies at Argonne National Laboratory in 1982 and 1983. Pacific Northwest Laboratory sponsorship augmented independent ANL research in passive ice generation and storage.[a] However, only the northernmost region of the U.S. has sufficient subfreezing weather to efficiently generate enough ice for summer cooling. Therefore, other methods have been investigated for storing chill at higher temperatures. One of these methods has been clathrates.

Argonne National Laboratory conducted an extensive literature review to obtain information on the characteristics of various refrigerants for passive formation of clathrate hydrates. This review included published reports, patent searches on the use of clathrates as a freezing medium, and consultations with clathrate researchers.

Experimental efforts included the formation of clathrates of R-11 (CCl_3F), tetrahydrofuran (C_4H_8O), and methylene chloride (CH_2Cl_2). Results indicate that a congruent clathrate material should be used in a passive generation technique. Problems of supercooling have been solved in laboratory-scale experiments by means of surfactants and ultrasonic oscillation. Ten possible congruent hydrate formers have been identified to date and are listed in Table 3.3.

A conceptual design of a hybrid system, freezing both water-ice and clathrate-ice, has been developed. The hybrid system allows climatic tuning in terms of the required volumes of ice and clathrate for a given geographic location.

Low cost hydrate formers as well as hybrid systems are being evaluated for different site locations and differing economic environments.

(a)ANL sponsors and hosts the Annual Ice Storage Workshop.

TABLE 3.3. Candidate Congruent Clathrate Hydrates for STES

Clathrate Hydrates	Type	Melting Point at 1 atm.
H_2S 6.1 H_2O	Type I	0.4°C
Cl_2 7.3 H_2O	Type I	9.7°C
SO_2 6.0 H_2O	Type I	7.0°C
C_2H_4O 6.9 H_2O	Type I	11.1°C
C_4H_8O 17.2 H_2O	Type II	4.4°C
CH_2Cl_2 15 H_2O	Type II	1.7°C
$(CH_3)_3$ COH 2 H_2S 17 H_2O	Type II	7.3°C
$(CH_3)_3$ N 10.25 H_2O	Semi-clathrate	5.9°C
Bu_4NNO_3 32 H_2O	Semi-clathrate	5.8°C
$Bu_4NC_6H_5CO_2$ 32 H_2O	Semi-clathrate	3.5°C

The economics of clathrate storage are keenly dependent upon clathrate and tank costs. Because of this, inexpensive clathrates and configurations for reduced tankage requirements are being explored. Because capital costs can be more easily recovered in diurnal storage systems, clathrates are being carefully examined as part of the Thermal Energy Storage Program at Oak Ridge National Laboratory. They are continuing to fund additional study of thermal storage in clathrates at ANL. Pacific Northwest Laboratory is following this work but not sponsoring any further investigation of clathrates at this time.

3.2.4 Zeolite-Augmented Ice Storage

The previous section described preliminary studies to identify materials that form clathrate hydrates at temperatures above 0°C, as one method for extending the region that might be utilized for ice storage. Another method is to use the energy of sublimation of ice for cooling. This method would reduce by a factor of eight the amount of ice required for storage. The New Mexico Solar Energy Institute (NMSEI) was contracted to construct and test such a system in 1983.

The test system is illustrated in Figure 3.8. In addition to testing the use of zeolite driven ice sublimation for cooling, the system employed solar heat for desorption and evaporative cooling of the vapor driven from the zeolite during desorption and cooling of the zeolite following desorption. Basically, solar heat is used to dry the zeolite. The zeolite is cooled after drying. Then, piping between the zeolite and the ice is opened. The dry zeolite reduces the vapor pressure to the point of sublimation by adsorption of water vapor. The energy of sublimation is used to chill water for cooling during the day or to cool processes. A more complete description of the test apparatus can be found in Redman (1983).

Testing at NMSEI has proved the concept to be feasible. Recent tests gave energy balances near those predicted and provided valuable information concerning zeolite-driven sublimation. A summary of the projected energy flows is given in Table 3.4.

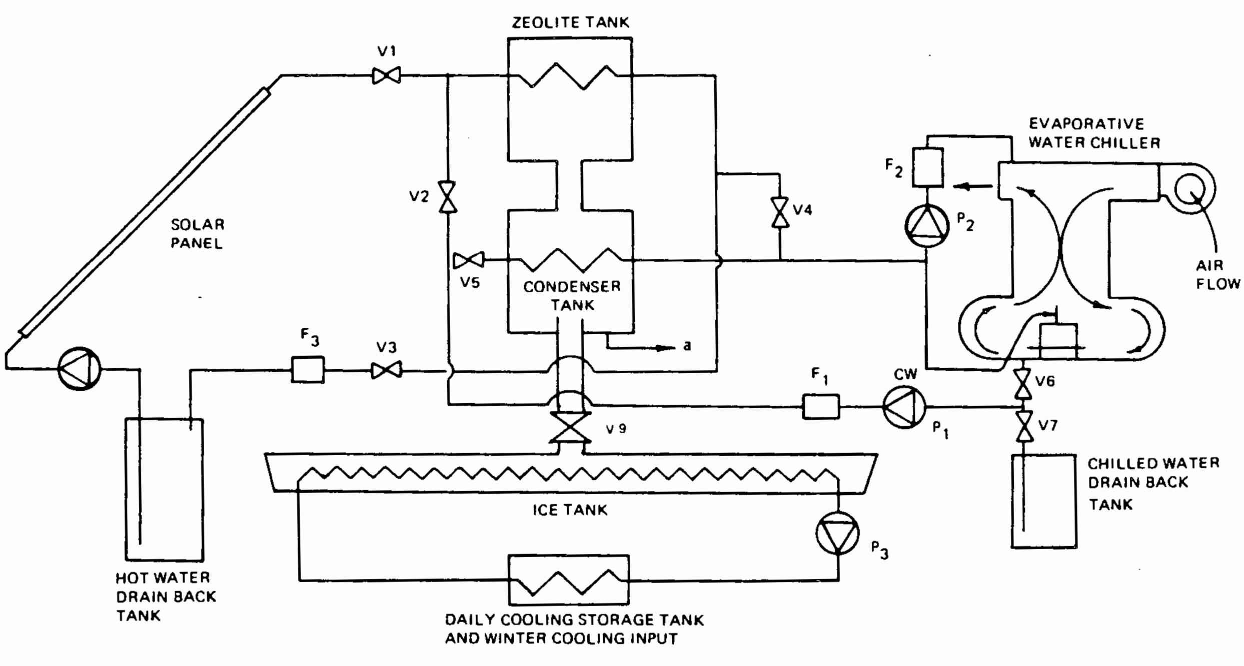

FIGURE 3.8. Solar Zeolite-Augmented Ice STES Test Schematic

TABLE 3.4. Summary of Energy Flows for Zeolite-Augmented Ice STES

Factor	Value
Projected sublimation	6 lb/day
Freezing	50.4 lb/day
Solar energy required	16,577 Btu/day
Cooling required	22,447 Btu/day
Hot water circulating pump	50 W
Chilled water circulating pump	50 W
Chilled water blower	150 W
Energy available from solar panel based on 6-hr operation	16,577 Btu/day
Chilled water cooling	5,000 Btu/hr
Solar energy/lb of ice	328.9 Btu/lb
Water chilling/lb of ice	445.4 Btu/lb
Electrical energy/lb of ice	81.1 Btu/lb

Several system features deserve note. The system as currently configured has substantial parasitic energy requirements. These requirements might be avoided by using other adsorbents or by developing new adsorbents having improved adsorption/desorption properties. (This latter alternative is now being explored; it could result in dramatic reduction of parasitic energy requirements while improving the effectiveness per cycle by as much as a factor of 5.) 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. Last, depending on how the system is configured, a daily chill storage tank will not be required.

A final report is in preparation. Additional study may be undertaken in selected technical areas supportive to both seasonal and diurnal energy storage with adsorbents, if appropriate.

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 tank, pit, cavern, aquifer, 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, whereas 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; instead, 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 last summer. 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 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 excavated pit. At Studsvik, Sweden, a 10,000-m^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. 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 solar/earth STES system near Vaulruz, Switzerland, and a 49,400-m^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.

4.0 COMPRESSED AIR ENERGY STORAGE

The U.S. Department of Energy has been active in CAES research and development since 1974. Along with the Electric Power Research Institute (EPRI) and various utilities, DOE has contributed significantly to the evaluation of conventional CAES technical, economic, environmental, and institutional issues. Both DOE and EPRI have also sponsored conceptual design and preliminary economic studies of second-generation CAES systems.

As noted earlier, PNL has served as the lead laboratory in CAES for DOE since 1975. In this capacity PNL developed a program to address the two major technical factors inhibiting utility construction of CAES systems. These are 1) stability of underground air storage reservoirs and 2) reliance on petroleum fuels. Most of the subsequent program funding was directed toward solving reservoir stability issues. This recognized that first-generation plants would have to be successful before second-generation systems would be seriously considered.

In 1981, DOE elected to close out its CAES research. Final reservoir stability criteria had been developed by PNL and its subcontractors for hard rock and salt reservoirs; the final phase of porous media reservoir studies, field testing, was underway. A limited-scale field test of CAES in an aquifer being sponsored by DOE at Pittsfield, Illinois, was transferred to EPRI in February 1983 for completion.

During this reporting period PNL has continued to serve DOE by participating, on their behalf, in EPRI Pittsfield Aquifer Test Technical Review Committee meetings, and by providing DOE and EPRI with brief monthly field test progress reports used by EPRI for subsequent reporting to the Illinois Environmental Protection Agency. The only remaining PNL activity is the review of the final report on the project being prepared by PB-KBB, Inc., under EPRI guidance. This report is expected in early summer 1984 and will be published by EPRI in cooperation with DOE at a later date.

Per DOE agreement with EPRI, final stability criteria for CAES in porous media reservoirs will be issued by EPRI. Pacific Northwest Laboratory published interim porous media stability criteria and guidelines in May 1983. These criteria and guidelines were summarized in the 1982 UES Annual Report (Kannberg et al. 1983).

Pacific Northwest Laboratory closed out second-generation CAES studies concurrent with issuance of the final technical and economic assessment of advanced CAES systems, and documentation of the thermodynamic cycle numerical simulation code used for preliminary screening of the systems. Preliminary screening of thermal energy storage materials for adiabatic and hybrid CAES systems was completed. Research on other promising second-generation systems--coal gasification/CAES, coal fluidized bed combustion/CAES, and other solar or steam plant CAES systems--was discontinued for budgetary reasons.

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