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# Underground Energy Storage Program

## 1982 Annual Report

June 1983

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

## 1982 ANNUAL REPORT

L. D. Kannberg
Staff Members and Subcontractors
of Pacific Northwest Laboratory

June 1983

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

Pacific Northwest Laboratory
Richland, Washington 99352

# PREFACE

This is the 1982 Annual Report for the Underground Energy Storage Program, which is administered by the Pacific Northwest Laboratory for the U.S. Department of Energy. This document describes all of the major research funded under this program during the period extending from March 1982 to March 1983.

The report summarizes the activities and notable progress toward program objectives in both Seasonal Thermal Energy Storage (STES) and Compressed Air Energy Storage (CAES). It also presents the amplified technical summaries of individual tasks and projects conducted during this reporting period. The activities of the authors reporting herein were actually broader in scope than may be reflected by the mini-reports. Readers wishing additional information on specific topics are invited to contact individual authors.

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

The efforts of many contributors are represented in this report. Progress achieved during the March 1982 to March 1983 reporting period is attributed to multiple subcontractors working with the Underground Energy Storage Program staff. These included Terra Tek, Inc., of Salt Lake City, Utah; W. Schertz and A. Michaels of Argonne National Laboratory, Argonne, Illinois; M. Walton, 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; J. Istvan of PB-KBB, Inc., Houston, Texas; W. E. Soderberg, University of Minnesota, Minneapolis; and F. J. Molz, Auburn University, Auburn, Alabama.

The program task and project leaders from the Pacific Northwest Laboratory also merit acknowledgment. These researchers and engineers include C. T. Kincaid, S. C. Blair, W. J. Deutsch, J. R. Raymond, D. A. Myers, L. Vail, R. D. Allen, T. J. Doherty, L. E. Wiles, D. R. Brown, J. S. Barnhart, R. L. Erikson, J. A. Fort, and F. R. Zaloudek.

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

# SUMMARY

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 to achieve reduced energy consumption, more effective use of current energy generation capacity, and reduced reliance on scarce energy resources. The DOE charter is limited to performing studies that eliminate barriers and obstructions to implementing underground energy storage (UES) concepts within the free marketplace.

In accordance with that charter, the objective established for UES studies is:

- to reduce the technical and economic uncertainties that inhibit entrepreneurial development and implementation of promising underground energy storage concepts.

Two principal underground energy storage technologies were identified for DOE investigation--Seasonal Thermal Energy Storage (STES) and Compressed Air Energy Storage (CAES). Programs were established within UES to research and develop each of these technologies in an effort to resolve and eliminate their associated technical and economic uncertainties. Activities conducted for STES differ markedly from those of CAES. This is because the technologies differ substantially in terms of primary market, unit scale, technical sophistication for commercialization, basic energy storage function, storage time frame, user interface, economic payback period, and financing structures. However, STES and CAES both use similar geologic media for storage and share similar phases of engineering evaluation and review required for technology development.

The Pacific Northwest Laboratory has served as the lead laboratory for DOE in its effort to advance both STES and CAES to the point of adoption by the private sector.

Activities funded by DOE in STES and CAES began in 1979 and 1976, respectively. Redirection of the DOE-funded activities in STES and CAES

have significantly reduced the scope of Federal efforts in these technologies during the last 2 years.

For all intensive purposes, the revised DOE CAES program has been completed during this reporting period. With the exception of tracking progress in formerly DOE-funded projects, no further DOE-funded R&D will be performed in CAES.

The scope of STES activities has been reduced nearly tenfold during the last 2 years. While the original emphasis of the STES program was on the demonstration of Aquifer Thermal Energy Storage (ATES) systems, current efforts have concentrated on the field and laboratory research of high temperature ATES systems and the development of STES systems that do not involve aquifers.

The major elements of STES and CAES studies during the reporting period are identified in Figure 1. The general scope of element activities and the principal performing organizations are also given in Figure 1. Progress in each of these elements is summarized in the following discussion. More detailed discussions of project progress are given in the body of the report.

## SEASONAL THERMAL ENERGY STORAGE PROGRESS

The seasonal thermal energy storage (STES) concept involves storing thermal energy, such as winter chill, summer heat, and industrial waste heat, for future use in heating and cooling buildings or industrial processes. Widespread development and implementation of STES would significantly reduce the need to generate primary energy in the U.S. In fact, 1980 data indicate that STES is suitable for providing 5 to 10% of the nation's energy with major contributions in the commercial, industrial, and residential sectors.

Research efforts in STES under PNL management were subdivided into two areas: aquifer thermal energy storage (ATES) and STES technology assessment and development (STES/TAD). Aquifers represent a logical

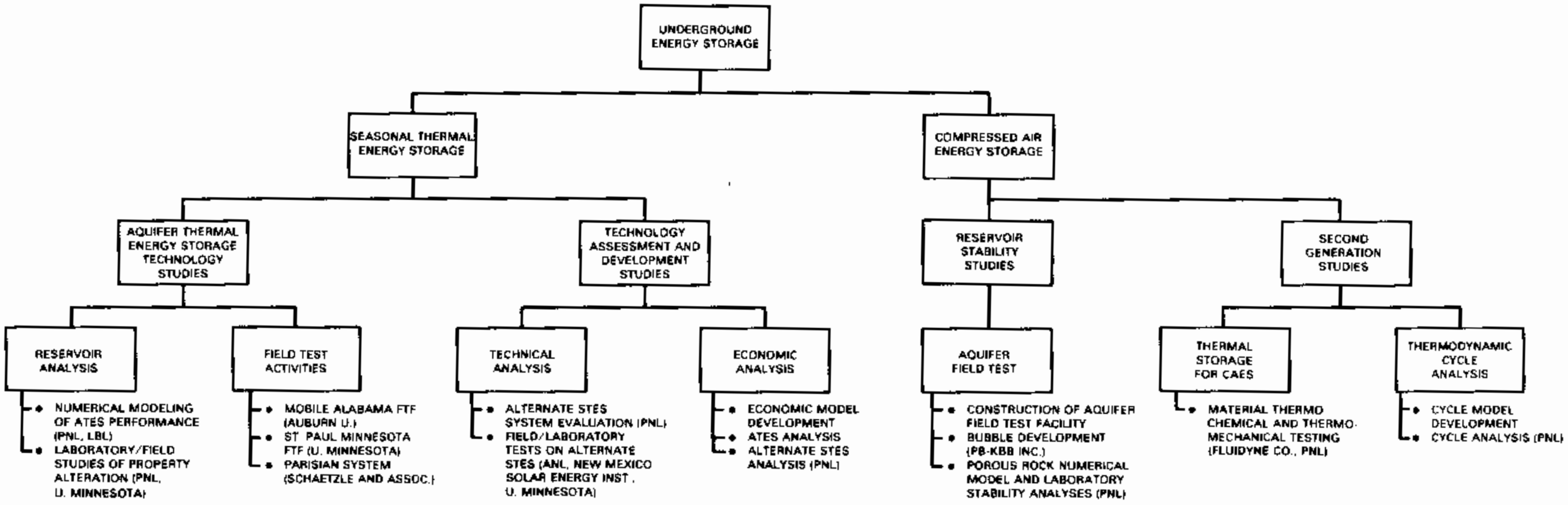

FIGURE 1. Underground Energy Storage Program Structure and Principal Activities

thermal storage medium because of their natural capacity for retaining heat and cold. Research in ATES has been aimed toward better characterizing system performance. Nonaquifer alternatives (e.g., lakes, earth, manmade storage structures) are being explored as part of the STES/TAD studies. This segment of the UES Program also includes an economic assessment of the STES reservoir alternatives. Publication of the quarterly STES newsletter was continued by Lawrence Berkeley Laboratory.

## Aquifer Thermal Energy Storage

The bulk of STES effort during this reporting period was concentrated on ATES Technologies Studies with a growing effort in Alternative STES Concepts. The first short-cycle heat injection test (90°C) at the St. Paul high temperature FTF was completed in December 1982. Data analysis is continuing and preparations are being made to initiate the second short-cycle heat injection test (125°C) by the end of April. The third and final cycle heat injection test has been completed at the Mobile FTF and activities are underway to terminate the FTF. Follow-on work at the Stony Brook ATES test facility to resolve well-plugging problems was completed with issuance of a final report on the problem. A project was started to instrument and monitor the Parisian Department Store chill ATES system in Tuscaloosa, Alabama, for comprehensive assessment and evaluation of system performance and efficiency. Development continued on modeling technology, and simulation/prediction studies were made for the third cycle Mobile FTF test. The Aquifer Properties Test Facility (APTF) and Field Injectivity Test Stand were completed and have been used for evaluation of tests for the St. Paul FTF.

### Numerical Modeling

Development of the Areal Flow Model (AFM) was completed. The AFM is an intermediate-level code for assessing ATES under basic geohydrologic conditions and in multi-well configurations. The AFM is a useful tool for screening applicability of ATES under a variety of situations to support management decisions.

Detailed simulation analyses were completed by Lawrence Berkeley Laboratory for the heat injection experiments at the Mobile, Alabama FTF, including the final third-cycle test. The results of these analyses compare very favorably with field-measured values, and verify the ability of numerical models to simulate and predict ATES performance in complex geohydrologic systems.

The University of Minnesota, under subcontract to PNL, is developing a simplified numerical model to evaluate ATES in unconfined aquifers.

Three documents were completed and published during the year on modeling technology as applied to ATES. The first publication reports on the CFEST (Coupled Fluid, Energy and Solute Transport) multi-dimensional finite element numerical code for simulation/prediction of ATES systems. The second document describes the Areal Flow Model (AFM); the third paper discusses modeling of the Mobile, Alabama FTF heat injection tests.

During this reporting period, geochemical modeling studies were carried out on the fluid injected at the St. Paul FTF.

### Laboratory/Field Analysis

Efforts during the past year were directed to completion of the laboratory Aquifer Properties Test Facility (APTF) and the Field Injectivity Test Stand (FITS). These facilities were completed and laboratory and field tests were initiated. Physicochemical tests utilizing the laboratory apparatus were started in May 1982, and a series of tests on core samples from the St. Paul FTF was completed during the last half of 1982. The FITS was used at the St. Paul FTF site to provide technical operational support. Tests were conducted to characterize the suspended solids content of injection/withdrawal fluids during isothermal and nonisothermal tests at the FTF.

### Field Test Facilities

Field tests on ATES are in progress at both the Mobile, Alabama and St. Paul, Minnesota FTF sites. The experiments are designed to assess the long-term effects of heat injection on ground-water systems. The Mobile FTF is the site of low-temperature (55°C to 90°C) ATES studies; and the St. Paul FTF is the site of high temperature (150°C) ATES studies.

Activities (other than heat removal and site restoration) have been terminated at the Mobile FTF with the completion and analysis of the third-cycle (80°C) heat injection test. Heat recovery efficiency was low (42%) due to buoyancy effects, even with use of a modified injection/recovery well system. The final report draft for the project was completed, and heat removal from the aquifer is in progress to meet state regulatory requirements. Several reports, papers and presentations were completed on activities and findings at the Mobile FTF.

The first nonisothermal injection tests were completed at the St. Paul FTF. Initial injection indicated that serious precipitation of calcite from the heated water occurred that would plug the heat exchanger, well screen and, potentially, the aquifer. This problem was solved by adding precipitator/filter elements immediately after the heat exchanger to remove the calcite and thus protect the aquifer and subsurface equipment. The first short-cycle heat injection/storage/recovery test was completed, and application for extension of the operating variance permit is under review. An interim report on the water chemistry and rock/water interactions was completed.

The follow-on work to resolve the well-plugging problem was completed at the Stony Brook ATES test site, and the final report on the work was issued. The investigation showed that the most likely cause of the well plugging was particulate material in the injection water. Recommended remedial actions, in this case, are prefiltering of the water, proper design of the injection well and back-flushing of the well at required intervals.

### Seasonal Thermal Energy Storage Technology Assessment and Development

During the reporting period, efforts continued in the investigation and development of several STES systems that serve as alternates to ATES.

Systems that were investigated included ice generation and storage (passive heat pipe systems and related studies of clathrate chill storage, and zeolite-augmented ice storage), storage in abandoned mine caverns, and storage of solar thermal energy in existing tankage. In addition to these technical studies, the economic features of ATES of chill were investigated and reported.

### Ice Generation and Storage

During this reporting period, studies were carried out by PNL and Argonne National Laboratory and initiated at the New Mexico Solar Energy Institute, to investigate the potential for various ice storage systems for STES applications. Previous study by researchers at PNL identified ice storage as the most promising nonaquifer STES technology.

Currently, ice storage systems are commercially available for diurnal chill storage and are in use at numerous locations. One notable seasonal ice storage effort is that being developed by Dr. Ted Taylor in Princeton, New Jersey. Dr. Taylor's system employs a snow-making machine to generate snow/ice during subfreezing periods in the winter for storage and use during summer for building air conditioning.

During this reporting period, Argonne conducted experiments to characterize the performance of modified heat pipes (thermo-siphons) for passive heat transfer from a water/ice tank to the winter environment. During the 1981-1982 winter over 16,000 kg of ice were generated in this facility. A variety of heat pipes were utilized including those which utilized Roll-Bond panels and copper coils in the evaporator. Systems using passive ice release mechanisms were also attempted. Cumulative ice formation around the coil evaporator was substantially greater than for other evaporator configurations tested. Theoretical analyses were performed to assist in characterizing the performance of heat pipes. Furthermore, statistical analyses were performed to relate system performance to environmental parameters such as freezing degree days and orientation of the roof-mounted condenser panels. Additional Argonne Ice

Storage Test Facility testing was performed during the 1982-1983 winter after modification of the facility. The 1982-1983 winter was exceptionally mild resulting in considerably less ice generation than for the 1981-1982 winter. Results from the 1982-1983 winter have not been completely analyzed; however, models of heat pipe operation have been completed.

In addition to the ice generation and storage effort, Argonne has initiated study of clathrates for seasonal passive chill storage. Having been initiated late in the reporting period, only preliminary results were obtained.

The augmentation of ice storage using zeolites is being investigated by the New Mexico Solar Energy Institute under a contract with PNL initiated in October 1982. The study involves the construction of an experimental unit to determine whether solar (or waste heat) energy source zeolite systems can be used to increase the chill energy obtained from ice by extracting the latent heat of vaporization as well as the latent heat of fusion. Once the experimental unit is constructed, the unit would be operated over a range of conditions to examine the performance of such systems.

During the reporting period, the design of the facility has been completed and available zeolites have been examined to identify the most promising candidates for testing and prototype operation. Testing is expected to start in June 1983.

### STES in Abandoned Mines

The University of Minnesota (Minnesota Geological Survey) conducted a study, jointly funded by DOE and the State of Minnesota, to determine the feasibility of utilizing abandoned mines for STES. Abandoned mine caverns at Ely, Minnesota, were examined for applications involving STES as well as geothermal heat pumps with district heating. Field study and analysis of mine charts indicate that over 6 million $m^3$ of storage volume exist and that the water in the abandoned mine shafts is thermally stratified inversely due to increasing water salinity with depth. A concept for STES utilizing these abandoned mine workings has been proposed. During winter, relatively warm saline water would supply heat for district heating through a heat pump. After heat transfer, the chilled saline water would be returned to the bottom of the mine where it would be heated geothermally. Except at the bottom of the mine, energy for storage in the mine would be returned seasonally by using a lake formed recently over the collapsed mine workings as a summer solar heat source. Additional hydraulic data and system analyses have been recommended and local organizations are currently considering constructing such a system.

### STES in Existing Tankage

A preliminary analysis of a seasonal storage solar heating system for the Charlestown Navy Yard in Boston, Massachusetts was completed by the Massachusetts Institute of Technology Energy Laboratory under subcontract to Argonne National Laboratory. The Charlestown Navy Yard area of Boston is being redeveloped for residential and commerical use. The system makes use of two large, buried concrete storage tanks totalling 5700 $m^3$ as a water heat store. Other storage facilities, including a dry dock, were found to offer additional STES opportunities for the Navy Yard as the redevelopment progresses.

The analysis made extensive use of the MINSUN computer code for optimization of the cost/performance of the integrated solar/storage components. The use of storage with any of several types of solar collectors, including parabolic, advanced CPC evacuated tubes and flat plate collectors proved to be economic (year 2000 costs). Sensitivity analyses were performed with respect to performance parameters and economic assumptions. Implementation of several of the systems is discussed relative to the various roles of the various parties involved and funding/financing possibilities.

### Economic Analysis of ATES of Chill

The cost of energy supplied by an ATES system from a seasonal chill source was investigated by staff at PNL. Costs were estimated for point demand and residential development ATES systems using the computer code AQUASTOR. AQUASTOR was developed previously at PNL specifically for the economic analysis of ATES systems. In this analysis, the cost effect of varying a wide range of technical and economic parameters was examined. Those parameters exhibiting a substantial influence on the costs of ATES delivered chill were:

- system size
- well flow rate
- transmission distance
- source temperature
- well depth
- cost of capital.

The primary constraint of ATES chill systems is the extremely low energy density of the chilled water for air conditioning (about 20 Btu/lb) compared to hot water (about 100 Btu at 325°F) for space heating. Because of the much lower energy density, equipment for handling the chilled water must be substantially larger to deliver the same amount of energy. This relationship puts a premium on factors affecting well field and transmission system design. Significant economies of scale are available for ATES systems and relatively large (5 MW) systems will typically be required to approach cost-effectiveness.

## COMPRESSED AIR ENERGY STORAGE PROGRESS

The compressed air energy storage (CAES) concept is a near- and mid-term technology for central station electric utility applications. This concept greatly improves the effectiveness of a gas turbine using petroleum fuels and could reduce petroluem fuel consumption of electric utility peaking plants by more than 100 million barrels of oil per year at probable market penetration. Studies show that the CAES concept is technically feasible and economically viable.

To facilitate technological development and commercialization of CAES, a series of projects was implemented at the request of DOE's Division of Energy Storage Technology. These CAES Technology Projects within the Underground Energy Storage Program have evolved into two major elements of research and development: CAES Reservoir Stability Studies and Second-Generation CAES Concept Studies. Because long-term reservoir stability is crucial to CAES system commercialization, the CAES Reservoir Stability Studies have received major emphasis. In recognition of the fact that even the modest petroleum fuel requirements of a conventional CAES system may be an obstacle to large-scale acceptance, Second-Generation CAES Concepts Studies were implemented to investigate a number of oil conservation technologies. These could reduce or eliminate the dependence on petroluem fuels.

## Reservoir Stability Studies

The objective of the Reservoir Stability Studies is to develop stability criteria and guidelines for large geologic air storage reservoirs in salt domes, hard rock, and porous rock aquifer structures. Three parallel studies evaluated each reservoir type for large central station utility application.

During this reporting period, activity centered around the construction and operation of the Pittsfield Aquifer Test and the development of interim stability criteria for porous rock reservoirs. Final criteria and guidelines for design of hard rock and salt dome air storage reservoirs were published early in this reporting period. At the end of this reporting period, DOE and PNL transferred the Pittsfield Aquifer Test to the Electric Power Research Institute, and published an interim porous media stability criteria and guidelines document.

### Stability Criteria Formulation

The task of assembling and integrating all the research results of the reservoir stability studies requires publishing a stability criteria and guidelines document for each of the three CAES reservoir types.

Preliminary and revised versions of these documents were published and issued for comment to reviewers during earlier years.

The criteria and guildelines resulting from this task are intended to be checklists of the technical concerns that should be considered by the utility and their engineering staff during development of the CAES option. They are not, nor are they intended to be, complete geotechnical engineering handbooks. Instead, they examine primarily those technical issues that are peculiar to siting, designing and constructing large-scale air storage reservoirs using geologic containment. Included are recommended practice adapted from related technology and results and conclusions from research conducted to examine a wide range of CAES specific concerns. Extensive references make the criteria documents a central source on CAES reservoir technology.

Early in this reporting period, the final versions of the excavated hard rock cavern criteria and the solution mined salt dome cavern criteria documents were issued. The publication of these two documents, listed below, signified completion of major research studies on each of the reservoir types.

- PNL-4180, Geotechnical Issues and Guidelines for Storage of Compressed Air in Excavated Hard Rock Caverns
- PNL-4242, Geotechnical Issues and Guidelines for Storage of Compressed Air in Solution Mined Salt Cavities

Most of the effort during this reporting period has been directed at developing, integrating, reviewing and revising an interim version of the criteria and guidelines document for air storage in porous media aquifer structures. This document, Factors Affecting Storage of Compressed Air in Porous Rock Reservoirs (Allen, Doherty, Erikson and Wiles 1983), is currently in publication. It is interim pending completion of the Pittsfield Aquifer Field Test and integration of those results. In its present form, it signifies completion of active DOE involvement in CAES research and development.

Pittsfield Aquifer Field Test Laboratory and Modeling Support

The objective of these support tasks is to use the capabilities and tools developed during the comprehensive generic research projects performed within the porous media reservoir stability study to support the design, construction and operation activities of the Pittsfield Aquifer Field Test. The primary elements involved in this support function are the reservoir numerical modeling capability available through the PNL code library and the laboratory reservoir simulation capability available in the porous media flow facility at PNL. In addition, the engineering, geologic and geophysical capabilities available within the program and the laboratory are available as necessary.

Numerical Modeling Support. Models developed at PNL specifically to address CAES reservoir specific issues can examine such processes as pressure response, bubble development, water coning, thermal development, and dehydration processes. The models have been used during this reporting period to assist in system design and equipment selection, to aid in baseline test planning and prediction of test performance. Once testing was underway, modeling was used for performance matching to assist in the interpretation of reservoir response to allow problem diagnosis in conjunction with the limited available instrumentation.

Three conclusions resulted from modeling work during this period. First, the field test facility is adequate to develop a 100-MMscf bubble in a 700-md St. Peter reservoir in a period of 60 to 90 days. Longer injection times in actual practice are a result of a reduced permeability region in the near-wellbore region. Second, water coning should not be a problem at Pittsfield in spite of the very thin reservoir if withdrawal volume flow rate is kept less than or equal to injection volume flow rate in the wellbore (equal delta pressure rule) and net cycle mass flow is equal to or greater than zero (daily mass balance). The last conclusion is not a modeling result, but a result of using the models in the situation of large instrumentation losses at the field site; modeling has been shown to be a tremendous asset in understanding the response of the test reservoir when used in conjunction with the limited field test data to match reservoir performance.

Laboratory Studies. The objective of all experimental work this reporting period is to evaluate the physical properties of the St. Peter sandstone under simulated reservoir conditions. The porous media flow facility, a CAES-specific reservoir simulator at PNL capable of prototypic flow, pore pressure, and thermomechanical environment, is the primary tool used to conduct these studies. Test types and general conclusions are summarized briefly below:

- confined permeability under transient thermal loads - No significant change
- long-term thermal loading - 10 to 20% permeability reduction that is partially recoverable. Structural response minimal but mixed.
- pore pressure variation under prototype conditions - No significant response.
- confining stress cycling under prototype conditions - 10 to 20% permeability reduction that is partially recoverable; structural response nearly elastic with slight hysteresis; very similar to thermal.
- thermal cycling (slow) under prototype conditions - Permeability reduction as under thermal and stress loading but this effect appears to damp out gradually with subsequent cycles to some stable lower permeability; structural response essentially elastic with observable hysteresis.

The general conclusion drawn from the studies to date is that the St. Peter can be expected to be a stable air storage medium. Long-term degradation mechanisms in the prototypic environment would appear to be permeability degradation under thermal and/or structural cyclic loading.

This might possibly be due to a minor thermo-structural damage mechanism that results in some particle generation, which, in turn, results in flow restriction.

As this reporting period ends, all laboratory study has ended at PNL and final report preparation is underway. The CAES-specific experimental facilities are currently being maintained in a standby status.

### Pittsfield Aquifer Field Test

The objectives of the Pittsfield Aquifer Test are 1) to demonstrate the use of aquifers as compressed air storage reservoirs, 2) to validate and modify stability criteria from earlier studies, and 3) to correlate field data with predictions developed by numerical modeling and laboratory experiments (Allen, Kannberg and Doherty 1981).

During early 1981, field exploration confirmed the presence of a domal structure near Pittsfield, Illinois, with adequate properties to satisfy air injection criteria. The site is located on the Pittsfield anticline about 110 km (70 mi) north of St. Louis. The air storage medium is St. Peter sandstone at about 200 m (650 ft) below ground surface.

Exploration, construction permitting, leasing and selection of a construction and operations contractor, PB-KBB, Inc. of Houston, Texas, were concluded during 1981. Design and construction were then initiated with drilling and completion of the injection/withdrawal well. The well is located at the highest point within the structure and penetrates through the Paleozoic shales, limestones and dolomites to the St. Peter, a quartzose sandstone. The Joachim, a shaly dolomite, is the primary caprock. An array of logging/sampling wells to permit the use of logging tools and allow water sampling was drilled at various azimuths and radii. Two closed instrument wells were drilled within the near-wellbore region to enable measurements of temperature, pressure, humidity, and relative water saturation at different levels within the reservoir.

Design and procurement of major surface facility components were just underway at the beginning of this reporting period. The equipment includes a compressor skid with a 0.72-kg/s (1250-scfm) compressor and a process and instrumentation skid to treat the air and control and monitor the injection/withdrawal process. The surface facility also includes the equipment building, office area, access roadway, sanitary system and telephone. Subcontractors completed construction and assembly at the end of Fiscal Year 1982.

The instrumentation system was selected by PB-KBB and specialty subcontractors to meet basic experimental requirements. Instrumentation procurement, calibration and installation were accomplished in 1982. The surface equipment records air flow rate, pressure, temperature, and humidity. The subsurface monitoring system monitors these parameters in the formation immediately around the injection zone. The subsurface instrumentation system was calibrated and assembled offsite, then shipped to the site for installation and integration into its data acquisition system. The instrumentation suffered significant losses due to lead damage during installation. Further losses of downhole instrumentation were attributed to transient voltages, peculiar local ground potentials and deterioration of lead splices. Approximately 15 downhole instruments, less than 30% of the planned total, are now functioning. There have also been chronic reliability problems with the data acquisition computer. Data acquisition for the downhole sensors has been transferred from the computer.

As of September 30, 1982, all construction activities, including well field development, subsurface instrumentation and all surface facilities, were adequately completed and installed to allow the start of operations (Allen and Doherty 1982).

Activity for the last half of this reporting period consisted of the operations phase of the field study. Changes in budget and system performance required several deviations from the original test plan.

The bubble development period was extended to 6 months due to lower than expected injection rate. Sponsorship and project management roles within the project changed during bubble development from DOE-PNL to EPRI under special agreement between DOE and EPRI. The test cycle, originally planned with 3-month increments, reverted to a 10-week schedule. The cycle will have equal volume flow rates during injection and withdrawal and will satisfy a mass balance each day.

Two phases of operation have been conducted during this period. The first phase, bubble development, involved continuous injection of air to create an air bubble within the aquifer structure. Pressure response and drainage processes were monitored with the geophysical and surface instrumentation. Bubble development was initiated on October 2, 1982 and proceeded through March 1983. Dry air was injected near the top of the St. Peter sandstone over an approximately 2.5-m (8-ft) interval. The air injection pressure was limited to 2.07 MPa (300 psi) based upon the environmental operations permit. This pressure enabled displacement of ground water within the aquifer because the discovery pressure is 1.035 to 1.104 MPa (150 to 160 psia). The actual flow rate during bubble development never exceeded 40% of the system capacity. This required extending the bubble development period to 6 months.

Mass flow rate for the bubble development phase from October 1, 1982 through the end of March 1983 is shown in Figure 2. Figure 3 displays the integrated bubble volume for the same time period.

Gamma ray-neutron logs divulged stable air storage in the uppermost St. Peter formation. The top of the peak was at 198 m (648 ft), indicating some air in the Joachim dolomite/St. Peter sandstone transition zone and excellent retention of air below the Joachim proper. Continued operation showed a gradual but significant increase in the injection rate throughout the bubble development period. This was due to various workover techniques and the gradual drying effect of continued operation. Transient test data were used for numerical modeling to match the reservoir's steady-state and

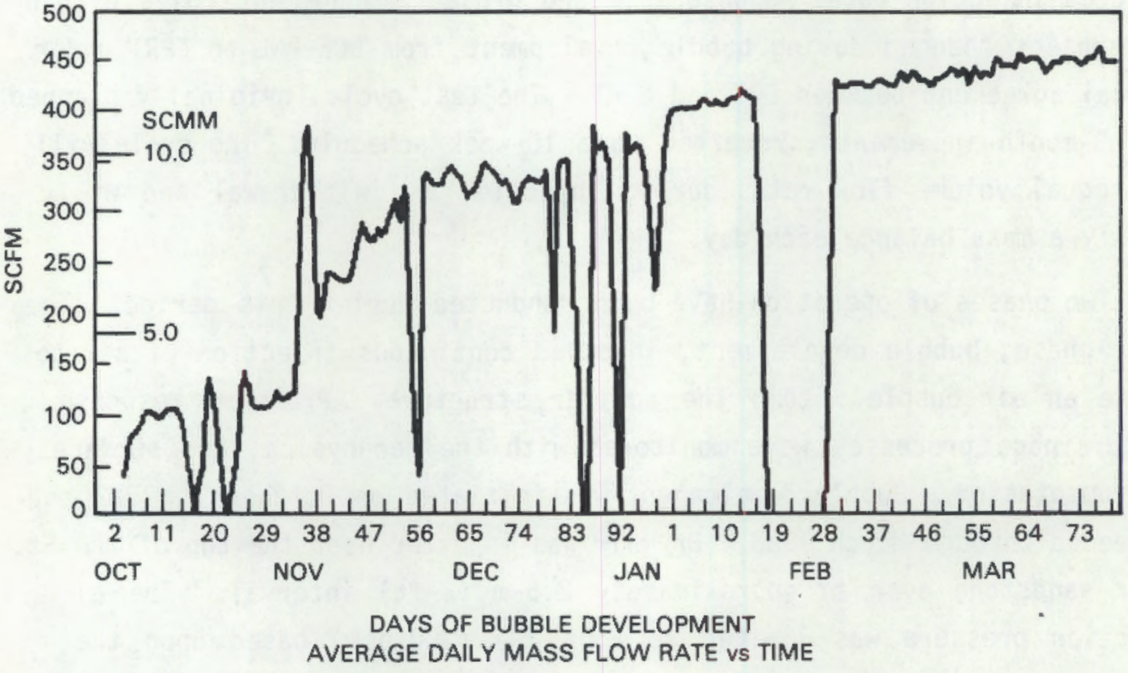

FIGURE 2. Average Mass Flow Rate in scfm for 180 Days of Bubble Development

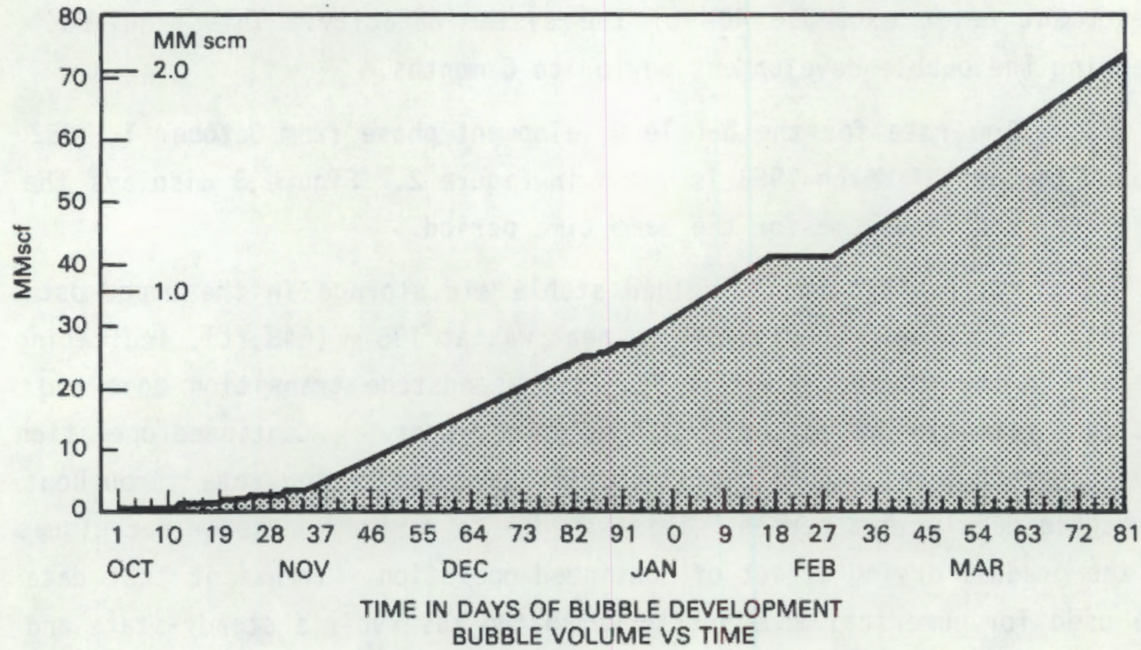

FIGURE 3. Cumulative Bubble Volume for the First 6 Months of Bubble Development

transient responses to assess whether the low injectability was caused by low formation permeability or a relatively impervious well completion. A model with a dramatically reduced permeability region immediately around the I/W well was able to match both steady-state and some of the transient performance. Residual cement or silica flour were considered to be potential pore plugging agents.

The facility was shut down on January 26, 1983 for lack of operating funds under DOE/PNL sponsorship. These funds were depleted earlier than anticipated due to the instrumentation problems and extension of the bubble development period because of low injectivity.

This completed the work sponsored by the Department of Energy at the Pittsfield Aquifer Field Test site. Sponsorship and responsibility for this test then passed to the Electric Power Research Institute (EPRI) under the transfer agreement. PB-KBB continues to manage work on the site (through separate contract) and the same staff will operate the facility. The operations permit was transferred from PNL to EPRI by a request to the Illinois Environmental Protection Agency.

The project transfer, completed in early February, took place under the terms of the agreement between the DOE and EPRI. Under this agreement, all property, leases and permits associated with the site were transferred to EPRI in exchange for completion of the basic scope of work of the project and free exchange of the data with DOE, its representatives, and the industry. The Pacific Northwest Laboratory functioned as DOE's representative with respect to the DOE portion of the project, and in matters pertaining to permitting this project under UIC rules with the Illinois Environmental Protection Agency.

Injection under EPRI sponsorship recommenced on February 7, 1983. The bubble continued expansion during shutdown toward the discovery pressure of the reservoir. Injection mass flow rate on the restart stabilized at 0.25 kg/s (430 scfm) and remained at that level into early April. At that time a bubble of about 2.13 MMscm (75 MMscf) had been created; this volume was adequate to perform some preliminary evaluative withdrawal and cyclic testing on the injection/withdrawal well.

Air cycling, the second phase of operation, is prescribed to simulate the operation of the unit length of a producing section of one well of a full-scale CAES aquifer installation. Preliminary cycling completed at the time of this writing indicates 0.26 to 0.32 kg/s (450 to 550 scfm) injection for 5 to 6 hours and 10 to 12 hours of withdrawal. Test withdrawal of mass flow rates of 0.09 to 0.15 kg/s (150 to 250 scfm) with backpressure of 0.65 to 1 MPa (100 to 150 psi) have been recorded.

Cycling data will be compared with analytical and laboratory predictions of physical reservoir relationships and petrologic response to determine predictability of reservoir response. Subsurface and surface measurements of temperature and saturation during cycling will yield information on thermal energy recovery, radial extent of thermal cycling, dehydration versus time and temperature, and radial temperature distribution in the near-wellbore region. Testing is planned for completion in Spring 1984.

## Second-Generation Concepts Studies

The objective of the Second-Generation CAES Concepts Studies has been to develop and evaluate second-generation CAES technologies that require little or no petroleum fuel for operation. During this reporting period, efforts have concentrated on the publication of all work performed thus far and an orderly completion of this activity.

A joint effort sponsored by DOE and the Electric Power Research Institute (EPRI) resulted in a report entitled An Evaluation of Thermal Energy Storage Materials for Advanced Compressed Air Energy Storage Systems (Zaloudek, Wheeler and Marksberry 1983). This report documents the study procedures used and results obtained in an experimental study to screen four proposed heat storage materials for performance and durability for use as sensible heat storage systems in adiabatic and hybrid advanced CAES plants. The study specifically addressed the problems of particle formation and thermal ratcheting of the materials during thermal cycling and the chemical attack on the materials by the high temperature and moist environment in an advanced CAES heat storage bed. The results indicate that from the durability standpoint Denstone, cast iron containing 27% or more chromium, and crushed Dresser basalt would possibly stand up to advanced CAES conditions. If costs are considered in addition to durability and performance, the crushed Dresser basalt would probably be the most desirable heat storage material for adiabatic and hybrid advanced CAES plants. Further research on this topic should be directed at evaluating the performance of Denstone and Dresser basalt under long-term cyclic temperature and high pressure conditions.

A computer code was developed to perform thermodynamic cycle analyses on alternative second-generation CAES plant designs (Fort 1982). The Compressed Air Energy Storage Cycle Analysis Program (CAESCAP) calculates property values and performance parameters for thermodynamic cycles using a variety of working fluids.

During this reporting period, analyses were performed on five CAES plant cycles using the CAESCAP code (Fort 1983). The designs analyzed were:

- conventional CAES
- adiabatic CAES
- hybrid CAES
- pressurized fluidized bed CAES
- direct coupled steam-CAES.

Inputs to the code were based on published reports describing each plant cycle. The thermodynamic station conditions, individual component efficiencies and overall cycle performance values were calculated. The resulting data were then used to develop availability and energy flow diagrams for each of the five cycles. The diagrams graphically illustrate the overall thermodynamic performance inherent in each plant configuration and enable a more accurate and complete understanding of each design.

## SIGNIFICANT ACCOMPLISHMENTS IN THE UNDERGROUND ENERGY STORAGE PROGRAM

There were many accomplishments during the reporting period. These accomplishments are identified below by technology.

### Seasonal Thermal Energy Storage

Significant accomplishments for STES activities during this reporting period were:

- Injection well modifications were made at the Mobile FTF in preparation for the third-cycle heat injection test (80°C), and the third-cycle test was completed. Seasonal thermal energy storage modeling technology was applied for test simulation/prediction.
- Isothermal and nonisothermal system and aquifer tests were completed at the St. Paul FTF. The first short-cycle heat injection test was completed and precipitators/filters were designed and installed to remove excessive calcium carbonate precipitate.
- Follow-on work was conducted at the Stony Brook site to resolve problems encountered with well-plugging during chill reinjection and the final subcontractor report was received.
- Monitoring and evaluation of the Parisian Department Store (Tuscaloosa, Alabama) chill ATES system were started.
- An RFP for development of novel chill storage concepts was issued, proposals evaluated, and a proposal selected for implementation.
- Research, cost-shared by the Minnesota Geological Survey, was initiated on utilization of existing flooded mines at Ely, Minnesota, for STES.

- Comparative analysis of first-generation seasonal ice storage concepts was completed.
- Argonne National Laboratory completed the first winter of experimental research on heat pipes for passive ice generation.
- The STES newsletter was published quarterly.
- The IEA Task VII ATES test case was analyzed by STES modeling technology.
- Additional development was completed on the geochemical model, and the model was used for evaluation at the St. Paul FTF.
- A user's manual was completed for the AQUASTOR economic model (PNL-4236).
- Development work was started on model technology of ATES in unconfined aquifers.
- Documentation of the CFEST numerical model for ATES evaluation was completed (PNL-4260).
- Fabrication of the Field Injectivity Test Stand (FITS) was completed; the system was used for analyses of St. Paul FTF injection tests, and documentation was completed.
- The Aquifer Properties Test Facility (APTF) was operational and tests were conducted on St. Paul FTF rock cores and generic aquifer materials.
- Documentation was completed on ATES costs with a seasonal chill source (PNL-4587).

## Compressed Air Energy Storage

Specific milestones and accomplishments in CAES during this reporting period were:

- The solution mined salt cavern reservoir stability study was completed and Geotechnical Factors and Guidelines for Storage of Compressed Air in Solution-Mined Salt Cavities was published (PNL-4242).

- The excavated hard rock cavern reservoir stability study was completed and Geotechnical Factors and Guidelines for Storage of Compressed Air in Excavated Hard Rock Caverns was published (PNL-4180).
- Preoperational experimental evaluations of St. Peter core from the Pittsfield Aquifer Field Test were completed.
- Preoperational numerical analysis of the operational response of the Pittsfield Aquifer Field Test was completed.
- A Form B operations permit was issued by the Illinois Environmental Protection Agency to allow testing at the Pittsfield Aquifer Field Test.
- Test planning for bubble development and cyclic injection at the Pittsfield Aquifer Field Test was completed.
- Construction of the Pittsfield Aquifer Field Test Facility was completed, including
    - well field
    - surface facility
    - instrumentation system.
- Air injection was initiated at the Pittsfield Aquifer Field Test and 4 months of bubble development were carried out at flow rates up to 450 scfm. A bubble volume of over 40 million scf was injected and stored within the Pittsfield St. Peter sandstone under DOE-PNL administration of the project.
- The Pittsfield Aquifer Field Test was transferred to the Electric Power Research Institute.
- The DOE-funded portion of the porous media cavern reservoir stability study was completed and Factors Affecting Storage of Compressed Air in Porous Rock Reservoirs was published (PNL-4707).
- Thermal/mechanical and thermochemical evaluation of thermal energy storage materials for CAES second-generation concepts was completed (PNL-4390).

- Screening and economic evaluation of CAES second-generation concepts were completed and an assessment of these concepts as a basis for further industrial development was prepared.
- Documentation was completed for transfer to industry of the CAESCAP computer program for thermodynamic optimization of CAES systems.

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# 1982 ANNUAL REPORT

## 1.0 INTRODUCTION

Rising prices and threatened shortages of natural gas and petroleum products are challenging U.S. electricity-generating utilities with increasing urgency. The utilities are confronted with the need not only to develop alternative energy sources, but also to find ways of using existing fuel supplies more efficiently.

To help meet the latter need, the U.S. Department of Energy (DOE) established a program to encourage timely implementation of underground energy storage concepts. 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 utilities could reduce energy consumption, increase the efficiency of existing generation capacity, and reduce their reliance on scarce energy resources.

Studies have shown that two 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 could reduce peak national demand for energy by as much as 7.5% if pursued aggressively. Estimates indicate that CAES could save up to 100 million barrels of oil annually by the year 2000 if vigorously implemented.

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 ground-water hydrologists agree that heated and chilled water can be injected, stored, and recovered from aquifers. Geologic materials are 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, garbage 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 rates above 70% for seasonal storage.

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 CAES systems. Some advanced CAES concepts would require no petroleum fuels.

Compressed air energy storage systems offer several advantages over conventional systems used by utilities for meeting peak load requirements. First, CAES plants consume less than a third of the petroleum fuel used by conventional combustion turbines, leading to long-term cost savings and less consumption of scarce fuels. Second, CAES plants do not experience siting limits of the degree confronting conventional pumped hydro plants. Finally, a well-designed CAES plant should have a smaller adverse impact on the environment than would a conventional peaking plant.

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 March 1982 to March 1983. Work performed prior to March 1982 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). The Underground Energy Storage Program objectives, approach, structure, 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 DESCRIPTION

Because of the potential benefits, the U.S. Department of Energy (DOE) has initiated activities to accelerate the successful introduction of the STES and CAES technologies. The strategy adopted by DOE was to identify factors inhibiting development of these technologies and then conduct research and development activities to evaluate and, if appropriate and possible, eliminate these factors.

### 2.1 STRATEGY AND RATIONALE

Early studies in both STES and CAES by DOE and others identified factors inhibiting development of these technologies. For STES these factors included technical uncertainties associated with using underground formations, principally aquifers, for cost-effective storage of relatively low-grade thermal energy (both heat and chill). Economic uncertainties were also identified as contributors to hesitant development of STES systems. It was further recognized that currently identified systems would not be feasible in all locations and that new concepts for STES should be explored and developed if promising.

For conventional CAES systems, a key factor is the question of 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. This factor could become a major barrier to future large-scale implementation of CAES technology. Thus, it was necessary to identify and examine second-generation CAES concepts, which are less reliant on petroleum fuel.

The Pacific Northwest Laboratory (PNL), operated for DOE by Battelle Memorial Institute, was selected as lead laboratory to investigate both STES and CAES technologies. In accordance with the strategy mentioned above, PNL was charged with development and management of programs in both STES and CAES. The resulting configuration of DOE-funded programs is shown in Figure 2.1. The CAES Program was initiated in FY 1975. The STES Program was started 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. Program management has been consolidated at PNL; however, technical activities remain separated because of primary differences in market, unit scale, technical sophistication for commercialization, and basic energy storage function.

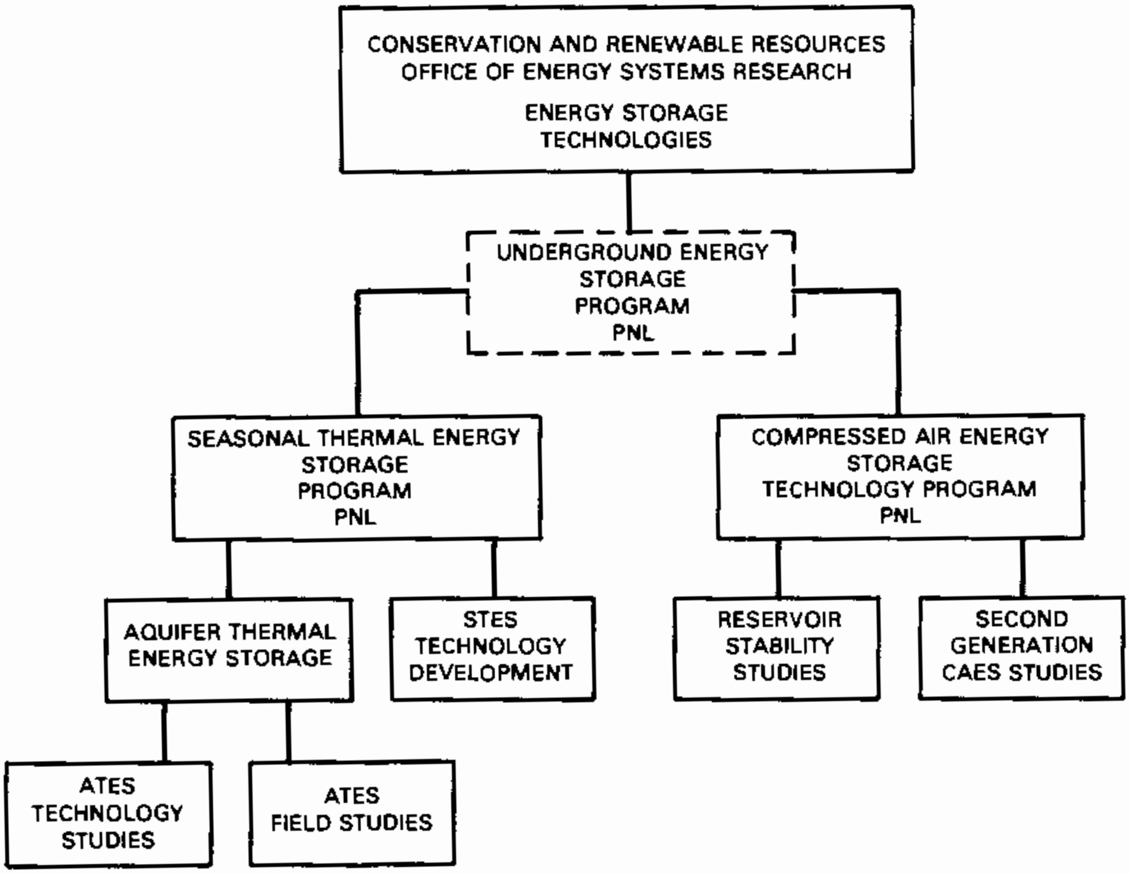


FIGURE 2.1. Department of Energy Programs to Pursue Development of Underground Energy Storage

## 2.2 GOAL AND OBJECTIVES

The ultimate goal of the UES Program is to reduce technical and economic uncertainties associated with underground energy storage technologies promising more effective, efficient, and economic utilization of energy resources.

Pursuant to the principal factors identified as inhibiting development, separate objectives were established for both STES and CAES. For STES, the objectives are:

- to establish guidelines and methods that permit the cost-effective appraisal of aquifer thermal energy storage (ATES) for utility, commercial or residential applications
- to screen and, as appropriate, develop promising STES concepts as alternatives to ATES. (This objective includes appraisal of technical, economic, institutional, and environmental issues.)

For CAES, the objectives are:

- to establish stability criteria for large underground air reservoirs in salt domes, hard rock, and porous rock formations that may be used for air storage in utility applications
- to develop advanced CAES technologies that would eliminate the dependence of CAES systems on petroluem fuels.

## 2.3 APPROACH AND STRUCTURE

The STES and CAES programs were consolidated into the Underground Energy Storage (UES) Program in FY 1981. Redirection of the program from technology demonstration to research and development was also received in FY 1981. Budget reductions constrained the shift from goals and objectives to those provided in the previous section. Further, direction from DOE requested that CAES activities be closed out in an orderly but expeditious manner. Thus, program management at PNL were faced with the challenge of redirecting and rescoping the program to meet the objectives with a significantly reduced budget while simultaneously closing out the CAES Program. The program was redirected and reduced in scope in FY 1982.

The approach identified in the STES program was to wind down the studies of low temperature ATES, concentrating future activities on technology research and development for high temperature (150°C) ATES systems and nonaquifer STES systems. Specifically, activities at the Mobile Field Test Facility (FTF) would be concluded and chill ATES activities would be reduced to monitoring the performance of the first such systems installed. Activities at the high temperature St. Paul FTF would be continued as a research project with more emphasis placed on investigating geotechnical issues and concept feasibility rather than operational performance and economic viability. Within funding constraints, new concepts in nonaquifer STES systems would be studied and those showing promise pursued aggressively. Analyses of institutional, environmental and legal issues of STES systems were terminated.

The approach now being pursued to satisfy the objectives for ATES is to support field studies at the St. Paul FTF in conjunction with laboratory studies at PNL and numerical modeling by the U.S. Geological Survey. Special technical studies have been initiated to address geochemical issues that have proved important to successful design and operation of high temperature ATES. (A small additional study has been initiated to determine the degree of geochemical problems that can be expected in ATES systems at other locations.) Testing at the St. Paul FTF will continue through short cycle testing in FY 1983 and, funds permitting, longer term testing in FY 1984. Supported by geohydrologic analysis in the laboratory, geochemical studies, and numerical modeling of the system, sufficient information would be obtained from testing at St. Paul to develop at least preliminary design and operating criteria for high temperature ATES. Decisions concerning participation in a demonstration type of project could be made when these activities were complete.

The approach employed in developing nonaquifer STES (NATES) systems was to screen known NATES systems for promise and solicit novel systems for evaluation and development, if appropriate. Screening of existing NATES systems determined that ice generation and storage systems were the best candidates. Additional investigation determined that their advantage was real but was confined to the northern states. The approach now being used is to investigate novel ice and other chill storage systems that promise improved performance, lower cost or greater operating range. Studies were commissioned at Argonne National Laboratory for testing passive winter ice generation and storage systems and, very recently, for investigating passive clathrate formation for chill storage. In response to an RFP for novel chill NATES systems, a study of the use of solar-driven zeolite-augmented ice storage systems was initiated at the New Mexico Solar Energy Institute, due for completion in late 1983. An additional RFP for novel heat NATES systems has been prepared and will be issued in May 1983. The effort to identify and develop novel NATES systems is consistent with the second STES objective as well as the overall direction of DOE toward R&D in high risk, high payoff technologies.

Given the willingness of private industry to continue CAES development, the approach adopted to satisfy the CAES Program objectives given earlier was to transfer remaining programs to other industry sponsors or truncate R&D activities at the nearest significant and appropriate milestone. Additional efforts were made to provide documentation of activities that were being terminated before completion or that had been given low priority for documentation previously because further study awaited results in other program elements.

Arrangements were made during the reporting period to transfer the major remaining long-term research project in CAES Reservoir Stability (the Pittsfield Aquifer Field Test) to the Electric Power Research Institute, once the facility was operational and preliminary testing was completed. Documentation on stability criteria in salt cavities and hard rock caverns was completed and interim stability criteria were prepared for porous media reservoirs for issue in May 1983. Except for providing technical consultation to the EPRI-sponsored activities at the Pittsfield Aquifer Field Test, no further effort is anticipated in CAES.

Studies of second-generation CAES thermal energy storage (TES) material performance, initiated in FY 1981, were completed during the reporting period. Plans to perform longer-term testing were abandoned. Studies to thermodynamically characterize the performance of several promising second-generation CAES systems were completed and the numerical model used to characterize system thermodynamics was documented.

The structure of the STES and CAES R&D efforts is shown in Figure 2.2. This figure shows the overall structure of the UES Program as well as the principal activities within the program. For the most part, the structure corresponds to the approach provided in the previous discussion except that additional details are given on program activities and the performers of those activities.

## 2.4 MAJDR MILESTONES

The major programmatic milestones are provided in Figure 2.3. The major milestones scheduled during the reporting period are listed in Table 2.1 along with short discussions of progress toward those milestones. The programmatic milestones are consistent with the objectives of the program. However, the reader will note that the discussion of progress in the various elements of the program given in Sections 3.0 and 4.0 will include activities in addition to those identified in Figure 2.3. These activities are either of lesser importance than those identified in Figure 2.3, or are required to conclude previously funded activities in an orderly fashion (e.g., Stony Brook FTF well rejuvenation efforts).

## 2.5 RESOURCE REQUIREMENTS

To achieve the program objectives, expenditures up to $28.9 million may be required for the period 1980 through 1985. Figure 2.4 shows the

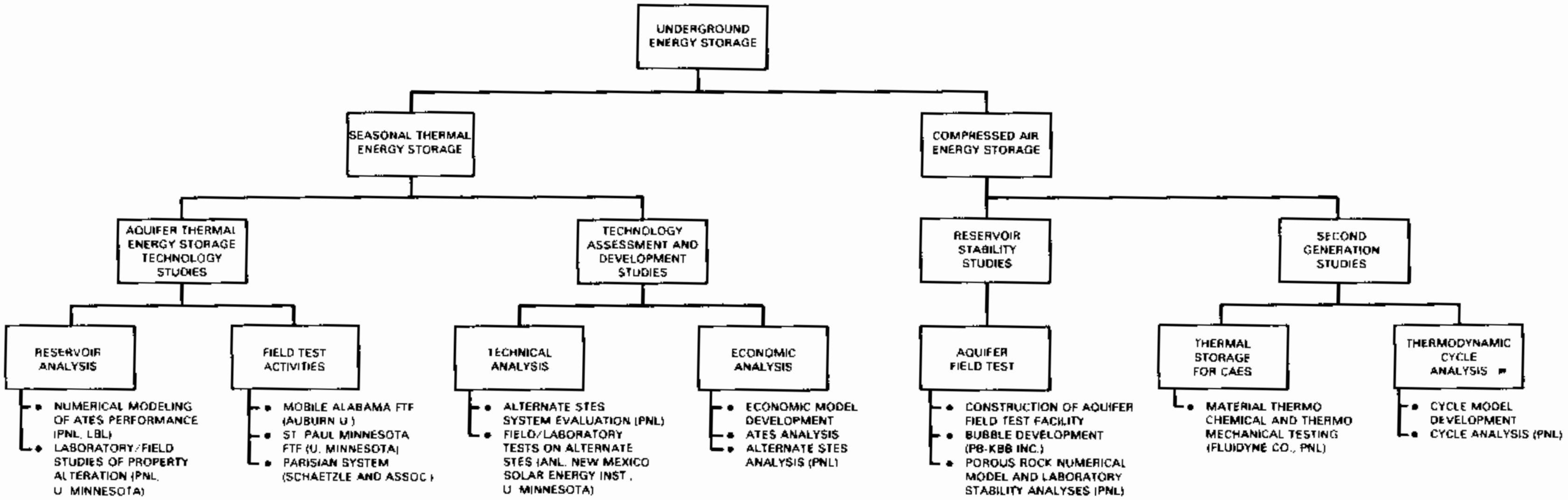


FIGURE 2.2. Underground Energy Storage Program Structure and Principal Activities

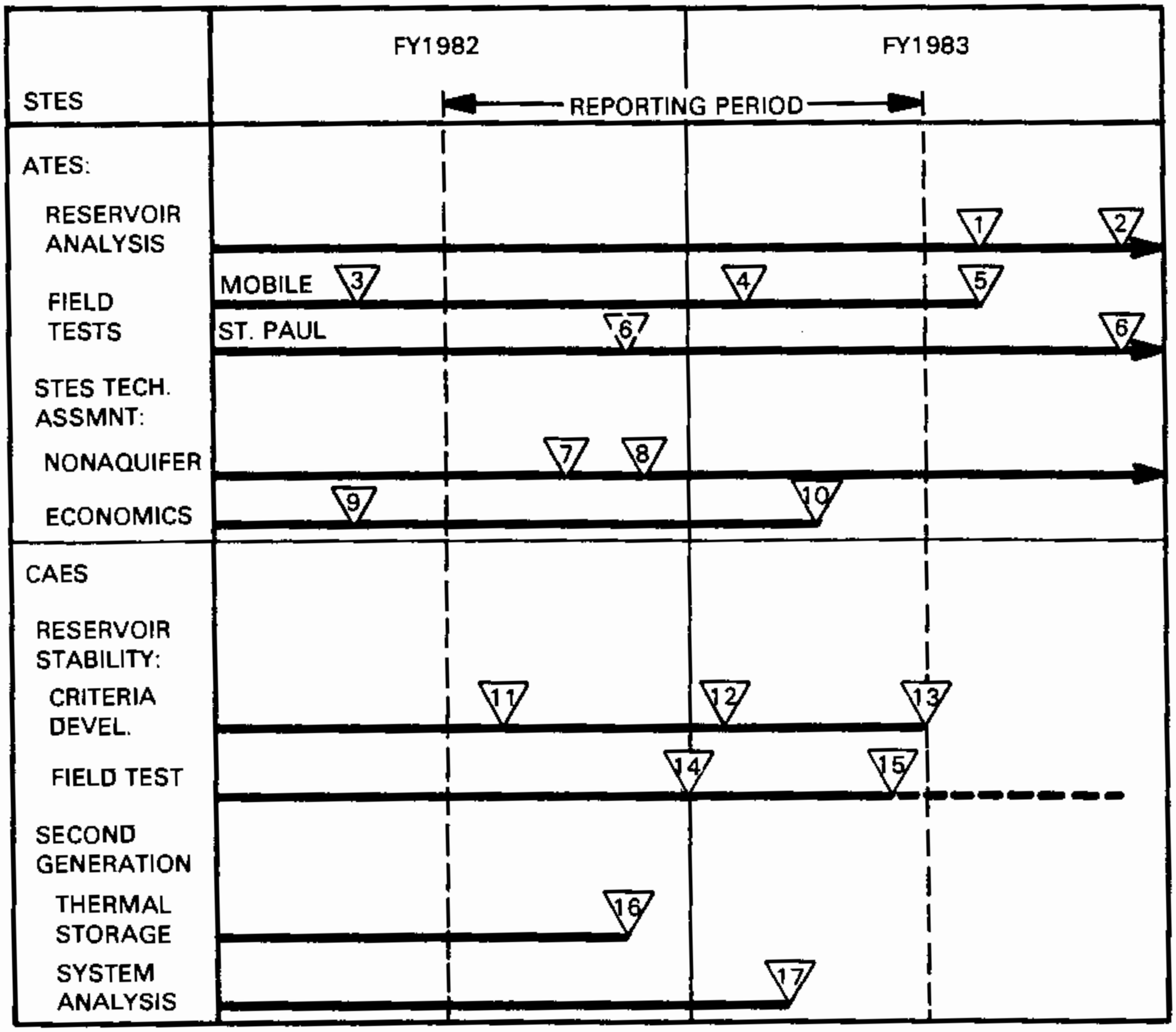


FIGURE 2.3. Major Underground Energy Storage Program Milestones

annual funding requirements by the four major program elements from FY 1979 through FY 1985. Activities in ATES include the demonstration studies funded into FY 1981.

As can be seen, increased resources will be required for the growing program in nonaquifer STES technology development. Additional support will be required for completion of high temperature ATES studies.

TABLE 2.1. Major Underground Energy Storage Program Milestones and Progress

| Milestone | Progress |
|---|---|
| 1. Complete model analysis of the Mobile FTF third cycle results | On schedule for completion in June 1983 |
| 2. Complete laboratory analysis of St. Paul FTF flow and geochemical properties | On schedule for completion in September 1983 |
| 3. Complete second cycle at Mobile FTF | Completed ahead of schedule in January 1982 |
| 4. Complete third cycle at Mobile FTF | Completed on schedule in November 1982 |
| 5. Complete all Mobile FTF activities | On schedule for completion in June 1983 |
| 6. Complete short cycle tests at St. Paul FTF | Calcium carbonate precipitation problems and associated permitting problems resulted in delay to September 1983 |
| 7. Award contract for non-aquifer STES concept testing | New Mexico Solar Energy Institute awarded contract for experiments on zeolite-augmented STES of ice |
| 8. Complete screening of non-aquifer STES concepts | Completed in August 1982 |
| 9. Complete economic analysis of ATES of heat | Completed in January 1982 |
| 10. Complete economic analysis of ATES of chill | Completed in January 1982 |
| 11. Issue final reservoir stability criteria for CAES in hard rock | Completed in May 1982 |
| 12. Issue final reservoir stability criteria for CAES in salt | Completed in November 1982 |
| 13. Issue interim reservoir stability criteria for CAES in porous media (aquifers) | Completed in March 1983 |
| 14. Begin air injection at the Pittsfield Aquifer Field Test | Completed October 2, 1982 |
| 15. Transfer the Pittsfield Aquifer Field Test to the Electric Power Research Institute | Completed February 1, 1983 |
| 16. Complete material screening laboratory testing for CAES thermal energy storage components | Completed August 1982 |
| 17. Complete thermodynamic cycle studies and model documentation | Completed February 1983 |

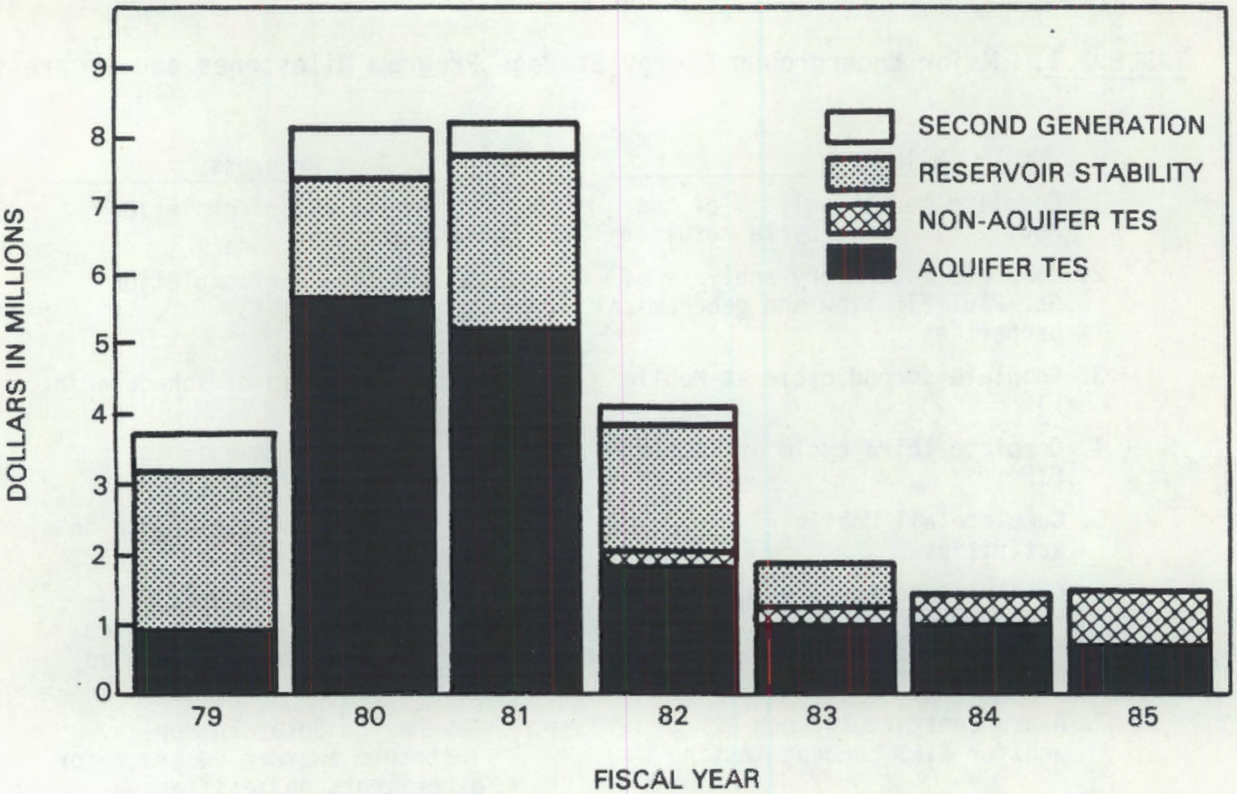


FIGURE 2.4. Underground Energy Storage Program Annual Funding Requirements

# 3.0 SEASONAL THERMAL ENERGY STORAGE TECHNOLOGY

The goal of the Seasonal Thermal Energy Storage (STES) Program is to develop the technology for economic storage and retrieval of energy on a seasonal basis to the point of adoption by entrepreneurial groups. The program scope encompasses studies of concepts that 1) utilize heat or cold available on a seasonal basis from waste sources or other surplus sources to reduce peak period energy demand; 2) reduce electric utility peaking requirements; or 3) contribute to the establishment of favorable economics for district heating and cooling systems. Aquifers, ponds, earth, lakes, and engineered structures are examples of physical systems that have potential for seasonal storage.

Achievement of significant entrepreneurial activities in STES will require the establishment of technical and economic feasibility and institutional acceptability of a variety of STES concepts. The principal research and development requirements may be met by fulfilling two objectives:

- Establish guidelines and methods that permit the cost-effective appraisal of Aquifer Thermal Energy Storage (ATES).
- Screen and, as appropriate, develop promising STES concepts as alternatives to ATES. (This objective includes appraisal of technical, economic, institutional and environmental issues).

Research and development on a broad range of topics is required if these objectives are to be satisfied.

Research beyond the reasonable scope of entrepreneurs is needed on aquifer characteristics and their interrelationship and impact on aquifer thermal energy storage. Investigation of earth media thermal characteristics and behavior are required for dry earth and rock thermal energy storage; studies of barrier and insulation materials are needed for wet earth and insulated pond TES. Economic and institutional studies are needed to provide for acceptance of all types of large- scale, commercial STES methods. Development and application of modeling technology is required to simulate, optimize and predict performance of STES systems. Modeling requirements range from system/distribution performance to geochemical, hydrologic and heat transport simulation.

Research and development efforts required to meet program objectives are being carried out in the ATES Technology Studies Task and the STES Technology Assessment and Development Studies Task.

## 3.1 AQUIFER THERMAL ENERGY STORAGE TECHNOLOGY STUDIES

Aquifer thermal energy storage has the potential to significantly conserve and/or displace relatively scarce and costly petroleum fuels using near-term technology. Work on ATES continued during this reporting period on ATES model development/application and laboratory/field studies.

### 3.1.1 Goal and Objective

The objective of the Aquifer Thermal Energy Storage (ATES) research is to develop the required technology that will permit the economic development of thermal energy storage and retrieval in aquifers on a seasonal basis. Heat and cold from waste sources or surplus thermal energy from other sources would be stored for retrieval when needed to reduce peak period energy generation requirements and contribute to implementation of district heating and cooling systems.

### 3.1.2 Strategy

To meet the goal and objective, the ATES Technology Studies are divided into two tasks. Task 1, Reservoir Analysis, includes efforts designed to provide the technology for implementation of ATES. Task 2, Field Test Facility (FTF) Testing, is a major activity of the ATES Technology Studies. The FTFs are sites established to test heating and/or chilling technologies for energy storage in aquifers, and serve as in-situ laboratories for testing and verification studies leading to establishment of ATES guidelines. The activities encompassed by the two project tasks are outlined in Table 3.1, and described in the following subsections.

TABLE 3.1. Aquifer Thermal Energy Storage Studies Tasks and Projects

| Task/Project | Contractor | Status as of March 1983 |
|---|---|---|
| Task 1. Reservoir Analysis | | |
| Subtask i. Numerical modeling | | |
| a. Site analysis | Lawrence Berkeley Laboratory | Completed |
| b. Unconfined aquifer model development | University of Minnesota | On schedule |
| c. Areal flow model development | PNL | Completed |
| d. Geochemical modeling | PNL | Delayed by funding recission |
| e. Administration, coordination | PNL | On schedule |
| Subtask ii. Laboratory field studies | | |
| a. Laboratory testing of ATES core samples | PNL | On schedule |
| b. Critical particulate velocity study | Terra Tek Inc. | Completed |
| c. Development of improved core sample preparation | PNL/Terra Tek Inc. | Completed |
| d. Field injectivity analysis | University of Minnesota/PNL | Delayed by FTF operations |
| e. Technical support | PNL | On schedule |
| Task 2. Field test facilities | | |
| Subtask i. Mobile FTF | Auburn University | Completed |
| Subtask ii. St. Paul FTF | University of Minnesota | 3 months behind (Regulatory problems) |
| Subtask iii. Parisian project monitoring | W.J. Schaetzle | On schedule |
| Subtask iv. Dames & Moore follow-on | Dames & Moore | Completed |

### 3.1.3 Project Descriptions

In the following sections, the individual projects under Tasks 1 and 2 are described. Accomplishments during this reporting period are also discussed.

Task 1, Reservoir Analysis, provides information on subsurface performance of ATES systems for technical, economic and environmental evaluation. This task is divided into a numerical modeling subtask and a laboratory/field studies subtask. Assessment of ATES systems requires the utilization of numerical modeling techniques for both system analysis and design. Laboratory/field studies are needed to determine significant changes that may occur in the host aquifer under ATES conditions.

Task 2, Field Test Facility Testing, is being performed to obtain engineering design data and to conduct supporting research for solving ATES technical problems.

Two field test facility sites were selected to accommodate the variability of aquifer characteristics and the differences in low- and high-temperature storage concepts. Research includes the injection/storage/recovery of thermally enhanced water and the monitoring of thermal plume development during test cycles. The planned research program will provide data to test the validity of numerical analysis methods and a means of developing optimal thermal recovery systems and methods.

Parallel experiments on injectivity were carried out at both the Mobile and St. Paul FTF sites. The experiments will assess the long-term effects of heat injection on the ground-water systems. In addition, follow-on work was completed at the Stony Brook ATES Field Test Site to resolve well plugging problems. A final report on this problem was issued, completing the Stony Brook work.

Monitoring and assessment of the Parisian Department Store Chill ATES system (Tuscaloosa, Alabama) was initiated.

### 3.1.3.1 Numerical Modeling

C. F. Tsang (Lawrence Berkeley Laboratory), H. Haijirma (University of Minnesota), L. W. Vail (Pacific Northwest Laboratory)

#### Objective

Numerical modeling work has been performed by Lawrence Berkeley Laboratory, Pacific Northwest Laboratory, and the University of Minnesota. The objective of this work is to develop and utilize simulation technologies capable of predicting the behavior of ATES facilities. These simulation technologies will aid in the designing and evaluating the performance of ATES facilities.

#### Tasks

The numerical modeling work was subdivided into three tasks:

- Task 1. Areal Flow Model Development
- Task 2. Site-Specific Analyses
- Task 3. Evaluation of ATES Facilities in Unconfined Aquifers

#### Technical Progress

#### Task 1. Areal Flow Model Development

During this reporting period, PNL staff developed a numerical Areal Flow Model (AFM) capable of screening injection/pumping policies in multiwell ATES facilities. The AFM couples basic geohydrologic and economic considerations in an efficient user-oriented computer code.

The user controls system inputs (i.e., injection/pumping rates) interactively. These inputs represent management policies. The temperature of the injected water is controlled by a hypothetical counterflow heat exchanger. The tradeoff between increased flow rate (decreased temperature change) and decreased flow rate (increased temperature change) is defined by a heat exchanger efficiency function.

The AFM combines an uncoupled fluid and heat transport algorithm with a numerical description of steady areal flow. The projected costs of simulating multiwell ATES facilities with state-of-the-art transport codes justified the development of this simple multiwell ATES model.

The AFM is predicated on defining a representative set of streamlime planes. It transforms a three-dimensional aquifer into a set of streamline planes by numerically integrating an analytical expression for velocity. Convection is simulated as a one-dimensional translation of temperatures. Conduction is simulated as a one-dimensional (vertical) process with fixed temperature or thermally insulated boundary conditions.

### Task 2. Site-Specific Analyses

Earlier, Lawrence Berkeley Laboratory performed numerical simulations of the first two cycles of ATES field experiments conducted at Mobile, Alabama by Auburn University. The results of simulations are documented in Tsang et al. (1981) and Buscheck et al. (submitted to Water Resources Research). During this reporting period, LBL performed simulations in support of UES planning of the third cycle experiment and completed analysis of the third cycle test. A report on this analysis was drafted.

Alternative injection and production schemes were studied to maximize the recovery factor for a 3-month cycle with a constant injection flow rate of 112 gpm and temperature of 82°C. Using the knowledge that buoyancy flow is strong (gained from the first- and second-cycle simulations), three approaches were taken. Shown schematically in Figure 3.1, the approaches were:

1. Simply inject into and produce from the upper portion of the aquifer where most of the hot water would naturally flow because of buoyancy effects (labeled U).
2. Attempt to maintain a compact shape for the injected fluid. Buoyancy flow is counteracted by pumping from the bottom of the aquifer as hot water is injected into the top (labeled S).
3. Inject into the upper portion of the aquifer. Then, while producing from the upper portion, produce (and discard) colder water from the

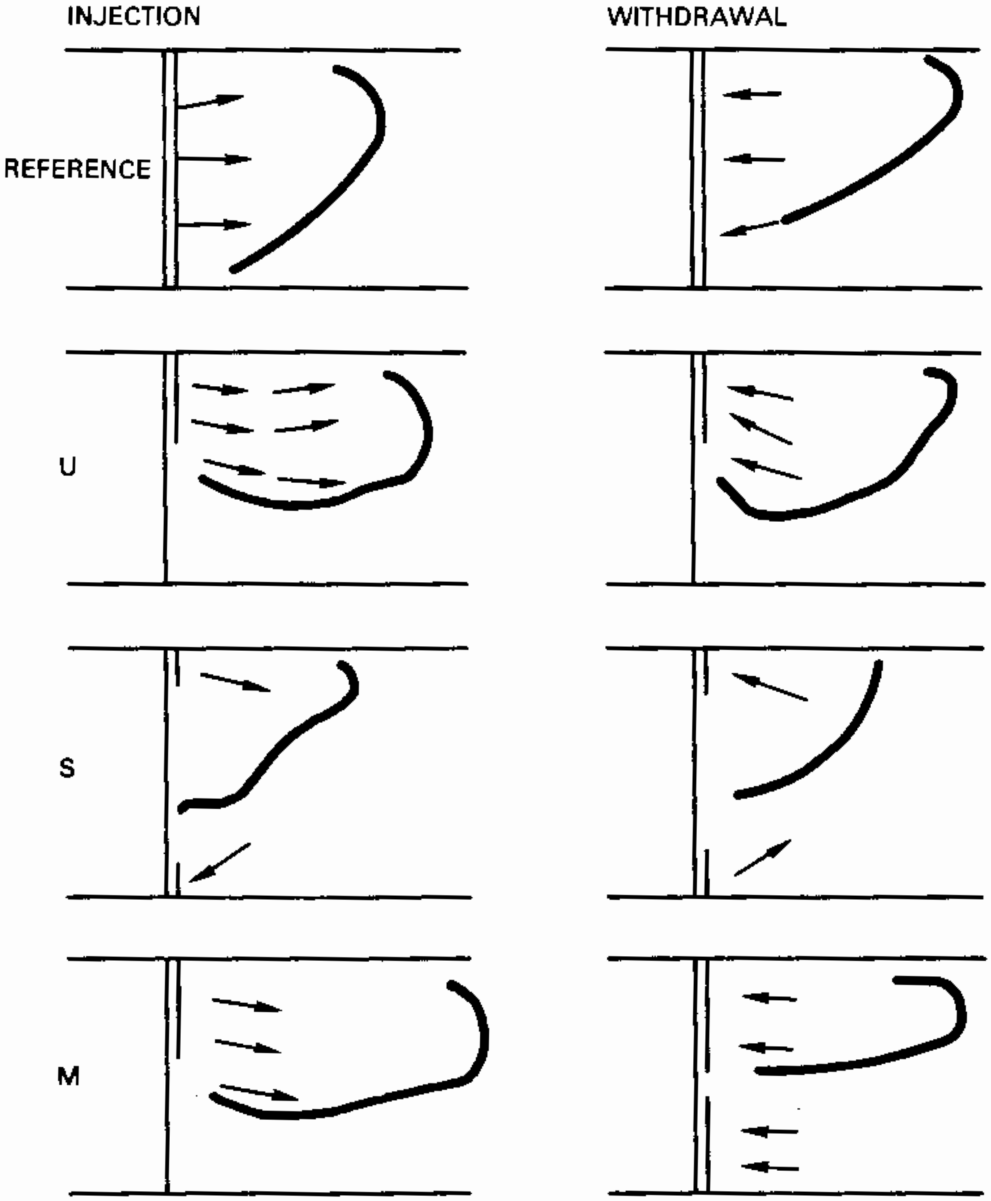


FIGURE 3.1. Injection Scenarios Modeled

lower portion of the aquifer. Thus, the colder water will not be pulled into the upper well where it would lower production temperature (labeled M).

For reference, Figure 3.1 also depicts an approach using full penetration during injection and production. Table 3.2 summarizes the results of the numerical simulations. For a cycle consisting of 1 month each of injection, storage, and production, the maximum recovery factor is approximately 0.52, representing an improvement of roughly 0.12 over the reference case. However, if the 3-month cycle is altered so that 2 months of injection are followed immediately by 1 month of production (at twice the injection flow rate, thereby doubling the storage volume), a recovery factor of approximately 0.66 is possible. Hence, for this system, the volume of fluid injected is as important as the manner in which it is injected and produced.

The successful prediction of the first- and second-cycle energy recovery factors demonstrated that the main physical processes occurring in the Mobile ATES field experiment are probably well understood and can be properly simulated by the numerical model PT. These third-cycle design studies consider a substantial number of alternative injection/production schemes. Results were transmitted to PNL and Auburn University for consideration in their decisions concerning the third-cycle experiment. These successful predictions demonstrate the value of numerical modeling. If one were to experimentally carry out all the alternative designs, an order of magnitude increase in budget and time would be required.

### Task 3. Evaluation of ATES Facilities in Unconfined Aquifers

The University of Minnesota began to develop a numerical model capable of evaluating the efficiency of ATES facilities in unconfined aquifers. This effort will result in a computer model that solves transient ground-water flow problems in unconfined aquifers by means of superposition of analytical functions. Heat transport phenomena will be incorporated in an approximate fashion. Horizontal heat conduction will be incorporated in a simplified manner.

## TABLE 3.2. Third-Cycle Design Studies

I. 1 month each injection, storage, production. $V = 18{,}300\ m^3$, $T_i = 82°C$, $Q = 112$ gpm

| Case | Well Screen Interval<br>Injection | <br>Production | Recovery Factor |
|---|---|---|---|
| Ref. | Full | Full | 0.404 |
| U1 | Upper 40% | Upper 40% | 0.448 |
| U2 | Upper 40% | Upper 20% | 0.501 |
| S1 | Upper 20%<br>Lower 20% | Upper 20% | 0.516 |
| S2 | Upper 20%<br>Lower 20% | Upper 20%<br>Lower 20% | 0.487 |
| M1 | Upper 40% | Upper 40%<br>Lower 55% | 0.500 |
| M2 | Upper 40% | Upper 20%<br>Lower 55% | 0.521 |

II. 2 months injection, 1 month production. $V = 36{,}600\ m^3$, $Q_p = 2Q_i$, $T_i = 82°C$, $Q = 112$ gpm

| Case | Injection | Production | Recovery Factor |
|---|---|---|---|
| U1-2 | Upper 40% | Upper 40% | 0.609 |
| M1-2 | Upper 40% | Upper 40%<br>Lower 55% | 0.629 |
| M3-2 | Upper 40% | Upper 40%<br>Lower 20% | 0.631 |
| M4-2 | Upper 40% | Upper 20%<br>Lower 20% | 0.661 |

### Publications

Three publications document the numerical modeling task in more detail.

Buscheck, T., et al. 1983. "Prediction and Analysis of a Field Experiment on a Multilayered Aquifer Thermal Energy Storage System with Strong Buoyancy Flow." Submitted for publication to Water Resources Research.

Gupta, S. K., et al. 1982. A Multi-Dimensional Finite Element Code for Analysis of Coupled Fluid, Energy, and Solute Transport (CFEST). PNL-4260, Pacific Northwest Laboratory, Richland, Washington.

Vail, L. W. and C. T. Kincaid. 1983. A Simple Areal Flow Model--A Screening Tool for Managing Aquifer Thermal Energy Storage Systems. PNL-SA-11126. Pacific Northwest Laboratory, Richland, Washington.

## 3.1.3.2 Laboratory/Field Analyses

S. C. Blair (Pacific Northwest Laboratory)

### Objective

The objective of this task is to describe the nature of changes on the in situ conditions of a host aquifer resulting from the operation of a Field Test Facility (FTF) and to assess the potential impact on the environment and/or the FTF itself. This will be accomplished by physicochemical analysis to characterize the properties of the aquifer materials and the ground-water fluids involved in the system.

### Tasks

The laboratory/field analyses encompass laboratory studies using the Aquifer Properties Test Facility (APTF), geochemical modeling of aquifers used for STES, and field studies using a Field Injectivity Test Stand (FITS).

#### Laboratory Studies

The laboratory studies were conducted to provide baseline data on dominant physicochemical processes active in aquifers used for ATES. In particular, these tests provide data on response of aquifer rock when invaded by water that is not in thermal or chemical equilibrium with the formation. This research uses an advanced rock mechanics apparatus specially designed to provide data on permeability, pore fluid chemistry and rock material properties at pressures, temperatures and flow rates equivalent to those imposed on a storage aquifer by an ATES facility.

### Field Studies

The field studies were conducted to provide onsite technical support and guidance for the operation of the St. Paul FTF, especially during critical testing periods.

### Geochemical Studies

The purpose of this task is to study chemical reactions that occur as a result of heating ground water and due to interactions between the heated solution and host aquifer sediments. These studies are important as many cases have been reported where such chemical reactions have caused injection problems. Potential reactions can be studied in the field and laboratory, plus the rock/water system can be modeled using computerized chemical modeling codes.

## Technical Progress

### Laboratory Studies

Early in 1982, activities on this task were directed toward developing an operational laboratory facility at PNL. One aspect of facility development was formulation of a detailed Operational Readiness Plan (ORP) for the Aquifer Properties Test Facility (APTF) and hydrotesting of all APTF components. The ORP was completed and the facility certified for operation in May 1982. A second important aspect of facility development was extensive shakedown testing of the various APTF systems to evaluate performance and data quality. In addition, a computerized data acquisition system was developed, which monitors up to 20 data channels and stores data in a form compatible with a variety of data processing utilities.

Six laboratory tests were conducted during 1982. These tests were designed to measure permeability of core samples at pressure and flow conditions equivalent to in situ conditions in an ATES storage aquifer and to assist in determination of major physicochemical processes active in an ATES aquifer as a function of temperature and time. Cores were tested from the most permeable zone of the St. Paul FTF storage aquifer.

Data from these tests indicate that 1) permeability remained essentially constant over a range of temperature from 25 to 150°C (Figure 3.2) and 2) during the first 30 hours, an increase in permeability was observed under conditions of reversed flow (Figure 3.3). Initial interpretation is that migration of internal fines was the major physicochemical process affecting permeability for these tests. These results are significant for the development of STES as they represent some of the first laboratory evidence that increasing temperature may not degrade the permeability of aquifer formations.

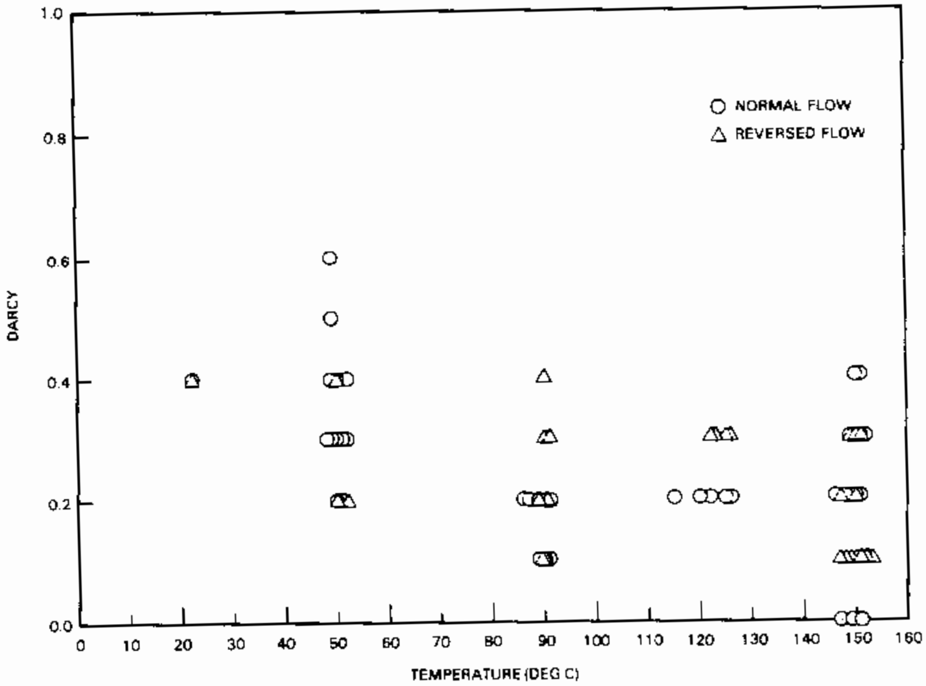


FIGURE 3.2. Permeability Versus Temperature, Normal and Reversed Flow

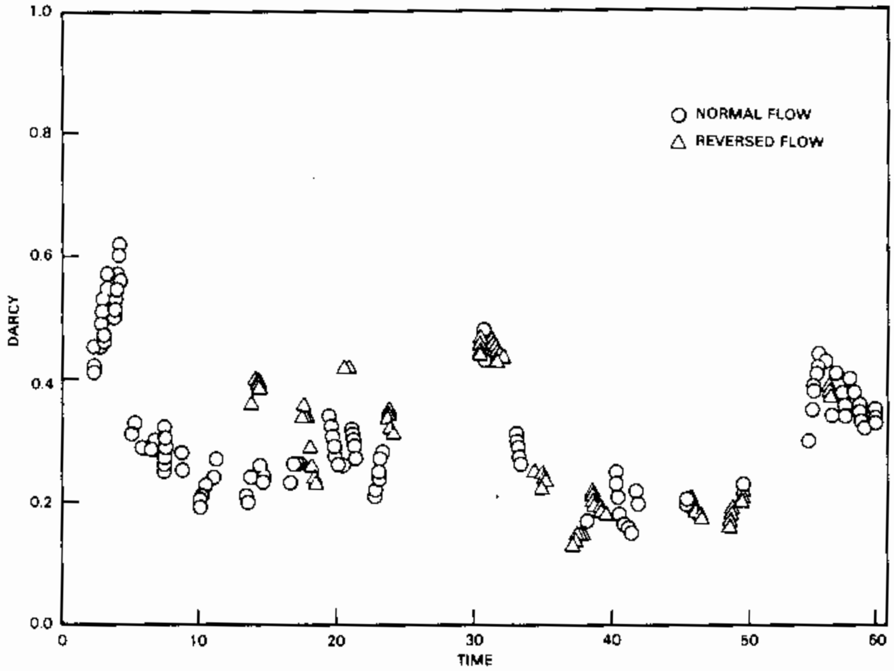


FIGURE 3.3. Permeability Versus Time, Normal and Reversed Flow

Research is now underway to further characterize important physicochemical processes occurring in the St. Paul FTF storage aquifer. This research includes studies of 1) chemical interactions between the injected fluids and the aquifer rocks, such as dissolution/precipitation of carbonate and silicate minerals, and 2) the effect of thermal cycling on physical properties of the aquifer rocks.

### Field Studies

During the past year, studies were made at the FTF site in St. Paul, Minnesota to characterize suspended solids content of injection/withdrawal fluid and to provide onsite support to University of Minnesota researchers during critical system tests. Particular intent and results of the various studies are summarized in the following paragraphs. These tests utilized a specially designed Field Injectivity Test Stand (FITS), which was installed at the St. Paul FTF in April 1982.

Injectivity Studies During Initial Startup and Cold Water Injection (April - May). Twenty-one successful filtration tests were done with the FITS during preinjection and cold injection activities. Filtration tests showed water to be injectable with suspended solids concentrations of no more than 0.13 mg/l for particles over 10 micron diameter. Massillon sandstone core was tested in the FITS and showed no significant decrease in permeability with time. Turbidity measurements made during preinjection pumping of Wells A and B at St. Paul indicated that 0.5 hour is required to flush the wells to obtain clear, injectable water.

First Hot Injection Cycle. Injection of heated Well B water into Well A began May 17, 1982. Filtration tests of the 60° to 85°C fluid stream were done with 0.45- and 10-micron pore-sized filters for two days before well impairment was experienced on May 18. Results from these tests and from SEM analysis of filter samples aided in diagnosing the impairment mechanism (precipitation of calcium carbonate).

Precipitator Testing. Injection impairment during the first injection cycle prompted development of a fluid conditioning system to improve injectability. Before implementing a full-scale system to precipitate calcite from the heated water, a model heater and precipitator were built. Utilizing this model system, a test series was conducted to evaluate the effectiveness of various precipitating agents. Results from these tests indicated that a crushed, sized limestone removed an acceptable amount of calcite from solution. The full-scale precipitator was filled with this material to treat heated ground-water for injection.

Second Hot Injection Cycle. The hot injection cycle of November was successful. Onsite filtration tests showed low suspended solids concentrations for the water at temperatures up to 90°C. Geochemical analyses showed that calcite was only slightly oversaturated. Fluid streams tapped upstream from the precipitator were less injectable and had much higher calcite contents. Core flooding tests using Well A core samples in the FITS showed no significant decrease in permeability with time.

No problems were encountered during the withdrawal and reinjection operations after 2 weeks of storage in Well A. Temperature of the withdrawal stream peaked at 76.6°C after 30 hours of pumping. Withdrawal was done for 5 days with a water temperature of 39°C at shutdown. Filtration tests indicated that the water was low in suspended solids; injectability was confirmed by the absence of plugging at Well B.

Suspended solids data for injection/withdrawal fluids are summarized in Table 3.3. In addition to providing data on the injectability of the fluid stream, the filtration tests provided valuable information on system performance. For example, metallic shavings found on several filters during the first storage test led to the discovery of a disintegrating pump bearing. Metallic shavings were also found on filters monitoring withdrawal during the second storage test.

TABLE 3.3. Summary of Suspended Solids Data for Injection and Withdrawal Fluids at Minnesota FTF (0.45-micron Filters)

| Field Study | Suspended Solids mg/l |
|---|---|
| Injection, Spring | 0.90 |
| Injection, Fall (after precipitator) | 0.33 |
| Withdrawal, Fall | 0.32 |

### Geochemical Studies

The MINTEQ geochemical modeling code and an empirical rate constant for calcite precipitation were used to determine the possible effect of mineral precipitation on St. Paul FTF operation and to aid in designing a method for eliminating this problem.

Using empirical data of the rate of calcite precipitation from solution and a rate constant that considers the surface area of the substrate on which the mineral is precipitating, it was found that the rate of calcite precipitation to expect from the heated Minnesota ground water is on the order of 200 mg/m$^2$-hr. This precipitation rate was used with data on the surface area of particles in the precipitator and the solution's residence time in the precipitator to estimate the amount of calcite removed from solution before injection.

Solution chemistry data were obtained from several of the laboratory tests. These data include results of inductively coupled plasma analysis of cations, ion chromatography analysis of anions, acid titrations for alkalinity and the pH measured immediately after sampling the system.

Analysis of the data suggests that at 25°C the dissolution of carbonate minerals requires a number of days to reach equilibrium with calcite and that a mineral more soluble than quartz is dissolving to provide silica to the water. Chalcedony may be limiting silica concentration in this solution.

Data for tests at 50°C show that chalcedony continues to limit silica concentration, although at a higher concentration level because of its increased solubility at this temperature. Carbonate minerals generally decrease in solubility with increasing temperature and the 50° solution was oversaturated with respect to calcite. A possible explanation may be that the dissolving carbonate mineral is not pure calcite but a more soluble phase such as magnesium-rich calcite. Apparently, calcite precipitation is not rapid enough to eliminate this oversaturated condition.

Additional geochemical studies of the APTF system are in progress. The composition of the solution used in the current study was designed to approximate that of heated storage water. Batch experiments with Minnesota ground water and mixtures of aquifer sediment and ground water will be performed to evaluate the precipitation rate of calcite in heated water and the effect of hot water/sediment interactions on solution chemistry and system performance.

A study is in progress to accumulate and organize a representative cross section of U.S. ground water analysis for classification of the waters by anion/cation concentrations and to allow calculation of geochemical stabilities for generic water types. This will permit identification of regional aquifers with greatest promise for ATES utilization. This approach has involved identification of specific impairment mechanisms originating in potential ground water-ATES system interactions. These mechanisms relate to specific states of water chemistry, water temperature, reservoir terrain, and system hardware. The nation's ground-water resources have been reviewed using U.S. Geological Survey Professional Paper 813 to delineate region boundaries and identify major aquifers within each region.

References to geochemistry and water quality have been obtained mainly by computer searches of the National Ground Water Information Center Data Base, Water Resources Abstracts, and GEOREF. Six 9-track magnetic tapes were obtained from the U.S. Geological Survey to provide ground-water quality data in backfile format.

Particular generic ground-water types are identified based upon ratios of dominant solute ions and molecules. These are usually coupled to associated aquifer mineralogy. Each ground-water type is qualitatively ranked for ATES applicability. Averaged ground-water chemical analyses are to be evaluated by the MINTEQ code up to 100°C to predict relative stabilities of solutions. Impacts of water qualities on associated aquifers are to be assessed assuming temperatures from 0° to 200°C.

The most favorable regions for ATES in the United States are being identified. These are based upon projected aquifer performance, energy availability and socioeconomic demand.

### 3.1.3.3 Mobile, Alabama Field Test Facility

F. J. Molz (Auburn University)

#### Objective

Auburn University's Mobile, Alabama test site was selected for low-temperature heat storage experiments. The Mobile experiments were injection/storage/recovery tests conducted with injection temperatures in the range of 55°C to 90°C. The aquifer ambient temperature was 20°C. The purpose of the tests was to demonstrate the technical feasibility of the ATES concept.

## Tasks

Work at the Mobile site was directed toward accomplishing four basic tasks. Field work during this reporting period was concentrated on cycle 3 of task 3. Data analysis and data reporting for cycles 2 and 3 were accomplished during this reporting period.

- Task 1 - Design and construct a doublet well field to conduct ATES experiments
- Task 2 - Determine through field testing the aquifer parameters necessary for ATES analysis
- Task 3 - Conduct 3 cycles of injection, storage and recovery experiments. The cycles are denoted 3-1, 3-2, and 3-3.
- Task 4 - Monitor the transient temperature distribution in the aquifer and the confining layers and provide data for developing and testing mathematical models.

## Technical Progress

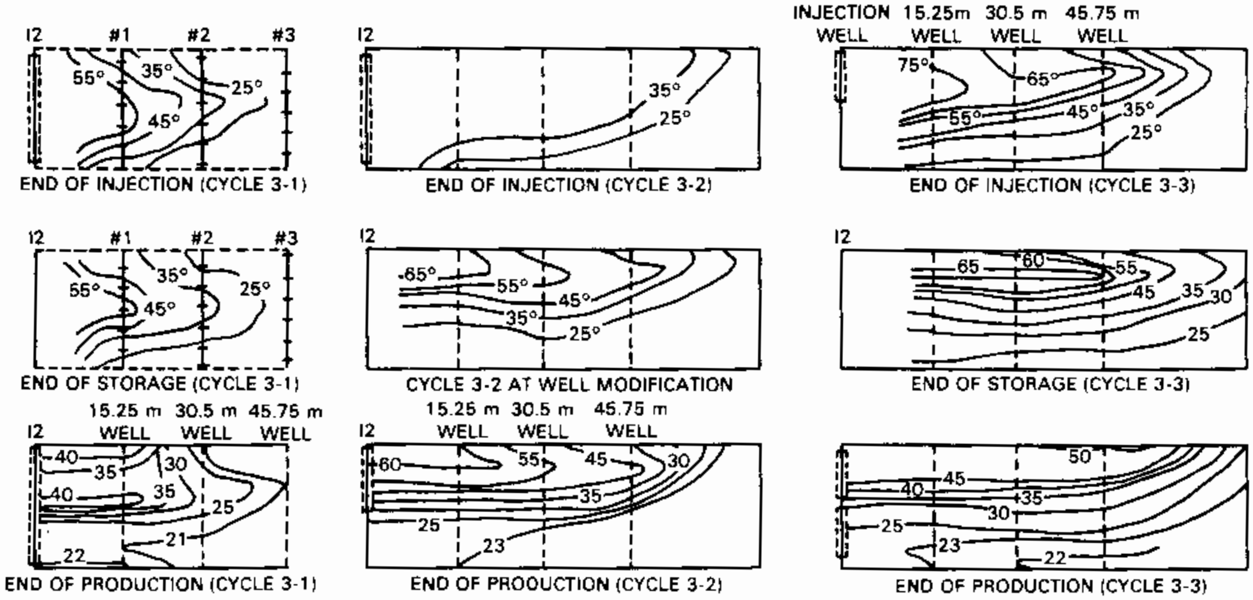
### Field Experiment-Cycle 3-3

Cycle 3-3 injection began on April 7, 1982 and continued intermittently until July 14, 1982, when a total of 56,580 $m^3$ of water had been injected. The average injection temperature was 79°C. A 57-day storage period ended on September 9, 1982, and recovery pumping with the dual recovery system began. Recovery pumping was officially ended on November 16, 1982. At this time 64,140 $m^3$ of water had been produced and 19,300 $m^3$ rejected.

Because of significant transport of energy to the upper zone of the confined aquifer in cycles 3-1 and 3-2, a modified recovery system was designed and constructed. The dual recovery system consisted of a production well screened near the top of the aquifer and a rejection well screened near the bottom of the aquifer. The purpose of the system was to recover warmer water from the top of the aquifer and to be able to reject cooler water located in the bottom of the aquifer.

Wells I2 and R1 constitute the dual recovery well system. During recovery, I2 is called the production well and R1 is called the rejection well. The wells are separated horizontally by 1.8 m, with I2 screened in the top 9.1 m of the storage aquifer. The rejection well screen is 9.1 m in length also and begins 1.5 m below the bottom of the upper screen.

Plots of isotherms showing the temperature distribution in the storage aquifer at various times are presented in Figure 3.4. Results from cycles 3-1 and 3-2 are also included in Figure 3.4 for comparison. The temperature history of the production and rejection wells during recovery pumping of cycle 3-3 is shown in Figure 3.5. Figure 3.6 shows plots of energy recovery fraction versus cumulative recovery volume with (curve A) and "without" (curve B) the dual well system. (To get curve B we simply combined the heat flows and pumping volumes from the production and rejection wells as if they were a single well.)



END OF INJECTION (CYCLE 3-1)
END OF INJECTION (CYCLE 3-2)
END OF INJECTION (CYCLE 3-3)
END OF STORAGE (CYCLE 3-1)
CYCLE 3-2 AT WELL MODIFICATION
END OF STORAGE (CYCLE 3-3)
END OF PRODUCTION (CYCLE 3-1)
END OF PRODUCTION (CYCLE 3-2)
END OF PRODUCTION (CYCLE 3-3)

FIGURE 3.4. Plots of Isotherms in the Storage Aquifer at Various Times

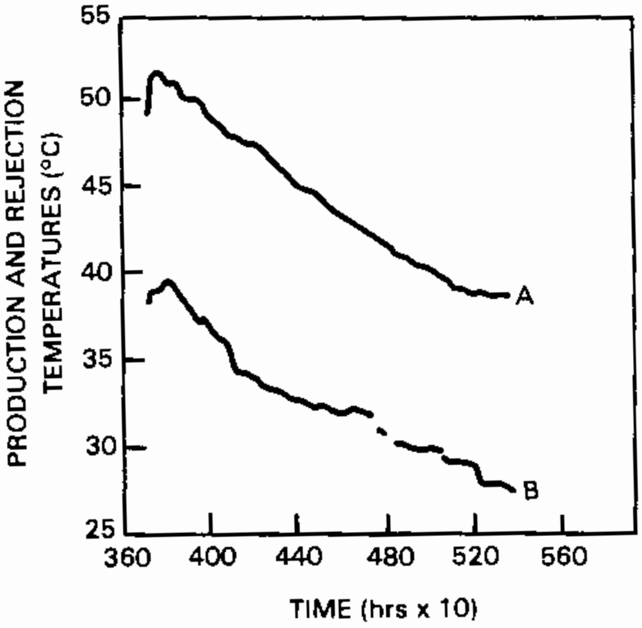


FIGURE 3.5. Production (Curve A) and Rejection (Curve B) Temperatures Versus Time for Cycle 3-3

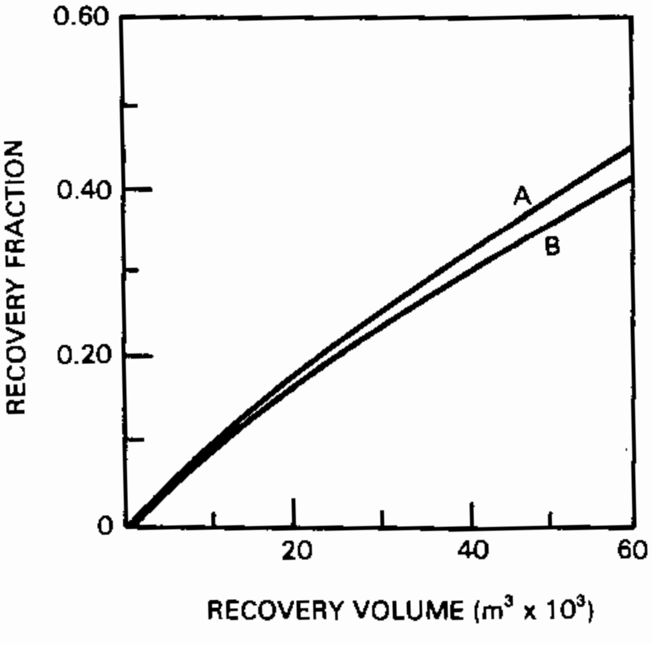


FIGURE 3.6. Cycle 3-3 Energy Recovery Fraction Versus Volume: A, with the Dual Recovery System; B, with a Single Equivalent Well

### Data Analysis

After analysis (see final report, publications, and manuscripts under review for publication for details), the following observations were made.

1. There is a layer of high intrinsic permeability near the horizontal center plane of the aquifer around the injection well I2. During injection much of the flow occurred in this layer, which caused significant lateral spreading of the injected volume (Figure 3.4).
2. During storage, thermal convection in and above the high permeability layer coupled with conduction caused more lateral distribution of the heat.
3. Hot water in the top of the aquifer, having spread over a large area, resulted in a large conductive heat loss to the upper confining layer.
4. The selective, dual recovery system had a very minor effect (c.f. curves A and B in Figure 3.6) because the aquifer nonhomogeneity at the location of the current experiments and anisotropy controlled the velocity distribution to a significant extent.

Because of the above phenomena, the initial production temperature in cycle 3-3 was 51.5°C, well below the average injection temperature of 79°C, and the recovery factor of cycle 3-3 was 42%.

The degree of aquifer nonhomogeneity inferred at the location of the current experiments was not apparent during previous experiments at a location only 109 m away. Therefore, aquifers with the same transmissivity can behave quite differently in a thermal energy storage sense. Vertical variations of horizontal hydraulic conductivity are difficult to detect, and moderate-scale hot water injection testing along with computer simulation may be an economical procedure for making an overall and final evaluation of an aquifer's suitability for ATES.

### Publications and Presentations

Auburn University. 1982. "Mobile Field Test Facility." Presented at the Underground Energy Storage Midyear Review, May 18, 1982, Richland, Washington.

Guven, O., J. G. Melville, and F. J. Molz. 1983. "An Analysis of Surface Heat Exchange on the Thermal Behavior of an Idealized Aquifer Thermal Energy Storage System." Technical note, accepted for publication in Water Resources Research.

Melville, J. G., F. J. Molz, and O. Guven. 1982. "Thermal Energy Storage in Confined Aquifers Using the Doublet Well Configuration." Presented at the U.S. Department of Energy Annual Contractors' Review Meeting, August 23-26, 1982, Arlington, Virginia.

Molz, F. J., O. Guven and J. G. Melville. 1983. "Aquifer Thermal Energy Storage Experiments at the Mobile Field Test Facility: Recent Results." To be presented at the International Conference on Subsurface Heat Storage in Theory and Practice, Stockholm, Sweden, June 6-8, 1983.

Molz, F. J., O. Guven, J. G. Melville, R. W. Falta, and C. V. Camp. 1983. "Effects of Buoyancy Flow and Nonhomogeneities on Aquifer Thermal Energy Storage." Presented at the AGU Spring Meeting, San Francisco, California.

Molz, F. J., J. G. Melville, O. Guven, and A. D. Parr. 1983. "ATES: An Attempt to Counter Free Thermal Convection." Accepted for publication in Water Resources Research.

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Molz, F. J., Chin Fu Tsang, M. Walton, J. G. Melville and O. Guven. 1983. "ATES: Results and Simulations of High and Low Temperature Experiments." To be presented at the 1983 Intersociety Energy Conversion Engineering Conference, August 22-23, 1983, Orlando, Florida.

Parr, A. David, J. G. Melville and F. J. Molz. 1983. "HP41C and TI59 Programs for Anisotropic Confined Aquifers." Ground Water. 21(2):212-220.

Parr, A. D., F. J. Molz, and J. G. Melville. 1983. "Aquifer Testing for Thermal Energy Storage." Ground Water. 21:22-35.

### 3.1.3.4 St. Paul, Minnesota Field Test Facility

W. E. Soderberg and M. S. Walton (University of Minnesota)

#### Objective

The University of Minnesota's St. Paul campus is the site of the high temperature FTF. This site will provide the data necessary to evaluate the feasibility of high temperature storage.

#### Tasks

Principal efforts during the reporting period have been directed toward tasks for conducting and evaluating ambient and heated water injection tests:

1. testing and operating the mechanical and monitoring systems
2. conducting aquifer tests using each pumping well
3. conducting injection tests of both ambient (cold) (11°C) and heated ground water
4. calibrating the isothermal computer model
5. monitoring and modeling aquifer water chemistry
6. planning for long-term tests.

#### Technical Progress

##### Testing the Mechanical and Monitoring Systems

From February through March 1982, the below-ground monitoring system was tested during an aquifer test of well A. During April 1982, prior to any injection tests, the heating side of the system tested the aboveground monitoring systems for the first time. The water heated in the tests was run to waste. Results proved that the heat exchangers were capable of heating the aquifer water from 12°C (53°F) to approximately 116°C (240°F). The aboveground monitoring systems were checked during these tests. Concurrent with these tests, the Field Injectivity Test Stand was installed and tested.

## Aquifer Test

A 4.5-day aquifer test using well A and a 1-day aquifer test using Well B were conducted at pumping rates of 340 gpm (21.4 l/sec$^{-1}$). Analysis of test results indicates a transmissivity of 365 ft$^2$/d (3.9 x 10$^{-4}$ m$^2$/sec$^{-1}$) for the upper Franconia portion and of 690 ft$^2$/d (7.4 x 10$^{-4}$ m$^2$/sec$^{-1}$) for the Ironton-Galesville portion of the FIG aquifer. Total transmissivity for the layered FIG aquifer is 1055 ft$^2$/d (1.1 x 10$^{-3}$ m$^2$/sec$^{-1}$), agreeing closely with initial pump test data (900 to 1050 ft$^2$/d). Analysis of the test results suggests that the FIG aquifer is areally anisotropic in addition to being distinctly zonal.

## Injection-Cycle Tests

Two ambient-temperature ground-water injection cycles (hereafter referred to as cold-injection cycles) and two heated ground-water injection cycles were started. Only the second of each of the cycles ran successfully. Clogging problems curtailed the other test cycles.

The first cold-injection cycle was run using the system as the design engineer had proposed, i.e., the water was introduced to injection well A through the annular space between the column pipe and the outer casing. For the first 24 hours of this test, well B was pumped at 350 gpm (22.1 l/sec$^{-1}$) and water was introduced at well A at a rate of 125 gpm (7.9 l/sec$^{-1}$). Excess flow was discharged to a nearby storm sewer. Flow was then increased into well A over a 30-minute period to 300 gpm (18.9 l/sec$^{-1}$) and the pumping rate of well B was adjusted to an equal rate.

This test was terminated 6.7 hours later because of the high rate of head buildup in well A (Figure 3.7, A-A') caused by clogging of the aquifer due to air entrainment. Redevelopment pumping of well A was immediately begun to pump out the entrained air. Pumping at increasing rates continued for 19 hours. Initial water pumped out was very turbid and frothy. Dissolved oxygen levels were greater than 12 ppm and turbidity levels were as much as 163 NTU. Dissolved oxygen and turbidity at the cessation of

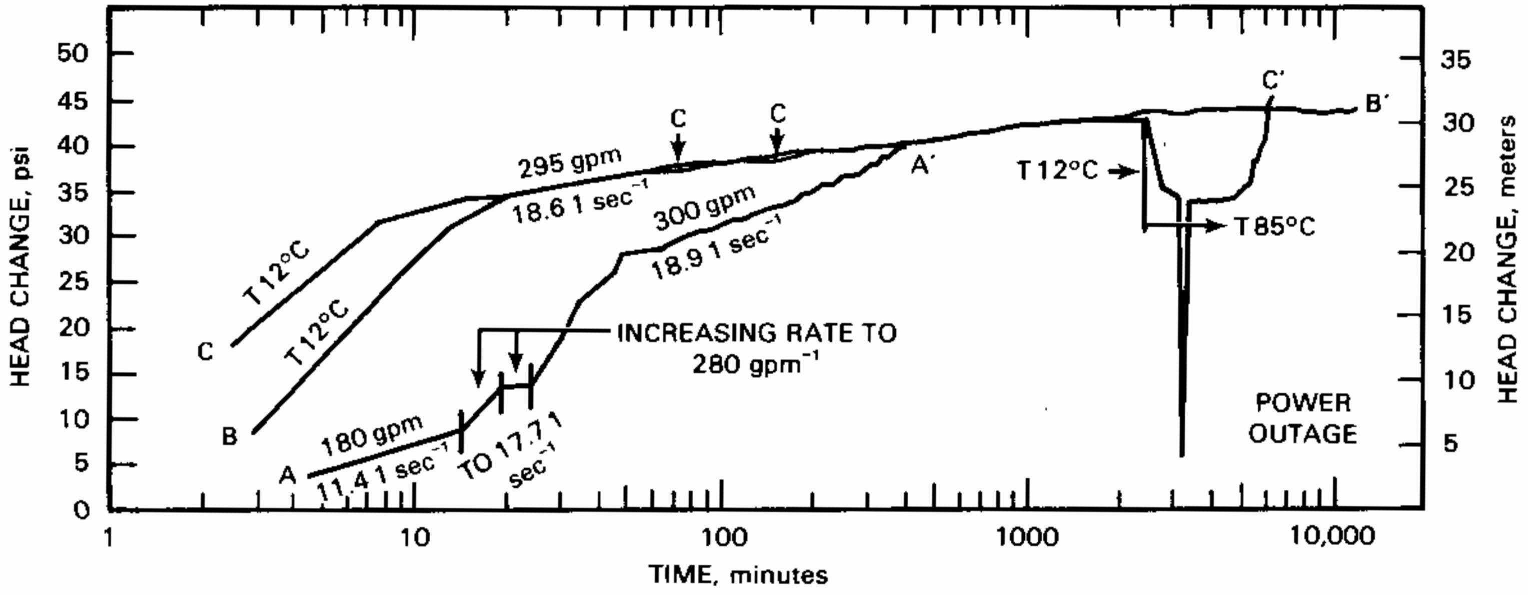

FIGURE 3.7. Head Changes in Well A as a Function of Time During Injection. A-A' - Ambient temperature (12°C) water introduced through annular space (A-A' begins 24 hours after start of injection). B-B' - Ambient temperature (12°C) water introduced through column pipe. C-C' - Ambient temperature (12°C) water followed by 82° to 85°C water introduced through column pipe.

pumping were less than 0.5 ppm and 0.29 NTU, respectively. Water supplied for injection had a dissolved oxygen level of less than 0.1 ppm and a turbidity value of 0.15 NTU. Air entrainment occurred because it was impossible to maintain positive pressure on the water entering the annular space of the well.

Following recovery and system flushing, a second cold-injection cycle began with the water routed through the column pipe of well A. The column pipe was a completely water-filled pressurized system and no air clogging resulted. A completely successful 8-day test followed (Figure 3.7, B-B'). The average injection rate was 295 gpm (18.6 $l/sec^{-1}$). Head buildup in well A appeared to approach equilibrium at about 44 psi.

Following plans for the first hot-injection cycle, ambient-temperature water was injected for two days, allowing comparison with the previously run cold-injection test (Figure 3.7, C-C'). At the appointed time, steam was introduced, heating the injected aquifer water to 85°C (185°F). The heat dropped immediately by 7 psi in the injection well as a result of the decrease in kinematic viscosity of the water from 0.013 to 0.003 stoke as the water was heated by 73°C. Approximately 9.3 hours later, a power outage at supply well B required that the steam be shut off and the system be configured for restart. The spike on curve C-C' (Figure 3.7) shows clearly the drop in head when injection stopped. Upon resumption of injection, the pressure trends continue. From this point to the conclusion of the test the injection temperature was about 82°C (180°F) and the flow rate approximately 295 gpm (18.6 $l/sec^{-1}$).

Pumping continued until it was clear that clogging was taking place in well A (Figures 3.7 and 3.8). The constant and increasing rate of head buildup in well A, along with the relative head changes in the Ironton-Galesville and the upper Franconia portions of the aquifer observed in monitor wells, suggested that the Ironton-Galesville was clogging first and the clogging was continuing. Differential pressures across the condenser increased during the heated-water cycle, indicating that scale buildup was taking place in the heat exchanger as the water was heated. Following

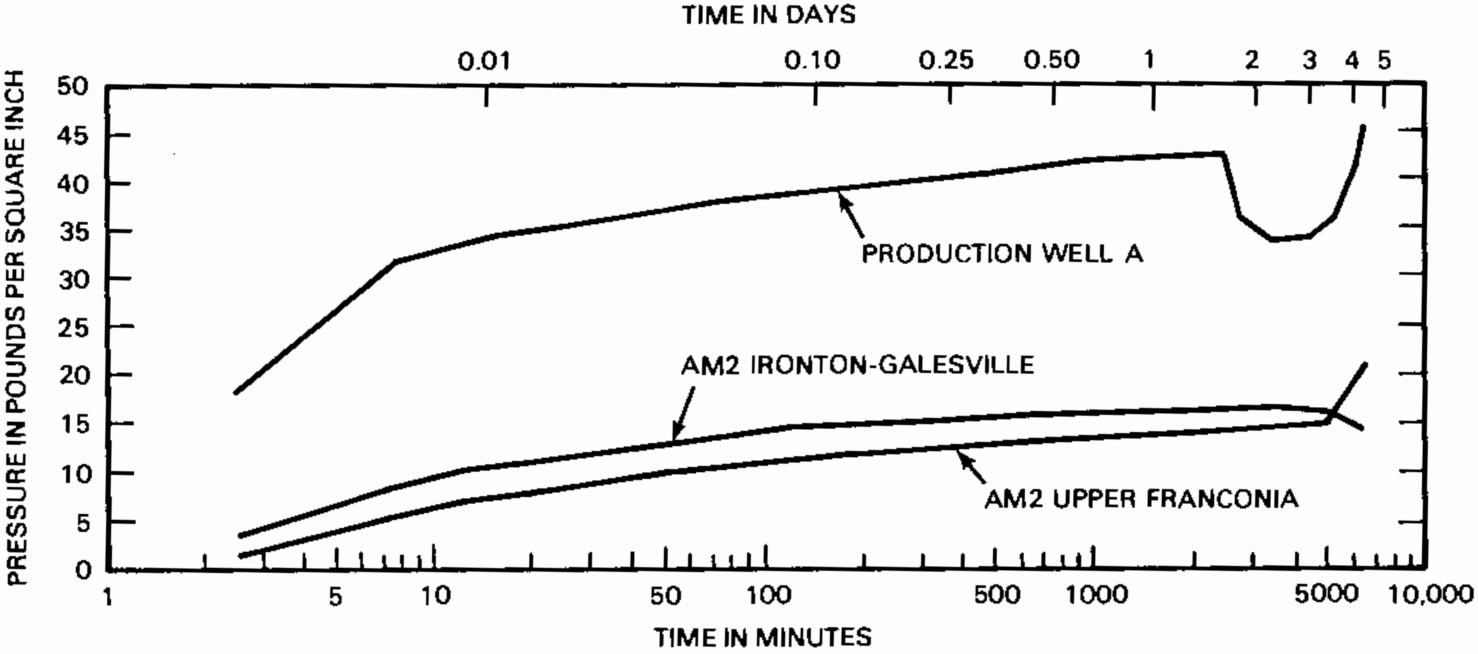

FIGURE 3.8. Pressure Change in Well A and Observation Well AM2 During Initial Hot-Water Injection Test. Two days of ambient temperature water injection followed by two days of 82° to 85°C water injection at 295 gallons per minute.

shutdown, the injection well recovered rapidly to a head pressure slightly higher than before the test, suggesting that the Ironton-Galesville screen was more clogged than the upper Franconia screen.

Temperatures began to rise at the Ironton-Galesville level of the aquifer in wells nominally 7 m from the injection well about 17 hours after heated-water injection began, and climbed to 46°C (115°F) over an 11-hour period at the 744-foot level in well AS1. Only thermocouples in the Ironton-Galesville portion of the aquifer showed a temperature rise during injection.

Filters run on the Field Injectivity Test Stand (FITS) during the testing above indicated that the FIG water is very low in particulates and very suitable for injection at low temperatures. Results with heated ground water indicated a significant increase in particulates due to formation of crystallites.

Attempts to pump well A following shutdown were unsuccessful because bearings on the pump shaft did not work properly when hot. The pump bearings proved to be of the wrong materials and have since been replaced. A thermal profile and a downhole television inspection of well A both confirmed that the upper screen in well A was relatively clean and the lower screen was clogged. The well screen was acid-cleaned and the defective shaft bearings were replaced in September 1982.

A step-drawdown test was conducted on the redeveloped well A, which indicated that the well efficiency was higher than during the original test. Following a 4-day pumpout of the heated water, a 2.5-day cold-injection test at a rate of 295 gpm to evaluate the injectability of well A after acid treatment showed a leveling off of pressure buildup at about 5 psi greater than during the initial 8-day test.

Because clogging resulted from calcium carbonate precipitation during the initial heated-water injection, a search followed for a permissible method of solving this problem. Inquiries with state regulatory agencies, however, indicated that they would not allow ion-exchange water softening, which calculations indicated would easily have solved the problem and would have had minimum impact upon the aquifer.

A decision was made to precipitate calcium carbonate from the supersaturated aquifer water where it would not affect the injection well or the aquifer, and would meet the conditions of the injection permit. A precipitating filter (fixed-bed reactor) filled with a bed of crushed, high-calcium limestone was added to the system after the heat exchanger. Experiments were conducted with this reactor and a small-scale reactor to determine the proper material content and particle size for satisfactory reduction of calcium carbonate supersaturation.

Sized, high-calcium crushed limestone proved satisfactory. As the heated water flows through the bed, the interstices become filled with precipitated carbonate from the supersaturated solution. When the head loss across the bed becomes too high (greater than 100 psi), the rock medium is replaced. To increase the efficiency of the units, the target temperature for the following test was changed back to 100°C.

The first complete short-term test cycle of the St. Paul ATES facility was successfully conducted from November 16 to December 22, 1982. Ambient temperature water at 12°C (53°F) was heated to a mean temperature of 91°C (195°F) ($\Delta T = 80°C$) and injected at a mean flow rate of 292 gpm (18.4 $l/sec^{-1}$) for 125.7 hours between November 16 and December 3. Injection was in five phases of approximately one day each followed by one or more days of maintenance work on the aboveground systems and replacement of the reactor media. A total of $8.3 \times 10^3$ $m^3$ of heated water was injected.

The storage phase lasted for 13 days, ending with the initiation of heat withdrawal on December 16. The water withdrawn reached a peak temperature of 76.7°C (170°F) after 12 hours of pumping. Water temperature decreased linearly from this peak with flow to 39°C (103°F) at the end of the five days (125.4 hours) of heat withdrawal. Mean temperature of water withdrawn was 60°C (140°F); 8.2 x $10^3$ $m^3$ of heated water was withdrawn from the storage well and returned to the supply well.

Heat recovery from this first cycle is 0.5. This result is slightly above the recovery predicted by the initial modeled cycles.

Temperatures in well AS1, nominally 7 m from the injection well, reached 80°C (176°F) at the most permeable horizon of the Franconia-Ironton-Galesville aquifer by the conclusion of heat injection (Figure 3.9). Following heat withdrawal, the peak temperature in well AS1 was 26°C (79°F).

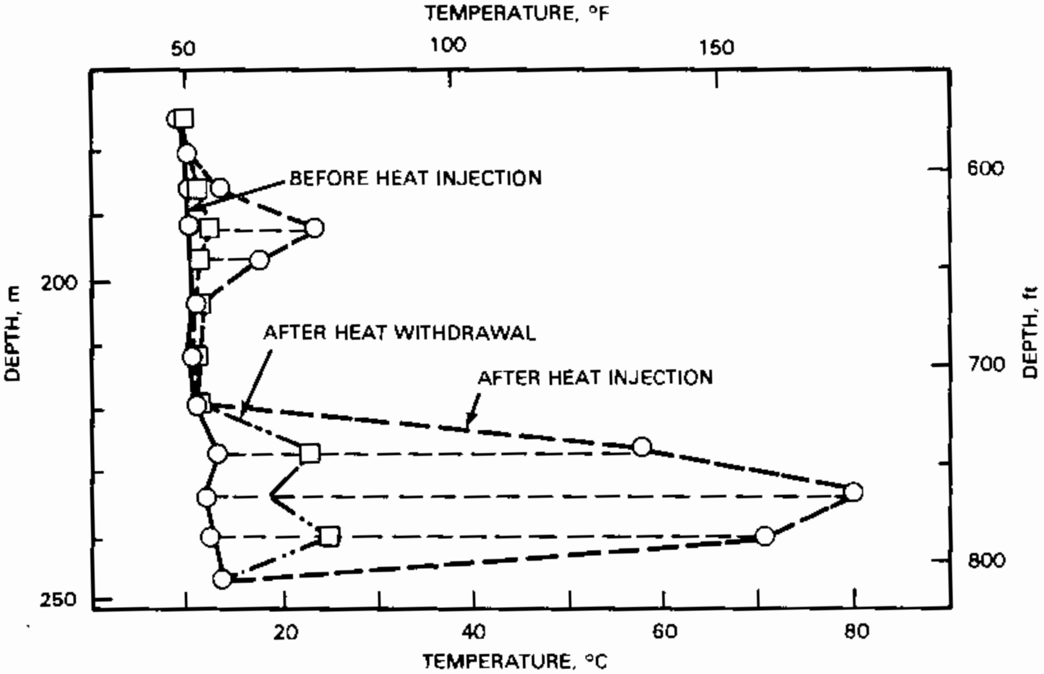

FIGURE 3.9. Temperatures Recorded at Different Depths in Well AS-1, Cycle I

The successful test was made possible by the operation of the precipitation filters installed to decrease the degree of $CaCO_3$ supersaturation in the heated aquifer water. This reduction was sufficient to reduce total hardness from about 2.0 mM to about 1.7 mM and to allow a complete cycle to be completed with no apparent clogging. This amounts to an accumulation of 31 kg of calcium carbonate per day in the precipitating filters. Water withdrawn following storage showed chemical changes that closely followed predictive models. Dissolved sulfate increased as the temperature decreased. Total calcium, hardness and sulfate increased as the temperature decreased. Chloride showed an initial increase, then a rapid decrease toward background levels. Total dissolved solids were about 210 $mg/l^{-1}$ as compared to 180 $mg/l^{-1}$ during injection.

## Aquifer Characterization: Modeling and Monitoring

A two-dimensional radial flow model was constructed and calibrated with the data from the 4.5-day pump test. Areal anisotropy within the aquifer accounted for small but significant deviations of the modeled results from the drawdown data. A conclusion of that modeling study was that a fully three-dimensional model would more accurately represent the aquifer system. Analysis of aquifer-test data indicates that the FIG is areally anisotropic with principal axes of transmissivity not parallel to the well doublet as is assumed in the SWIP code (INTERCOMP 1976). The well doublet is at an angle of approximately 30° to the major axes of transmissivity for both parts of the aquifer. Therefore, a three-dimensional ground-water flow model was constructed of the Franconia-Ironton-Galesville aquifer and calibrated with data from the same test. The model dimensions in the horizontal directions are 1240 ft by 836 ft, and the individual grid blocks are 0.5 ft at the well and increase in both the x and y directions by a factor of approximately 1.5 to 2.0. The model dimensions in the vertical direction are divided into values representing the thickness of the hydraulic zones calculated from inflatable-packer test and geophysical-logging data.

The thickness and vertical position each layer represents are, respectively: 25 ft, St. Lawrence; 45 ft, upper Franconia; 80 ft, lower Franconia; 50 ft, Ironton; 20 ft, Galesville; 100 ft, Eau Claire for a total of 6 layers.

The horizontal (x, y) directions of the model were aligned with the principal axis of transmissivity of the aquifer. Because the areal boundaries are, for all practical purposes, infinite and there is no interference from other pumping wells, flow lines will be directed along the major and minor axes of transmissivity toward the pumping well. Taking advantage of this and the fact that two planes of symmetry exist, one along the major axis and one along the minor axis, the aquifer was modeled at one-quarter scale with the two planes of symmetry acting as no-flow boundaries. The well is simulated at the point where the two planes of symmetry meet. The remaining two areal boundaries were treated as being infinite, utilizing a method available in the computer code and described as the Carter-Tracy method (INTERCOMP 1976). The horizontal to vertical anisotropy was set equal for each hydraulic zone in the aquifer with the horizontal hydraulic conductivity 10 times greater than the vertical. The upper and lower confining beds were set at horizontal hydraulic conductivities 100 times the vertical hydraulic conductivity.

Figure 3.10 illustrates the drawdowns for the field-recorded data and the model-computed data for piezometers completed in well AM2. The total average transmissivity simulated by the model was 944 $ft^2/d$, which is well within the range of 900 to 1050 $ft^2/d$ calculated from field data from the aquifer test. Because the field observation points are not exactly in the center of a model grid block, it is fruitless to attempt matching model-simulated pressures with field-observed values by adjusting model-input parameters. The match between field-observed and model-simulated pressures is sufficient for the available data.

Data obtained during the isothermal injection test were analyzed with flow-net analysis to aid in the design of a SWIP finite-difference grid that is practical for analysis around the injection well. A variable grid that shows very good isothermal calibration was obtained. Modeled head changes closely approach observed head changes (Figure 3.11).

The finite-difference grid was designed based on the shape of the equipotential around the injection well. A variable grid was designed with

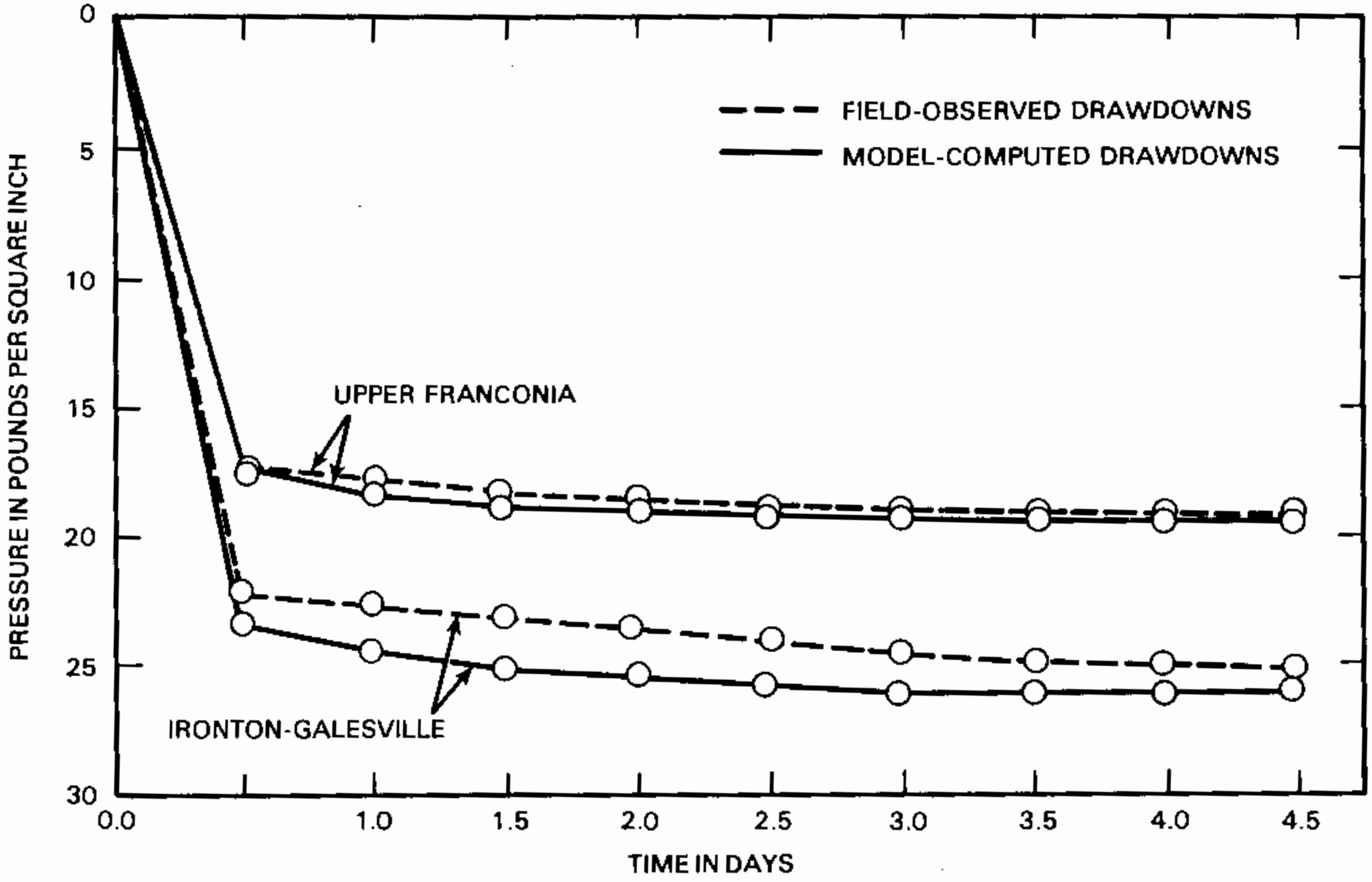

FIGURE 3.10. Field-Observed Drawdowns (Solid Lines) and Model-Computed Drawdowns (Dashed Lines) in Monitor Well AM2 While Pumping Well A at 340 gpm

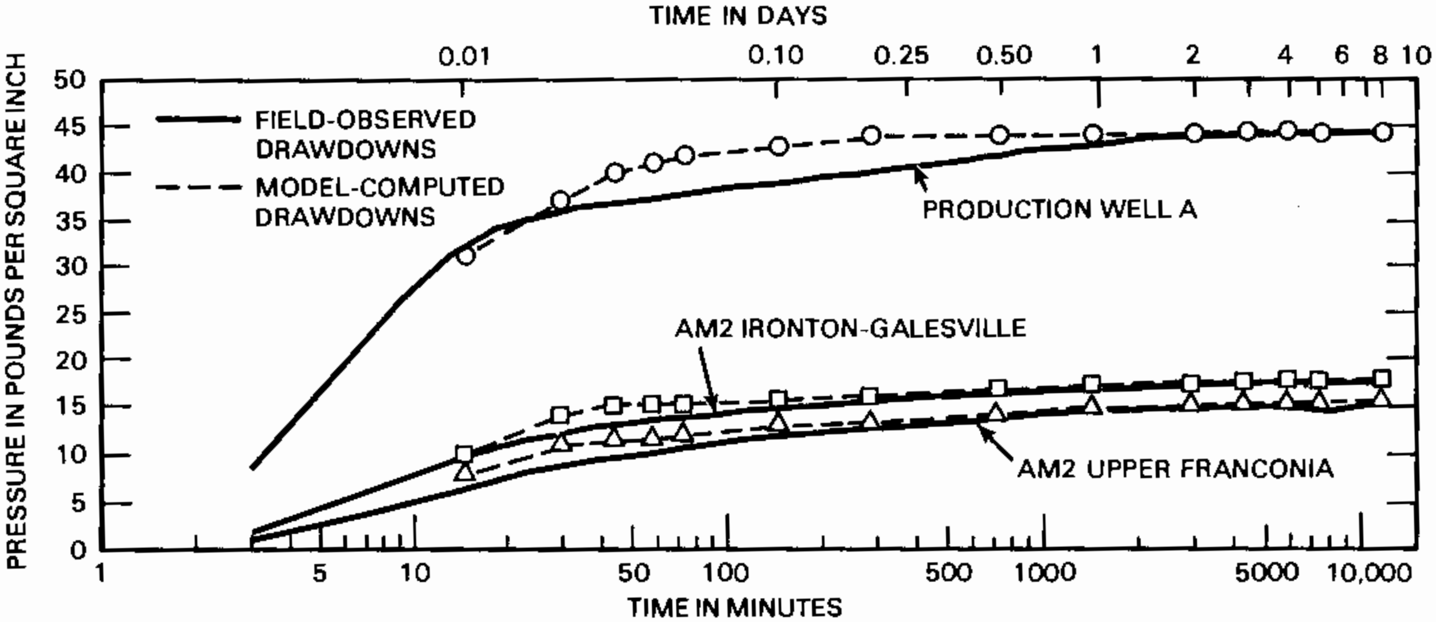

FIGURE 3.11. Field-Observed Drawdowns (Solid Lines) and Model-Computed Drawdowns (Dashed Lines) for the 8-Day Ambient-Temperature Injection Test at Well A and Monitor Well AM2

the smallest spacing for both the x and y grid between 1.0 ft and representing the well. The grid spacing increases by a factor of less than 1.5 equally in all directions away from the well to a maximum of 15.0 ft, and continues at this spacing for several grids. A variable grid was chosen to minimize the error in drawdown near the well during the hydraulic flow calculation. The smaller grid spacing will also lessen the effect of "smearing" the calculation of the thermal front in the energy calculation. The thermal front calculation may experience some smearing for calculations in the 15-ft grid blocks. A reduction in the larger grid block size may be necessary and will have to be evaluated during model calibration with heat flow data.

### Water Chemistry and Chemical Equilibrium Modeling

Important results and investigations of this reporting period include:

1. monitoring ambient and heated ground-water chemistry
2. improving monitor well sampling
3. modeling effects of heating FIG water
4. experimenting with heated FIG water in contact with rock materials
5. investigating effects and effectiveness of possible mitigative measures to prevent scaling caused by carbonate precipitation.

In November 1982 an interim report entitled Water Chemistry and Laboratory Studies of the University of Minnesota ATES Project by T. R. Holm, H. C. Lee, and S. J. Eisenreich, which includes studies and results obtained up to early October 1982, was submitted to PNL. The method of sampling monitor wells was modified slightly to obtain samples that are more representative. Air-lift pumping is used to flush the wells. Then a grab sampler is lowered to the depth of the screen to obtain a sample. Measurement of dissolved oxygen in grab samples indicated that the sampler was not isolating the grabbed sample from the aerated water above. The grab sampler has since been modified by the addition of a second check valve to better isolate the water collected from any contact with water from higher in the pipe. In addition, the sampling method has been modified by several flushings of the sampler by rapidly raising and lowering it several feet at a depth of about 100 ft above the sampling depth to remove any aerated water which entered on the way down. This has resulted in obtaining samples from the observation wells with very low dissolved oxygen levels, indicative of little or no interaction with overlying water.

A fixed-bed reactor (precipitating filter) was designed and constructed to reduce the oversaturation of injected water with respect to calcium carbonate. Both a model unit (4-in. cylinder, 54 in. long) and system unit (3- to 14-in. cylinders, 72 in. long) were built. The units were tried with crushed dolostone (locally available) and crushed high-calcium limestone. Temperature and flow rate were varied. Water samples of ambient ground water, heated ground water immediately downstream of the heat exchanger and immediately downstream of the fixed-bed reactor, were tested.

The high-calcium limestone reduced oversaturation significantly, and was chosen for use in the units. It should be noted that the heat exchanger significantly reduced the oversaturation, indicating significant accumulation of carbonate scale in the heat exchanger. Model reactor performance was affected by residence time (flow rate); the system reactor did not show any effect of flow rate during tests.

During cycle I, the reactors behaved consistently. Results shown in Table 3.4 are typical; total hardness was reduced from about 2.1 mM to 1.7 mM, which means that the units removed 167 kg (368 lb) of calcium carbonate. The injected water remained supersaturated, but by a much lower factor.

Chemical equilibrium modeling, using MINEQL and a program for temperature correction of equilibrium constants in the MINEQL file, predicted that

- the water withdrawn from storage would show significantly higher concentrations of $SiO_2$

TABLE 3.4. Fixed-Bed Precipitator Reduction of $CaCO_3$ Saturation

| Date | Logarithm of $CaCO_3$ Saturation Index | | Transfer Units |
|---|---|---|---|
| | Reactor Influent | Reactor Effluent | |
| 11/16 | 0.75 | 0.50 | 0.76 |
| 11/17 | 0.67 | 0.38 | 0.97 |
| 11/19 | 0.77 | 0.44 | 1.02 |
| 11/24 | 0.80 | 0.51 | 0.86 |
| 11/30 | 0.76 | 0.46 | 0.93 |
| 12/1 | 0.74 | 0.44 | 0.94 |
| 12/3 | 0.73 | 0.36 | 1.22 |

---

$CaCO_3$ Saturation Index = $[Ca^{2+}][CO_3^{2-}]/K$

- Al should be detectable
- significant decreases in $Ca^{2+}$ and $Mg^{2+}$ concentrations and lower pH alters $K^+$ concentrations.

Equilibrium may be reached during the period of storage. However, it is highly dependent on the temperature.

Data from water withdrawn following storage during cycle I, at temperatures of 77°C and below, agree with the trends predicted from modeling. Water withdrawn following storage actually contained more calcium than the water introduced, suggesting approach to the equilibrium conditions.

All samples collected during ambient-temperature and heated water tests for bacteriological analysis were negative for coliform bacteria (less than 1 cfu/100 ml).

Publications

The following reports were submitted to PNL during the reporting period:

Aquifer Characterization Plan for Long-Term Tests, July 1982.

Plan for Environmental and Institutional Monitoring of Long-Term Tests of Aquifer Thermal Energy Storage, October 1982.

Management Plan for Field Testing of Seasonal Aquifer Thermal Energy Storage, September 1982.

### 3.1.3.5 Stony Brook Follow-on Work

J. A. Schultz (Dames & Moore, Inc.)

#### Objective

The objective of the follow-on investigation was to perform additional research and development work including well remediation and testing at the Stony Brook ATES site to resolve the well PI-2 injection problem encountered during the second half of the 1981 nonisothermal reinjection test.

#### Technical Progress

This work was completed and a final report was issued. The storage and recovery of chilled water by an ATES system has been shown to be feasible. However, as was the case with the previous injection tests at the SUNY Stony Brook site, well PI-2 could not be injected with chilled water at the same rate it was pumped from the well. The injection problem was observed during injection of both ambient temperature water and chilled water. Also, the injection problem did not occur instantaneously at the start of injection. The injection problem was manifested by a gradual increase of resistance to injection within the well. The resistance to injection within the injection well is characterized by an exponential increase in head with time as a linear plot on semi-logarithmic paper. Potential causes of the reinjection problem may be related to 1) differences in the viscosity of water at chilled versus ambient temperatures and its effect on the hydraulic conductivity, 2) plugging of the aquifer by suspended solids at the interface between the gravel pack and the aquifer, 3) chemical precipitation within the aquifer and/or gravel pack, 4) well construction, and 5) release of air bubbles into the aquifer along the interface between the chill water plume front and the ambient temperature aquifer as the plume front warms (not part of this investigation).

Aquifer hydraulic conductivity in the vicinity of PI-2 would theoretically be reduced to about 90% of the ambient value by reinjection of the chilled water. Thus, changes in viscosity could theoretically account for about a 10% reduction in the PI-2 specific capacity, but not the full 77% reduction observed during the chill injection test.

Vecchioli (1972) discusses problems related to injection into an aquifer in Bay Park, New York, which include injection plugging associated with water having a turbidity content "generally less than a few milligrams per liter". The analytical results of the follow-on work indicated the presence of total suspended solids (TSS) within the injection water in the same concentration range. Of particular interest is that the backpressure gauge installed on the filter bank initially registered an increase in pressure, but then stabilized. This suggests that the suspended particles present in the injection water may have been of small enough diameter to pass through the 5-micron filter bank, but plug the aquifer at the interface with the gravel pack. Because the initial water level rise measured in PI-2 was observed to be higher each time the injection was restarted, it appears that there is a carryover plugging mechanism. Also, potential for the presence within the aquifer of a check valve mechanism that could act as a one-way shutter (allowing water to be pumped from the aquifer, but not reinjected) does not appear to be a credible mechanism for plugging because the observed plugging is not instantaneous, but builds up slowly and continuously with time.

Chemical precipitation does not appear to be an active plugging mechanism based upon the fact that the original specific capacity of PI-2 was nearly achieved during Task 3 (which consisted entirely of mechanical surging with no chemical treatment), and the observed particulate matter in the discharge appeared to be all natural aquifer material.

Well construction may be indirectly related to the plugging problem in that a properly designed well may possibly trap suspended solids within the gravel pack rather than at the interface between the gravel pack and the formation. For example, no problems were observed during injection of PI-1 which is constructed of a casing twice the diameter of PI-2 and a gravel pack in a borehole that may be three times the diameter of the PI-2 borehole.

The Well PI-2 injection problem could be resolved by one or both of the following engineering solutions: 1) the design of a filtering system that would remove virtually all of the suspended solids from the injection water, and 2) the design of larger diameter injection wells constructed similar to PI-1, which would be less affected by suspended solids but would probably still require occasional redevelopment by overpumping to waste.

### 3.1.3.6 Parisian Monitoring

W. J. Schaetzle (W. J. Schaetzle & Associates)

The Parisian Department Store ATES system (Tuscaloosa, Alabama) is being instrumented and monitored for comprehensive assessment and evaluation of system performance and efficiency.

#### Objectives

The objectives of the study are 1) to determine the economic performance of the aquifer cooling system, 2) to determine the performance of the chilling system, 3) to determine the effectiveness of the aquifer thermal energy storage system, and 4) to evaluate problems in the operation of the system and the corrections to eliminate these problems.

#### Tasks

The tasks undertaken to meet these objectives are:

1. develop an instrumentation system to monitor the aquifer installation
2. install this instrumentation system in the aquifer cooling system
3. monitor the data output of the aquifer system for approximately 1 year

4. compile and evaluate the data
5. evaluate the performance of the aquifer cooling system
6. make recommendations for changes in future systems.

## Technical Progress

### Aquifer Cooling System

The ATES chill system has been incorporated into a 60,000 ft$^2$ department store in Tuscaloosa, Alabama. Parisian is one store in a chain specializing in quality wearing apparel. The system went operational in the Fall of 1981. It is estimated the aquifer can save an appreciable percentage of their chilling costs. Due to some risk, 100% backup for the chilling system has been installed. Maximum cooling capacity is 200 tons.

A schematic of the system is shown in Figure 3.12. The system uses parallel rows of wells (a row of two cold wells and a row of two warm wells), a cooling tower, sand filter, and cooling coils.

Cold water is withdrawn from the cold wells for air-conditioning and passes directly through water-to-air cooling coils. The water is injected into the warm wells. An intermediary heat exchanger is not used because of critical temperatures required for dehumidification. It was felt that the temperature difference across the filter could not be tolerated. The cooling coils at both locations are eight rows and eight fins per in. All flow is counterflow. Because water makes only one pass per year, temperature differences of 9°C and greater are expected. The coils have performed better than expected, with exit temperatures approaching 2°C of entering air temperature. Water chilling occurs in a 400-ton cooling tower using 50-hp centrifugal blowers to inject air. Air injection minimizes freezing of water on the fan blades. Ice has formed on the exit grates at the top of the tower in near -18°C weather. One ice block fell and damaged the water level control. A check valve froze and cracked during a power failure. Since then all systems have been modified to automatically drain during a power failure. At Parisian, water is chilled at a constant flow

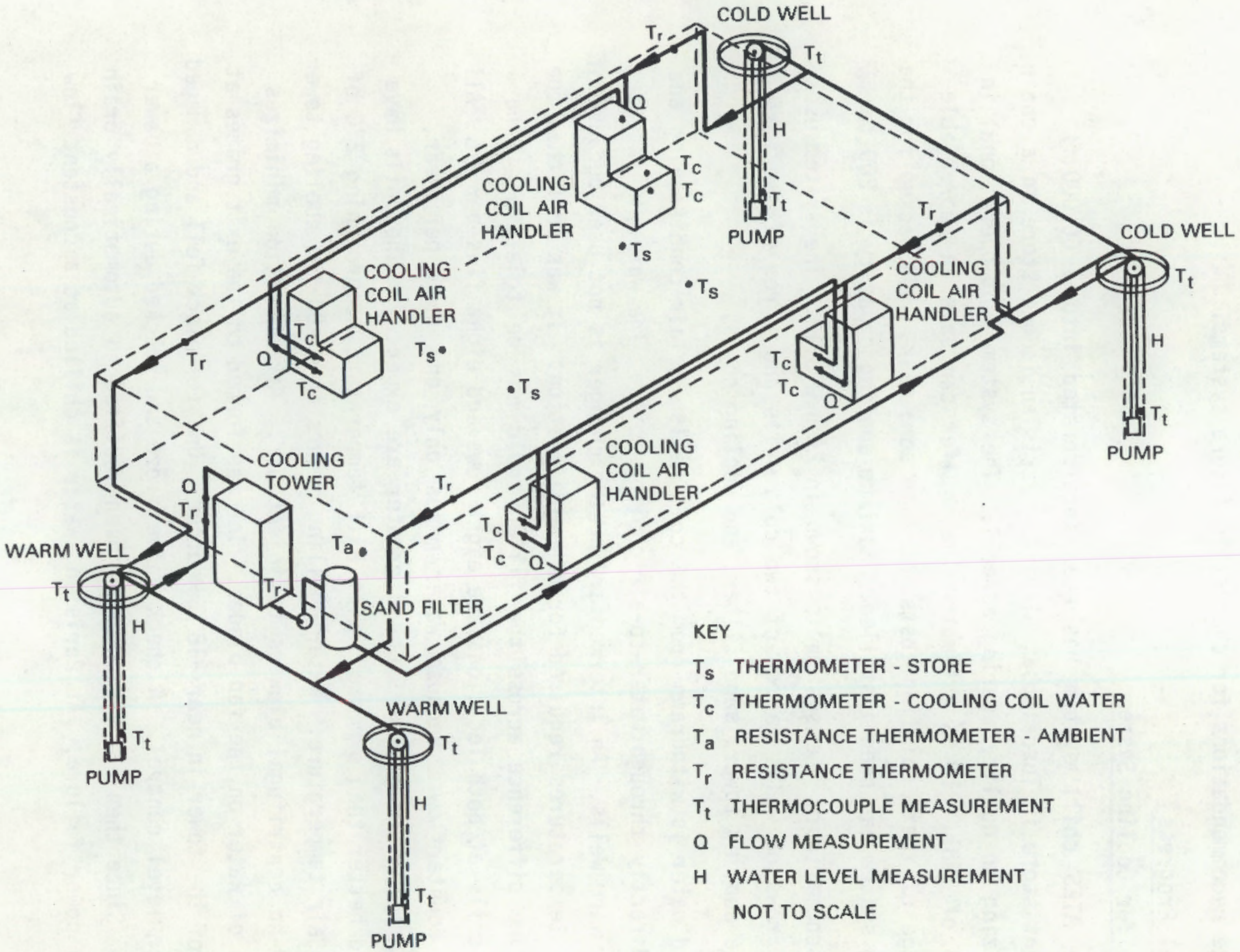

FIGURE 3.12. Parisian Department Store Aquifer Cooling System with Instrumentation Locations

rate whenever wet-bulb temperature drops below 10°C. At temperatures around and below freezing, vanes to the blowers that close to control water temperature have operated satisfactorily.

The water is filtered through a sand filter to prevent the addition of pollutants to the aquifer. The water is exposed to the atmosphere in the cooling tower only. The aquifer utilized at the Parisian site is unconfined and consists of alluvial and terrace deposits of the nearby Black Warrior River. These deposits lie directly on the Pottsville formation of Pennsylvanian age (coal measures). The aquifer at the site is approximately 40 ft thick and occurs in very porous sands and gravels. The Parisian wells are 80 ft deep with 6-in. PVC casing and sand screen, packed with sized gravel. It is critical that the slot size in the screens and the packing design be calculated to account for the grain size distribution in the formation in which the wells are constructed. At Parisian the wells permitted fine sand to pass through the packing during withdrawal and through the slots into the wellbore, creating an accumulation of fine sand in the cooling tower or in the opposite injection wells, depending on which way the water was being pumped. This fine sand accumulation necessitates flushing out the injection wells and cleaning out the cooling tower periodically. It is recommended that automatic blackflushing of wells (perhaps on a daily basis) be built into the system. It is also recommended that water be filtered in both directions.

### Instrumentation

The instrumentation was chosen for the system and is installed, completing Tasks 1 and 2. Locations for the aquifer cooling system instrumentation are shown on the store schematic in Figure 3.12. Flow probes measure flow at the cooling coils and cooling tower. Water height is measured at each well.

Temperature measurements are taken by resistance thermometers, regular glass thermometers, and thermocouples. The resistance probes have a 1-ohm variation per 1°F temperature variation. Signals are transmitted hourly to an in-store computer and by telephone line to the central environmental control computer for the Parisian store chain.

These resistance thermometers are located in the inlet and outlet piping for each pair of cooling coils and air handlers, and at the inlet and outlet of the cooling tower (Figure 3.12). Temperature wells with thermometers are located at the entrance and exit of each cooling coil and the entrance and exit of the cooling tower (Figure 3.12). Temperatures are taken as required of the water entering and leaving the wells and at a depth of 60 ft below the surface. These data are taken with copper-constantan thermocouples and Doric 410A Trendicator and Doric 407 power supply and calibrator. Some problems have developed with the power supply on this system.

Input power is determined from on/off signals recorded on the computer. The power input during the "on" phase is measured directly by a TIF 2000 Wattprobe Hand-held Digital Watt/Kilowatt Meter. The accuracy is ± 2% of reading ± digit. An assumed constant power input during operation has been confirmed with consistent readings.

The flow of water is measured with Wilgood liquid flow meters. A Wilgood F-215 flow probe has been injected into the pipes at each cooling coil and entering the cooling tower. The probe is a turbine measuring centerline flow velocity as impulses. The signals are sent to a Wilgood C-231 computer where the flow is converted to gpm. The integrated flow is recorded on a Wilgood C-220 five-digit electromechanical register.

Water level in the wells is measured by pressure gages reading in feet. Gages are installed on a 1/4-in. PVC pipe extending 60 ft into the well. Gage set point has been set by measuring water level physically (tape measure) to within ± 1 in. and pressurizing pipe line to match gage reading.

### Data Output

Water chilling occurred for part of the 1981-82 winter. Due to control problems, this water was used in March and April 1982 for air conditioning. No data are available for this period. During Summer 1982, 65 to 67°F water was used to supplement the air conditioning. Data are available for this period. During Winter 1982-83, a limited amount of water was chilled. Data are available for this period.

Basic data to carry part of the air conditioning load are:

| | |
|---|---|
| Gallons transferred | 15,000,000 |
| Air conditioning | $612 \times 10^6$ Btu |
| Power input | $69.5 \times 10^6$ Btu |
| COP (based on above numbers) | 8.81 |

In general, a baseload of 50 tons of air conditioning was supplied for this period. Water in excess of the above numbers was utilized but cannot be documented.

For Winter 1982-83, the following data indicate the water chilling.

| | |
|---|---|
| Gallons chilled | 10,212,850 |
| Chilling(a) | $1724 \times 10^6$ Btu |
| Power input | $191.5 \times 10^6$ Btu |
| COP for chilling | 9.00 |

Additional chilling after this reporting period will amount to approximately 15% of the above values. Average injection temperature is between 44 and 45°F.

The winter chilling potential for the system, doubling the flow rate and more chilling hours, is three to four times the above quantities.

The data verify that the system will operate effectively. Injection wells show some problems but the ability to absorb water has remained constant.

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(a) For input temperature to tower 65°F was used since this is the natural aquifer temperature. If the actual temperature (71°F) is used, chilling and COP would be 30% higher.

## General Operation Results

The general operation of the system has been good. This new concept, especially in the area of controls and the sand filter, required innovative work by both engineers and contractors. Numerous concepts related to conventional cooling water loops had to be redesigned for the system. Still, problems in the control area, valves and cooling coils occurred. The on/off valves turned out to be modified bypass valves that were unable to take the higher pressures. The 8-row single-pass cooling coil required for maximum temperature difference became an 8-row double-pass (water passes through every other row) used to decrease pressure loss in a normal closed loop chilling system. The vendor thought a superior coil was substituted.

Although sand filters are widely used in many water treatment systems, problems occurred in this area. When the system was turned on, the sand passed through the gravel, clogging the filter tubes and causing a chain of maintenance problems that existed for many months. The sand and gravel have gone through three complete changes. It has been concluded the slotted tubes at the bottom of the filter need to be replaced for proper operation.

Some problems with controls still require corrections. A few problems are directly related to controls and others to equipment and equipment specifications. For example, the well pump specifications are really minimums. The submersible pumps have 50% more flow at required pressures and an extra 40 psig at the required flow rate.

The use of PVC pipe caused some problems. Conventional hanging methods for steel pipe were used, but because PVC is more flexible, additional support was required and installed to prevent excessive pipe dynamics.

8ecause of the virtually unlimited supply of aquifer water, breaks in the piping system can cause significant property damage. In a water loop, supply is limited by loop contents. An overnight break in the aquifer system could pump 600 gpm into Parisian. Over a 10-hour period, this can amount to over 360,000 gallons. A piping break did occur during checkout but was caught immediately and minimal damage resulted. Pressure safety systems, which turn the entire system off in case of a break, have been installed. Parisian and their insurance companies are very sensitive to water damage because of past experience. In one case a water main under a store broke and caused $2 million damage. In another case, the fire sprinkler system response to a small fire resulted in $2.5 million damage. A new safety perspective is required in these applications.

Publications

Schaetzle, W. J., C. E. Brett and D. M. Grubbs. 1980. "Direct Cooling Utilizing Aquifer Thermal Energy Storage." ASHRAE Transactions. 86(2).

Schaetzle, W. J., C. E. Brett, D. M. Grubbs, and M. S. Seppanen. 1980. Thermal Energy Storage in Aquifers: The Design and Applications. Pergammon Press, Oxford, Great Britain.

## 3.2 SEASONAL THERMAL ENERGY STORAGE TECHNOLOGY ASSESSMENT AND DEVELOPMENT STUDIES

Aquifer thermal energy storage (ATES) is predicted to be the most cost-effective technology for seasonal storage of low-grade thermal energy. However, suitable aquifers underlie only about 60% of the U.S. Therefore, other methods of STES are required in areas where aquifer storage is not technically or economically feasible. The types of nonaquifer or alternative STES systems under consideration include pond, lake, cavern, tank, wet earth, rock, and ice thermal storage.

Entrepreneurial development of STES also depends keenly on factors other than technical feasibility and performance. Economic viability and legal, institutional, and environmental issues bear on the market potential of various STES systems. Because of the importance of these issues to the success of DOE efforts to develop and advance STES, studies have been conducted to assess their impact on commercial pursuit of STES.

### 3.2.1 Goal and Objectives

The goal of the STES Technology Assessment and Development (TAD) Studies is:

- identification and assessment of technical, economic, environmental, institutional, and legal issues affecting STES implementation and development of promising alternative nonaquifer technologies.

Pursuant to this goal, two objectives have been identified:

- Screen and, as appropriate, develop promising STES concepts as alternatives to ATES.
- Develop assessment methodologies for STES economics and apply these methodologies to STES technologies.

### 3.2.2 Strategy

To meet the goal and objectives identified above, STES/TAD studies have been organized into two tasks: a technical analysis task primarily for alternative STES technologies and an economic analysis task. Subtasks are shown in Table 3.5 for these tasks.

The strategy for assessing and developing alternative STES systems includes preliminary technical and economic screening and prioritization of promising technologies, technical research to evaluate feasibility, proof-of-principle testing, critical component engineering R&D, and technology transfer. It is expected that the development of various concepts would proceed at different rates along this strategy.

The strategy for economic analysis involves preliminary assessment of economic potential of ATES systems, characterization of acceptable source and user energy costs, parametric analysis of ATES economics and economic assessment of alternative STES technologies. Studies to assess energy costs in appropriate STES application sectors and estimate STES market potential and penetration schedule are performed when needed as funds permit.

TABLE 3.5. Seasonal Thermal Energy Storage Technical Assessment and Development Tasks

| Task/Project | Contractor | Status |
|---|---|---|
| Task 1. Technical Analysis | | |
| Subtask i. Analysis and Assessment of STES Technologies | PNL | Screening studies of first generation non-aquifer STES concepts complete. |
| Subtask ii. Passive Ice Generation and Storage Analysis | Argonne National Laboratory | Second season of passive ice generation and storage using heat pipes complete, clathrate systems being investigated. |
| Subtask iii. Evaluation of Zeolite Augmentation of STES Chill Storage | New Mexico Solar Energy Institute | Experimental facility design completed and construction underway. |
| Subtask iv. Analysis of STES in Caverns | U. of Minnesota Minnesota Geological Survey | Analysis complete, final report due in May 1983 |
| Subtask v. Analysis of STES in Existing Tankage | Massachusetts Institute of Technology through Argonne National Laboratory | Analysis complete, final report available |
| Task 2. Economic Analysis | | |
| Subtask i. Parametric Analysis of ATES for Chill | PNL | Analysis complete, final report issued in January 1983 |

### 3.2.3 Project Descriptions

The following sections briefly describe the STES/TAD projects conducted during the reporting period. Project results are given special emphasis.

#### 3.2.3.1 Technical Analysis

The objective of this task is to provide for assessment and development of nonaquifer STES systems such as large pond storage, earth storage, chemical storage, ice storage, and other more advanced concepts as well as assessment of broad ATES technical issues. Nonaquifer concepts showing promise will receive detailed engineering and economic assessment and selected research efforts will be performed on these concepts. This task is divided into five subtasks.

##### 3.2.3.1.1 TES Analysis and Assessment

D. E. Blahnik, D. R. Brown, R. D. Allen (Pacific Northwest Laboratory)

Objective

The objective of this subtask is to evaluate and screen STES concepts and to define research and development required for promising concepts.

Tasks

Preliminary Assessment of First-Generation STES Ice Storage Concepts

The purpose of this effort is to estimate which ice storage technologies will likely be economically competitive and what R&D will be required on those technologies.

Technical Progress

The assessment was completed in July 1982 and reported at the DOE Physical and Chemical Storage Annual Contractors' Meeting in Washington, D.C. in August 1982. The in-house document was prepared. No formal publication of the results is anticipated. This assessment is discussed further in Section 3.2.3.2, under Task 3.

### 3.2.3.1.2 Ice Production and Storage Utilizing Heat Pipe Technology

#### Objective

The objective of this task is to characterize the technical features of formation, collection and storage of ice naturally grown during the winter by means of innovative heat pipe technology. During FY 1983, work is continuing on this chill storage concept at the Argonne Ice Storage Test Facility. Additional passive ice generation and storage tests will be conducted on several heat pipe configurations. The system will be modified to explore passive supply and storage of winter chill in gas or liquid hydrate clathrates.

#### Tasks

The passive generation and storage program has three tasks:

- Task 1. Modification of test facility
  - installation of large coil unit
  - instrumentation of ice-forming region
- Task 2. Monitoring of the winter ice formation utilizing heat pipes
  - preparation of final report from FY 1982
  - monitoring of energy flux
  - modeling the performance of reflux condensers
- Task 3. Investigation of winter chill storage in clathrates
  - refrigerant review
  - preliminary design and economic characterization
  - test facility modification and testing
  - data analysis.

#### Technical Progress

##### Task 1. Modification of Test Facility

a. Installation of the large coil evaporator has been completed. This design represents the preferred design for freezing ice based upon tests performed in the winter of FY 1982. Two large coils were fabricated in the tank and are connected to the condenser panels on the roof. The coils each contain 200 ft of 5/8-in. diameter copper tubing, spaced such that the ice can grow to a thickness of 6 in. before overlap occurs. The tests from the previous winter indicate that this design will allow a greater accumulation of ice before the resistance to heat transfer becomes too great.

Task 2. Monitoring of the Winter Ice Formation Utilizing Heat Pipes

a. The final report on the performance of the system for the winter of 1982 has been submitted for word processing. This document includes an extensive mathematical model describing the formation of ice on plate-type freezing surfaces when coupled to the condenser units that are exposed to the winter chill. Also included is an economic analysis that shows that the system for storage based on ice formation is viable in cases of new construction for single-family dwellings if the cost of electricity is currently above 10¢/kWh. The report is expected to be submitted for printing by May 1, 1983.

b. The testing of the energy flux into the ice tank has been performed on a regular basis whenever the weather is adequately cool. The Chicago area has experienced a very mild winter this year, and with the arrival of the funding for the year in March, only limited testing has been possible. The testing phase of this work (ice formation) is considered to be over until the resumption of cold weather in the fall.

c. Reflux condenser performance modeling has progressed to the stage that the formulation and testing of the model have been completed, and the results are being written up for inclusion in the final report. The model will be used to evaluate the performance data obtained from Task 1b, and can be used to project the performance of the system to other locations and for different climatic conditions. The model is of a coil evaporator coupled to a flat panel condenser that rejects the energy to the winter chill. The model can simulate a wide variety of coil configurations, and will be useful in determining improved system configurations.

### Task 3. Investigation of Winter Chill Storage in Clathrates

a. The refrigerant review is now in progress and a large body of literature on clathrates has been compiled. This literature is now being evaluated to determine clathrates for potential use in passive winter chill storage devices. This evaluation will be documented in the project final report.

Most of the known clathrates melt incongruently into two immiscible liquids or to a liquid and a gas. Incongruence may be a major concern in some daily cycling systems. The effect of incongruent melting in a heat pipe system is yet to be determined. Only clathrate hydrates and semi-clathrate hydrates melting above 0°C will be considered in this work.

Many clathrates can be eliminated from evaluation because of corrosion or chemical activity. A sealed heat pipe system with internal clathrate formation must have minimal corrosion and chemical activity that would release inert gases. The sealed environment of the heat pipe may allow the use of materials that are less stable in an exposed environment. In the final system, if clathrate is formed external to the heat pipes, this requirement may be less severe.

Pressure is another consideration in addition to temperature and corrosion. Only clathrates forming at relatively low pressures (1 to 3 atm) will be considered in this work. The necessity of a large pressure vessel would impose unacceptable economic constraints on a seasonal storage system. Other considerations affecting the selection of a suitable refrigerant include heat of fusion, toxicity, chemical stability, flammability, and cost.

Table 3.6 lists materials on which detailed clathrate formation information is available. Less comprehensive information has been obtained on many other possible clathrate-forming materials.

TABLE 3.6. Refrigerant/Clathrate Composition

| Refrigerant | Chemical Name | Hydrate (Clathrate) Form |
|---|---|---|
| Freon® 11 | Trichlorofluoromethane | R11 16.6 $H_2O$ |
| Freon® 12 | Dichlorodifluoromethane | R12 15.6 $H_2O$ |
| Freon® 13B1 | Bromotrifluoromethane | R13 B1 15.6 $H_2O$ |
| Freon® 22 | Chlorodifluoromethane | R22 12.6 $H_2O$ |
| Tetramethylene oxide | Tetrahydrofuran | THF 16.86 $H_2D$ |

Argonne National Laboratory has performed some small-scale laboratory tests using fluorocarbon clathrate formers. The R-11 clathrate was formed successfully in a glass simulated heat pipe that allows visual observation of the clathrate formation process. The clathrate has been formed by evaporating the R-11 by means of a mechanical vacuum pump. The next experiment with this system will be operation in a sealed heat pipe mode. This will be the first test of a clathrate-forming heat pipe system known to the authors. Figure 3.13 shows regions of stability for the R-11 clathrate with respect to temperature and pressure. This clathrate is stable up to 8.5°C (47°F) and exists at pressures well below atmospheric. In addition, some tests on Freon-TF were performed, and no clathrate was formed.

The next series of tests will be performed using tetrahydrofuran as the clathrating agent. This material is attractive because of its low cost, but has problems of toxicity and stability that need to be addressed before it can become a serious candidate.

### Task 2b. Preliminary Design and Economic Characterization

This task has not been started yet.

### Task 2c. Test Facility Modification and Testing

Not started until after review meeting.

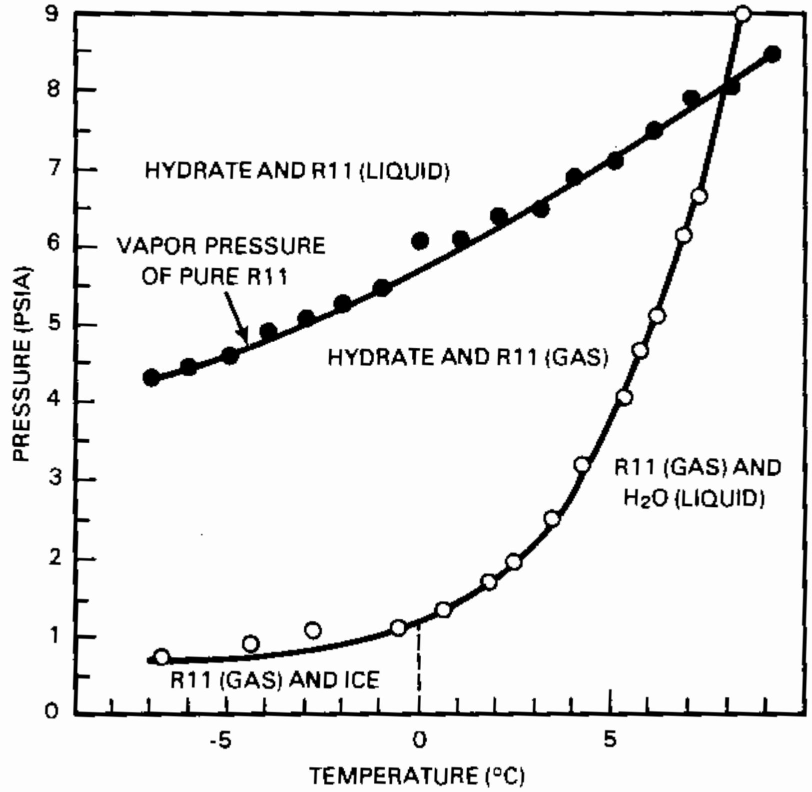

FIGURE 3.13. Phase Diagram for Water - R11

Task 2d. Data Analysis

Not started until after 2c.

Publications and Presentations

On August 24, 1982, the results of this work were presented at the Physical and Chemical Storage Annual Contractors Review Meeting in Washington, D.C.

A paper and special presentation on ice storage techniques was made at the Seventh National Passive Solar Conference in Knoxville, Tennessee, on August 31, 1982. The paper "Passive and Hybrid Ice Systems for Comfort Conditioning and Chilling Applications" was coauthoried with Professor C. E. Francis from Illinois State University.

The results of ice storage research were also presented at Technology Education Symposium IV, "New Technologies and Implications for Curriculum at Illinois State University". Symposium IV is cosponsored by Illinois State University and the Technical Foundation of America.

On January 20, 1983, a presentation was made at the Electric Power Research Institute Thermal Energy Storage Workshop in Palo Alto, California.

The Second Annual Workshop on Ice Storage for Cooling Applications was held at Argonne National Laboratory on May 13-14, 1983. This workshop included presentations from 14 ice researchers from the U.S. and Canada.

A. Gorski chaired a technical session on ice storage at the First U.S.-China Conference on Energy, Resources and Environment held on November 7-12, 1982, in Beijing, People's Republic of China. This was the first technical session on natural ice storage techniques held at a major energy conference.

### 3.2.3.1.3 Solar Zeolite Chill Storage System Evaluation
New Mexico Solar Energy Institute

#### Objective

The objectives of this study are to design, construct and test a solar zeolite seasonal storage (SZSCS) system to freeze ice in the winter and furnish cooling in the summer. The system utilizes the water adsorptive power of zeolite to sublimate seasonally generated ice for cooling. Water is desorbed from the zeolite daily by solar thermal energy.

#### Tasks

#### Task 1. System Design

An experimental system will be designed to test the performance of a novel method to utilize both winter chill and summer heat to provide chill for building air conditioning in the summer.

### Task 2. Zeolite Research

Currently, there are many differing forms of zeolite material for operation under a variety of conditions. Therefore, an evaluation will be performed to determine the optimal technical and cost-effective zeolite material for testing in Task 3. Both zeolites (molecular sieves) and desiccants will be evaluated.

### Task 3. Construct and Test SZSCS System

Tests will be conducted in a facility according to the design developed in Task 1. Testing will be performed parametrically for various operational and design factors. Time and funds permitting, several different molecular sieves and desiccants will be tested.

## Technical Progress

### Task 1. System Design

Design has been completed for the general system and major components. Design of some minor system elements remains to be completed. A schematic of the system is shown in Figure 3.14. The design has three major subsystems: the zeolite solar desorption subsystem, the condensation and zeolite cooling evaporative subsystem, and the ice and daily chill storage subsystem.

The solar desorption subsystem provides heat to the zeolite during the daylight hours to drive water out of the zeolite. Initially, the zeolite has a water content of 24.9 lb/100 lb zeolite and a temperature of 82°F. Solar heat is used to dry the zeolite to a water content of 18.9 lb/100 lb zeolite and a temperature of 180°F. During the desorption process, water chilled in an evaporative chiller (condensation and zeolite cooling evaporative subsystem) is used to condense the vapor driven off the zeolite. The condensate is removed from the system at the end of zeolite regeneration.

Some of the preliminary estimates of the experimental unit energetics are given in Table 3.7. The system is designed to utilize 10D lb of

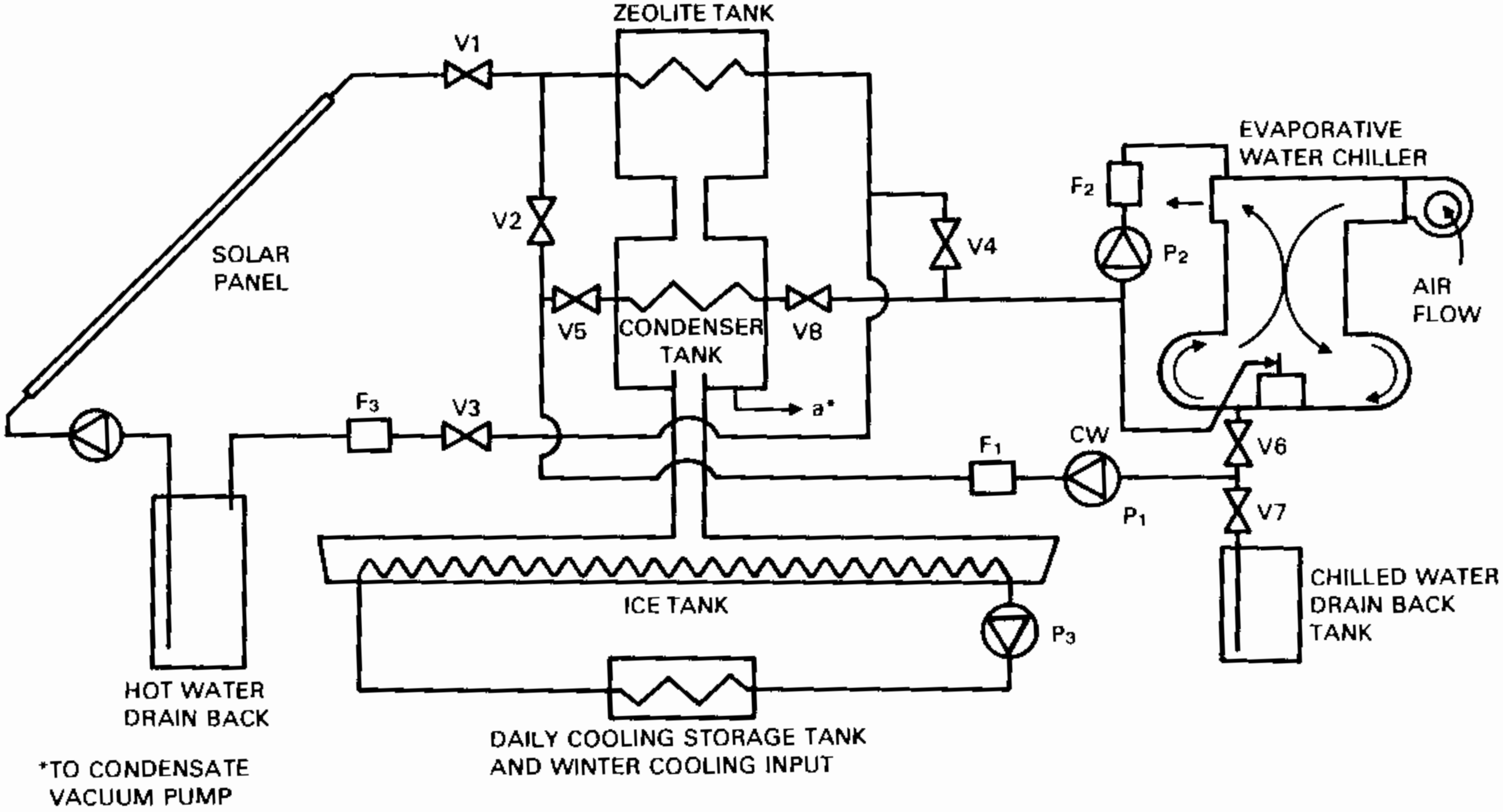

FIGURE 3.14. Solar-Zeolite Adsorptive Cooling

TABLE 3.7. Preliminary Energetics Estimates for the SZSCS Experimental Unit

Summer Solar Collection

| Factor | Value |
|---|---|
| 1. Zeolite vapor pressure of water | 0.222 psia |
| 2. Zeolite temperature, initial | 82.7°F |
| final | 180°F |
| 3. Water content, initial | 24.9 lb/100 lb |
| final | 18.9 lb/100 lb |
| 4. Heat of desorption | 1,314 Btu/lb |
| 5. Heat stored in 100 lb of zeolite<br>100 (180 - 82.7) 0.27 | 2.627 Btu |
| 6. Heat stored in 18.9 lb of water | 1,752 Btu |
| 7. Heat of desorption (24.9 - 18.9) 1296 | 7,775 Btu |
| 8. Total heat collected | 12,154 Btu |
| 9. Water removed | 6 lb/100 lb |

Summer Noctural Operation

| Factor | Value |
|---|---|
| 1. Zeolite vapor pressure of water | 0.0886 psia |
| 2. Zeolite temperature, initial | 147.7°F |
| final | 56°F |
| 3. Water content, initial | 18.9 lb/100 lb |
| final | 24.9 lb/100 lb |
| 4. Heat of desorption | 1,314 Btu/lb |
| 5. Heat removed from 100 lb of water | 2,476 Btu |
| 6. Heat removed from 18.9 lb of water | 1,733 Btu |
| 7. Heat added to 6 lb of water vapor<br>6 x .42 x (56 - 32) | 60.5 Btu |
| 8. Heat of sorption 6 x 1314 | 7,884 Btu |
| 9. Total heat removed from zeolite tank | 12,154 Btu |
| 10. Heat removed from ice (1075.4 + 144) 6 | 7,312 Btu |

zeolite in which 6 lb of water is adsorbed and desorbed during the daily cycle. It is expected that 7312 Btu of chill will be removed from the ice storage during the cycle at 32°F.

The ice and daily chill storage subsystem comprises the ice tank, pump ($P_3$) and daily cooling storage tank (see Figure 3.14). In this subsystem the relatively dry zeolite is connected to the seasonal ice storage tank. The dry zeolite adsorbs water such that the vapor pressure is quickly reduced to the triple point of water and the ice in the ice store begins to sublimate. Water from the daily storage unit is circulated through tubing in the ice storage tank. This circulating water is cooled, transferring heat to the ice storage unit, causing the ice to melt/boil. The vapor is transported to the zeolite until the zeolite has adsorbed sufficient water that its equilibrium pressure is above the triple point of ice. Water will continue to be adsorbed above this pressure; however, a residue of liquid will be generated in the ice storage tank that must eventually be adsorbed by the zeolite on subsequent cycles or else efficient operation will not be maintained. During the adsorption process the zeolite is cooled by water circulated from the evaporative chiller.

Instrumentation has been selected for the system and many of the major elements have been procured. To the extent possible, on-hand equipment is being used.

### Task 2. Zeolite Research

The primary zeolite research will be performed during April, May and June of 1983. Not funded by this project, but related to it, is a thesis paper being prepared by a graduate student. The thesis results will be included in reporting on this project.

### Task 3. Construct and Test SZSCS System

Final ordering of some of the more expensive materials is being delayed pending approval of the design. The zeolite tubes and some small items have been in construction, as their design did not appear to be controversial. A zeolite tube is currently undergoing tests.

The bench to mount the zeolite condenser tank, solar drainback tank, and the evaporative water chiller has been constructed, painted, and positioned on the roof of the Engineering Complex Building on the campus at New Mexico State University. The evaporative water chiller was placed on the north end of the bench and firmly guyed to the roof. It is being plumed for testing.

The solar panel is on hand and the solar system is scheduled for installation early in April.

Table 3.7 gives a typical projected performance. The projected performance is based on use of 100 lb of zeolite in 64 copper tube subsystems.

The seasonal storage will be initiated in the winter normally by freezing ice concentrically around a 1/2-in. copper pipe extending end-to-end of a 15-ft long 12-in. diameter copper pipe, which is used as an ice storage tank. Copper was selected for the ice tank because it is known to be suitable. Other cheaper materials could likely be proven suitable but would require additional testing.

The daily cycle of cooling will prepare the zeolite by drying it during the solar day and adsorb vapor into it during the night. The adsorption process freezes 8.46 lb of ice for each pound sublimated at night be means of the zeolite extraction of vapor out of the closed system. This causes the internal pressure to drop to 0.0887 psia, the sublimation pressure.

The solar heating and evaporative cooling processes add complexity to the ice storage system, but they also increase the effective storage by 8.46 times. In the example (Table 3.7), 6 lb of ice is sublimated to freeze 50.76 lb of water or transfer 7309 Btu of 32°F to a daily storage tank for the next day's cooling requirements.

The test instrumentation is designed to determine actual performance. The actual performance will be compared to the projected performance in Table 3.7 and any difference accounted for.

### 3.2.3.1.4 Ely Caverns Storage Analysis

#### Objective

The objective of this effort is to characterize abandoned mine workings at Ely, Minnesota to determine the feasibility of their use for STES. The methods used in this study will provide a basis for other groups to evaluate similar uses of abandoned mines or caverns for STES.

#### Tasks

##### Task 1. Characterize Existing Mine Workings

Abandoned mine workings at Ely, Minnesota, will be characterized to determine the available volume for storage, hydraulic conductivity between shafts and stopes in the workings, and to determine the natural thermal conditions in the mine shafts.

##### Task 2. Assess Potential for Seasonal Thermal Energy Storage

The characterization developed in Task 1 will be used to assess the potential for using the abandoned mine workings for STES or other related energy conservation systems.

#### Technical Progress

##### Task 1. Characterize Existing Mine Workings

Background. Iron mining began at Ely, Minnesota (Figure 3.15) in 1888 and continued until 1967. A total of 87,633,822 tons of high-grade hematite ore was mined and shipped by rail to Lake Superior ports. Ely grew from an uninhabited wilderness in 1883, when the deposit was discovered, to a city of more than 6000 at the height of mining. Its population has now fallen to less than 5000. Energy costs are significant in attracting and holding residents and business enterprises.

Early in 1981, Mr. Andrew Hill of Ely conceived the idea of using the water-filled underground mines as a source of geothermally stabilized water for a heat pump energy source. Hill called on the Minnesota Geological Survey (MGS) for an opinion on the potential heat capacity of the mines and the feasibility of the concept.

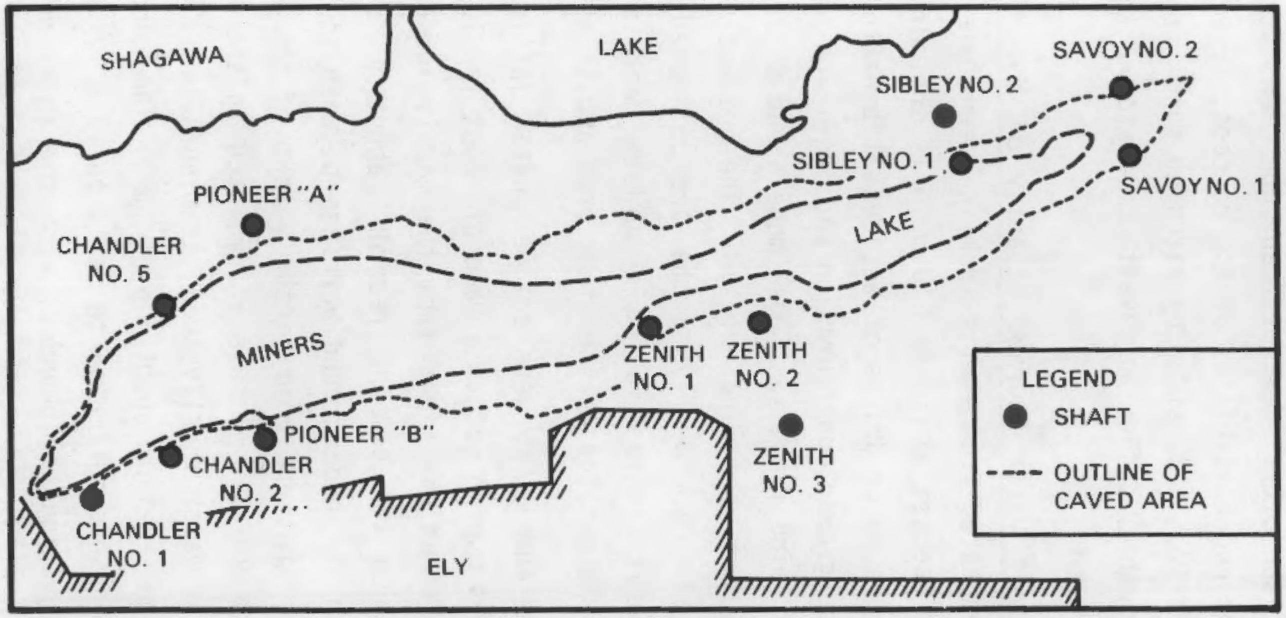

FIGURE 3.15. Ely and the Locations of the Principal Mine Shafts. A lake, caused by subsidence of the land surface, occupies the area over the mined-out ore body.

A preliminary inspection of the site and review of the literature (van Barneveld 1913; Machamer 1968; Reid 1956) suggested that the heat capacity of the mines might well be potentially large relative to the energy requirements of the city. However, many questions needed to be answered to assess the scope and feasibility of the concept. Investigations were begun by the MGS March 17, 1982, aided by matching funds from the U.S. Department of Energy through Pacific Northwest Laboratory, under subcontract B-D4459-A-0.

Structure and Water Storage Capacity of the Mines. Five mines (Figure 3.15) operated from shafts sunk in greenstone with drifts into the ore body. The deepest shaft is 510 m. All the mines were eventually connected underground by drifts or accidental breakthroughs. Most of the data on the underground configuration and condition of the mines have come from unpublished mine maps, sections, models and other records preserved by citizens of Ely when the mines closed. The ore was mined by undercutting and caving. Waste rock overlying the ore collapsed into the stopes. Subsidence above the mines formed a surface depression which roughly coincides with the outline of the mined area and is as much as 60 m deep.

So long as the mines were active, water infiltrating from local precipitation was pumped out at a rate of about $1 \times 10^6$ $m^3$ per year. Very little water entered the mines from the massive greenstone wall rocks. Extrapolating from the pumping records, about $6 \times 10^6$ $m^3$ of water disappeared into the underground workings between the closing in 1967 and 1974 when water first appeared in the bottom of the surface depression. Since 1974, 8 or $9 \times 10^6$ $m^3$ have accumulated in the surface depression, forming a body of water locally known as Miners Lake, which is as much as 50 m deep with an area of about $5 \times 10^5$ $m^2$. The total volume of water stored in the mines is estimated to be 14 to $15 \times 10^6$ $m^3$, which is in good agreement (with various allowances) with the total volume of ore removed from the mines (17 to $18 \times 10^6$ $m^3$). The $6 \times 10^6$ $m^3$ of water stored underground can be pictured as filling a labyrinth of shafts, drifts and stopes. The strong massive greenstone contains the main shafts and access drifts, which are believed to be open. The stopes within the ore body are no doubt a maze of collapsed rubble with random interstices and bridged spaces of all sizes filled with water.

Underground Investigations. It is possible to breach the reinforced concrete covers of two of the deepest and most strategically located main shafts, Pioneer A and Zenith 3 (Figure 3.15). Figure 3.16 shows temperature-depth profiles measured in the shafts in relation to essential geometric elements of the mines shown diagrammatically. Elevations (given in parentheses) are referred to mean sea level. Pioneer A was sounded to the 15th level (2 m), where it is obstructed. Zenith 3 is vertical and open to the bottom (-78 m). It connects with the ore body and other workings only from the 14th level (58 m) to the 18th level (-78 m), the deepest level mined.

Thermal soundings in two mine shafts revealed three distinct zones or layers of water separated by sharp inverted thermoclines (see Figure 3.16). The colder layers overlie the warmer layers. The elevations of these thermoclines are significantly different in each shaft and appear to be related, at least in part, to specific differences in the geometry of each shaft (Figure 3.16). Measurements of specific conductivity, pH, alkalinity and density show that the thermoclines coincide with chemoclines. Thermal convection is inhibited by chemical stratification.

The pumping tests show that there are open underground connections between the Pioneer and Zenith shafts, which are 1353 m apart and on opposite sides of the lake. Pumping in Zenith 3 quickly induced a 21-cm drawdown in Pioneer A, indicating that there is appreciable resistance to flow between the lake and the underground workings, but lake level rose less than 0.05 cm during the entire test. If infiltration between the lake and the underground mines had not taken place at a significant rate, a rise in lake level of about 2 cm should have occurred. These results encourage ideas about the design of a system to use the heat storage capacity of the mine, but more extensive hydraulic tests are needed.

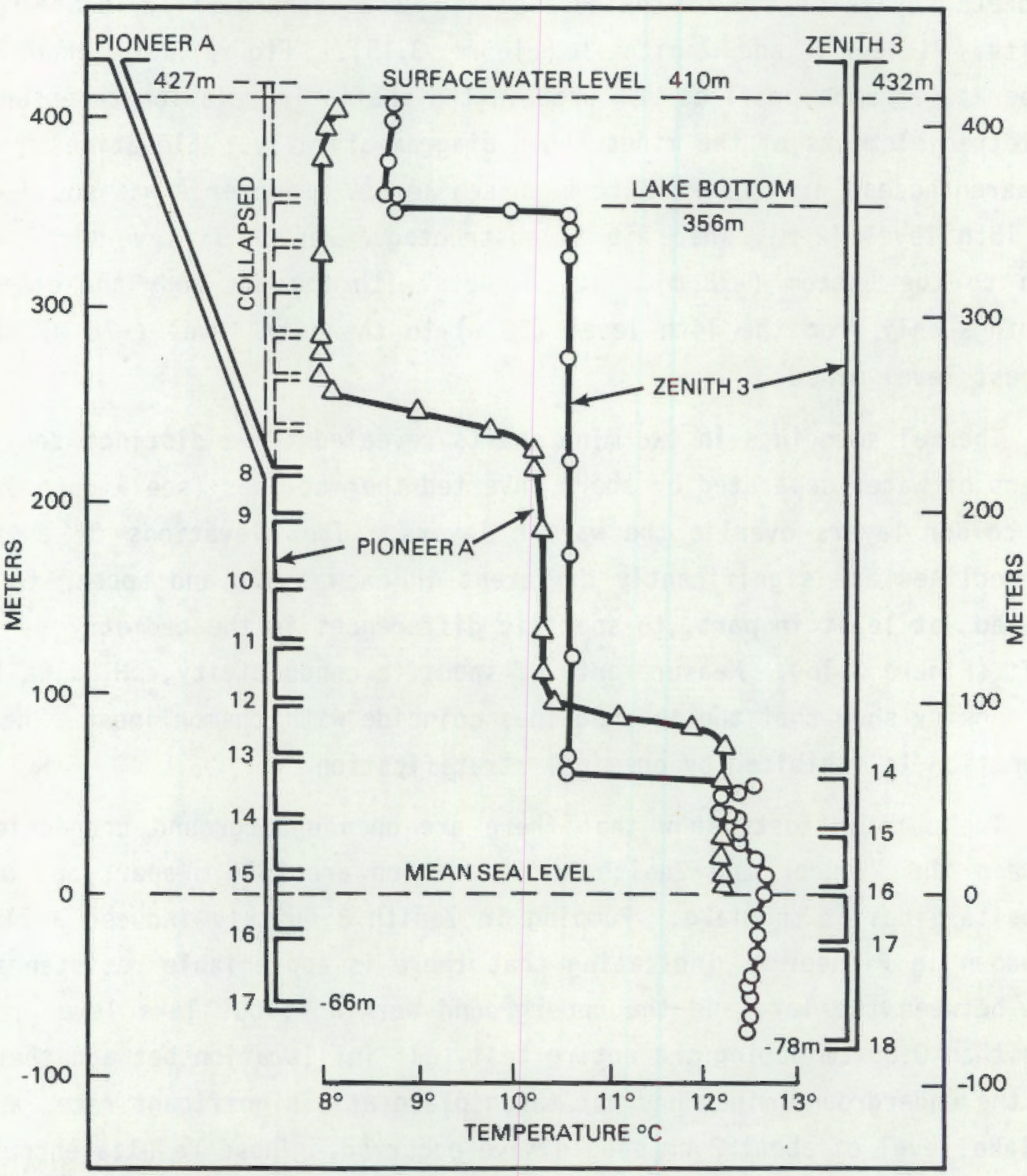

FIGURE 3.16. Water Temperatures in the Pioneer A and Zenith #3 Shafts with Geometry of the Shafts and Drift Levels Shown Schematically

## Task 2. Assessment Potential for Seasonal Thermal Energy Storage

Based on data gathered to date, a tentative plan for developing the mines as an energy resource has been produced.

An intake pipe could be placed in a shaft to withdraw sulfate-rich water from the top of the lowest layer, just below the lower thermocline. After heat extraction by heat pump, the chilled saline water would return through a deep outlet pipe to the lowest level of the mines. As the relatively warm water was replaced by chilled waters, the deep layer of saline water would become increasingly stable and isolated from further circulation. When the effective $\Delta T$ of the deep water layer was used up, the intake and outlet pipes would be raised to the middle layer, leaving the chilled lower saline layer to accumulate geothermal heat over a period of years, thus avoiding any mixing or discharge of this water.

A similar cycle of heat extraction and chilled water discharge would then proceed within the middle layer, but heat replenishment would be accomplished by using the lake as a seasonal solar heat collector. By early summer a surface layer of water 3 to 4 m deep with a temperature of 20°C to 23°C forms on the lake. A shallow intake in the lake could skim warm water and discharge it underground on the top of the water column, while chilled water from the bottom of the middle layer would be returned through an outlet pipe to the bottom of the lake. Because there is no head difference between the lake and the mine, water circulation would require little energy, and a large input of solar energy might be obtained at low cost.

This circulation scheme ultimately entails mixing relatively pure surface water with somewhat saline water from the middle layer. Although the saline water will be diluted and its alkalinity has buffering value, the effect on the quality of the net discharge from the system will need to be evaluated. Also important in evaluating environmental impacts is the very tangible positive impact of substituting seasonal solar and geothermal heat for oil heat.

The foregoing design considerations will require modification as more is learned about the mines. Nevertheless, the investigations to date have shown that the energy accumulation and storage capacity of the Ely mines is large; the potential for producing heat at a substantial cost saving over conventional fuels should encourage development of this resource.

### 3.2.3.1.5 Analysis of STES in Existing Tankage

Massachusetts Institute of Technology

Objective

The objective of this study is to assess the use of existing tankage at the Charlestown Navy Yard (CNY) (Boston, Massachusetts) for STES integrated with solar-derived building heating. The analysis was performed under the direction of the Solar Thermal Storage group at Argonne National Laboratory and serves as DOE input to the International Energy Agency Solar Energy Programme, Task VII, Solar Heating and Cooling with Seasonal Storage.

Tasks

Task 1. Characterization of Solar/Seasonal Thermal Energy Storage Opportunities

The current site conditions at CNY will be identified, as will the current plans of the Boston Redevelopment Authority (BRA) for renovating this area. Tankage having the potential for seasonal storage of warm water will be identified and characterized as well as the probable location and extent of solar panels for heating of water for storage.

Task 2. Parametric Analysis of Solar/Seasonal Thermal Energy Storage Systems

Solar/STES systems will be analyzed to determine the performance and economics of various system configurations. To the extent possible, the economic sensitivity of solar collector and storage components will be characterized.

## Technical Progress

### Task 1. Characterization of Solar/Seasonal Thermal Energy Storage Opportunities

Background. Solar energy heating systems using seasonal storage are a most promising alternative to conventional heating means, particularly in northern climates such as New England. These systems exhibit significant economies of scale, making them applicable for larger loads and district heating schemes. The International Energy Agency has devoted a particular task to the assessment of solar/STES and this project has been conducted in collaboration with the U.S. team at the Argonne National Laboratory.

The Charlestown Navy Yard is located in the Boston Inner Harbor and served the U.S. Navy for 175 years until 1974. A large portion of the Yard is now being redeveloped under the direction of the BRA into residential and commercial buildings and public area. The western-most section is maintained and operated by the National Park Service (NPS) and is a main tourist area in Boston. Figure 3.17 shows a schematic site plan of the Yard highlighted with the various opportunities for solar systems, which are discussed next.

The attraction of the Charlestown Navy Yard as a site for a seasonal storage system stems from the availability of substantial storage facilities. A number of facilities exist around the Yard so as redevelopment progresses various opportunities can be considered.

This study focusses on the use of two large concrete underground tanks totaling 5700 $m^3$ located in the NPS area. One of the tanks is divided completely in half by a concrete wall; therefore, three distinct volumes actually exist. The tanks were built in the 1940s but preliminary inspection indicated that the tanks are in good condition. All are filled to near the top and no leakage is suspected.

Two smaller buried concrete tanks and an underground pump house exist in the redevelopment area and offer opportunities for seasonal ice storage

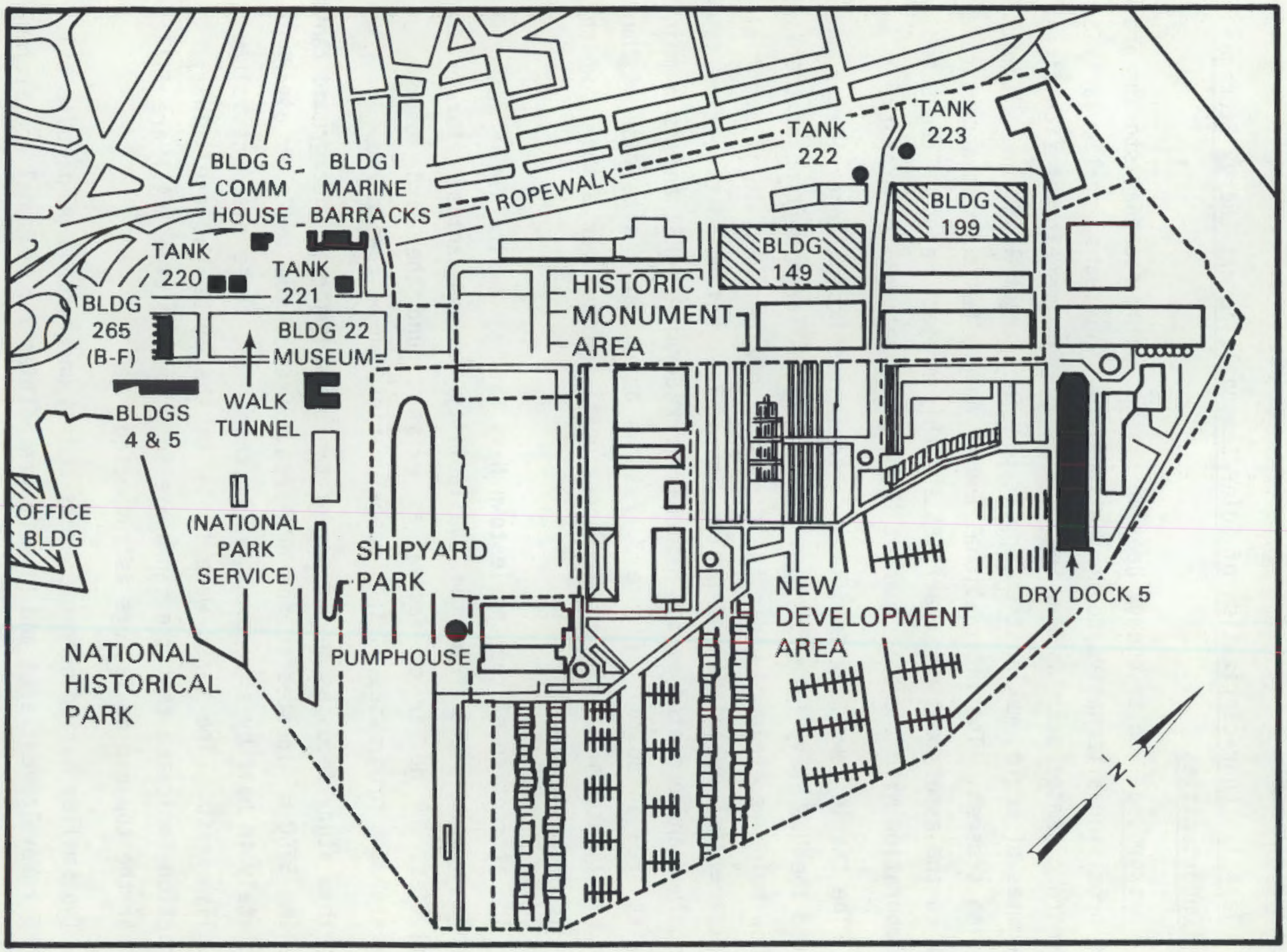

FIGURE 3.17. Charlestown Navy Yard Schematic Site Plan

for air conditioning or for a diurnal storage working in conjunction with a larger seasonal storage system.

A most intriguing and unique storage facility available in the Navy Yard is the dry dock located at the far eastern end by the proposed hotel. For aesthetic reasons it is necessary to keep the appearance of the dry dock as an open body of water, and therefore the idea of setting up a salt pond has been considered. Due to the depth of the facility, additional collectors (beyond the salt pond surface area) would be required to take advantage of the large storage capacity available. The redevelopment of the area around the dry dock will not occur for 7 to 10 years, so this opportunity was not pursued in detail.

Areas for solar collectors are available on the flat roofs of the two taller buildings in the Yard. These areas should be sufficient for the system analyzed, provided most of the unusual roof structure can be eliminated. Compared to conventionally designed seasonal storage systems, these collector sites are fairly distant and elevated; thus, piping and pumping requirements and heat loss will be greater. A preferable collector site in terms of pumping and piping exists on a two-story office building just to the west of the Navy Yard, although this structure is first to be renovated and plans and structural capability are uncertain.

An extensive underground tunnel network existed in the Navy Yard for the distribution of steam heat. Although a large portion of the network has been destroyed in the redevelopment area, in the NPS area it is still intact. The distribution network layout for the system analyzed in this study makes use of the walk tunnel along 1st Avenue and the long Ropewalk (Building 58).

For practical and political reasons, the NPS buildings around the large storage tanks are used as the heat load for the system. The buildings were determined to have an annual heat load of about 2000 MWh and a hot water demand of 19,100 W. The buildings include apartment units, office space, room for social functions, and a museum.

System Summary.

- Storage: Tanks 220 and 221 in NPS area (5700 $m^3$)
- Collector sites: 1) Buildings 149 and 199 in redevelopment area
  2) two-story office building (to be renovated)
- Distribution network: Takes advantage of NPS walk tunnel and Building 58
- Load: NPS buildings surrounding storage tanks (2000 MWh space heat, 19,000 W hot water).

### Task 2. Parametric Analysis of Solar/Seasonal Thermal Energy Storage Systems

Methodology. The analysis of the system was performed with extensive use of the computer simulation routine MINSUN written by the Swedish team in the International Energy Agency project. The computer model was written specifically for solar/STES systems and is capable of performance and economic analysis. System cost-effectiveness is indicated by the system solar premium (SOLPRM), which is the incremental cost of the system per MWh of conventional fuel displaced. This variable thus accounts for the system cost as well as its solar fraction and is directly translated to the objective function of cost-effectively displacing conventional fuel.

System Input Parameter File. The important system parameters required as input to MINSUN are listed in Table 3.8. Cost information for collectors was derived from a study done as part of the U.S. effort in the IEA program (Bankston 1982). Other costs and product information were gathered through communications with equipment vendors. These parameter values were used as a base case and were then systematically varied for a sensitivity analysis.

Base Case Analysis. The performance of the system was examined for four collector types--flat plate (FLPT), evacuated tubes (EVAC), advanced CPC evacuated tubes (ADEVAC), and parabolic trough concentrators (PARB). The most important result was that the system solar fraction (proportion of

TABLE 3.8. Summary of Base Case Input Parameters

| | | | | | |
|---|---|---|---|---|---|
| Storage volume | 5700 $m^3$ | | | | |
| Storage insulation thickness | 0.076 m (3 in. with R = 7/in.) | | | | |
| Space heat load | 2000 MWh | | | | |
| Tap water load | 19,100 W (167 MWh annually) | | | | |
| | Year | FLPT | EVAC | ADEVAC | PARB |
| Collector costs ($\$/m^2$) | 1985 | 270 | 300 | 300 | 350 |
| | 2000 | 200 | 200 | 200 | 200 |
| Storage renovation cost | \$6/$ft^2$ surface area<br>\$846/$m^3$ insulation (derived to account for total cost)<br>\$218,915 total | | | | |
| Distribution cost (collector and load) | \$60/m; \$102,480 total | | | | |
| Discount rate (real) | 4.0% | | | | |
| Fuel escalation rate (real) | 3.5% | | | | |
| Auxiliary/conventional fuel cost | 0.05/kWh | | | | |

load met with solar energy) continues to increase significantly as collector area is increased beyond the area sufficient to heat the storage volume to its maximum allowable temperature. Although the additional energy collected during the summer months is wasted, the additional winter collection is substantial.

System cost-effectiveness (SOLPRM) using the 1985 collector cost scenario is shown in Figure 3.18. The collector cost for FLPT, ADEVAC, and PARB are such that all exhibit comparable solar premiums in the range of \$10 to \$17 MWh of fuel displaced. The year 2000 cost scenario produces cost-effective (negative SOLPRM) solutions for FLPT, ADEVAC, and PARB collectors. System solar fraction in the range of minimum SOLPRM is approximately 0.5, which is very low for typically designed seasonal storage systems. In this case the system is volume-constrained: increasing the load decreases the average annual storage temperature, thereby increasing collector efficiency. Thus, more conventional fuel is displaced although the solar fraction is reduced (due to the larger load).

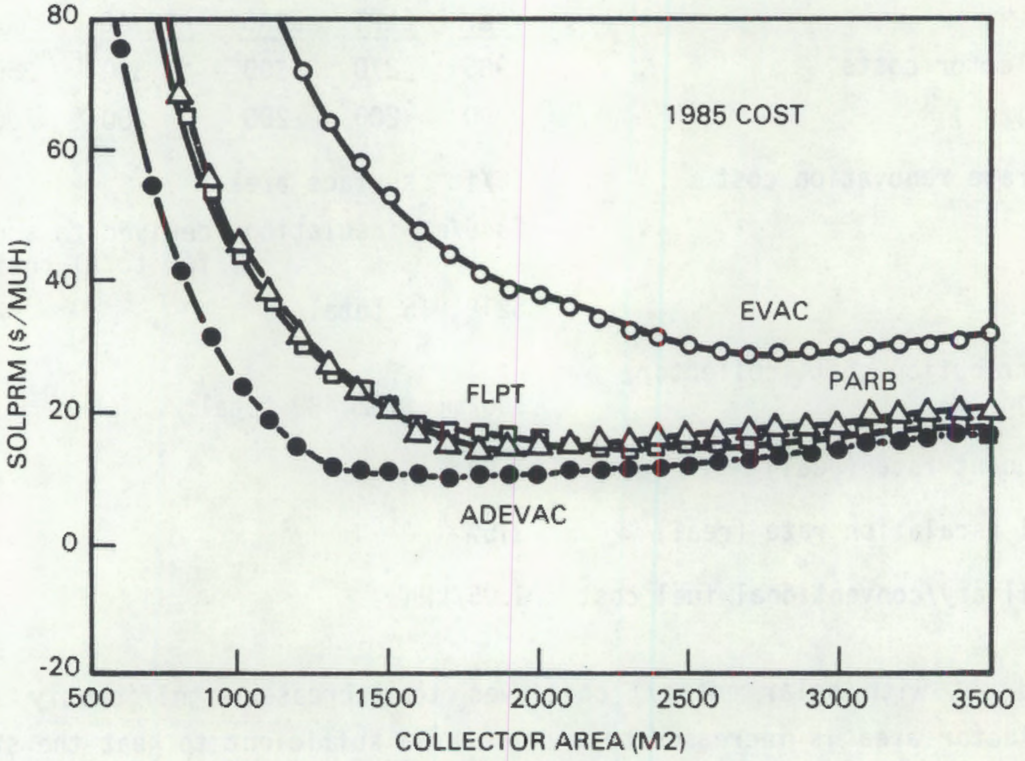

FIGURE 3.18. System Cost-Effectiveness--1985 Collector Costs

Of particular importance in Figure 3.18 is that the optimal system cost-effectiveness is insensitive over a surprisingly broad range of collector area. This observation implies that the marginal value of the additional solar heat provided by the incremental area is more or less equal to the collector marginal cost. Provided available area for collectors is not a constraint, the selection of a larger area is preferable so that more conventional fuel is displaced.

Sensitivity Analysis. A sensitivity analysis was performed by observing the change in SOLPRM due to iterative changes of parameters of interest, with all other parameters set at the base case. The results of this analysis are presented for ADEVAC collectors (2500 m$^2$, 1985 cost) in Table 3.9. System cost-effectiveness is particularly sensitive to load, collector cost, discount rate, and auxiliary/conventional fuel cost.

TABLE 3.9. Summary of Sensitivity Analysis
(for ADEVAC, 2500 m$^2$, 1985 cost)

| Parameter | | SOLPRM $/MWh | Parameter | | SOLPRM $/MWh |
|---|---|---|---|---|---|
| Load | 1000 MWh | 28.79 | Discount | 2% | -3.32 |
| | 2000(a) | 12.16 | Rate | 4(a) | 12.16 |
| | 3000 | 6.58 | (real) | 6 | 28.73 |
| | 4000 | 2.48 | | | |
| Collector | $\$200/m^2$ | -6.30 | Fuel | 2.5% | 18.63 |
| Cost | 300(a) | 12.16 | Escalation | 3.5(a) | 12.16 |
| | 400 | 30.62 | Rate (real) | 4.5 | 4.68 |
| Storage | $\$4/ft^2$ | 6.77 | Auxiliary | $0.04/kWh | 25.67 |
| | 6(a) | 12.16 | Fuel Cost | 0.05(a) | 12.16 |
| | 8 | 17.55 | | 0.06 | -1.35 |
| Distribution | $30/m | 8.38 | | | |
| Cost | 60(a) | 12.16 | | | |
| | 90 | 15.95 | | | |

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(a) Base case value

Heat Pump. It is suspected that including a heat pump in the system will improve system performance and cost-effectiveness. The storage capacity is the primary constraint on the system and optimal operation is characterized by substantial winter collection and summer heat wasted. A preliminary analysis indicated improved cost-effectiveness with smaller optimal collector area and greater solar fraction. This analysis was performed with insufficient understanding and confidence in the computer model, so these findings should not be considered inerrant or complete.

Preliminary results are therefore promising in that practical and cost-effective solar/STES systems can be identified. Discussions are continuing among the NPS, U.S. Navy, and BRA and others concerning development of a solar/STES system at the CNY.

### 3.2.3.2 Economic Analysis

#### Objective

The objective of this task is to perform economic analyses of promising STES concepts, including ATES, to evaluate the probable economic merit of new concepts and to identify the degree of cost reduction or performance improvement required to make the various concepts competitive with conventional technology.

#### Tasks

The economic assessment work has three tasks:

1. develop a methodology for economic evaluation of ATES configurations
2. provide a detailed economic evaluation of ATES chill storage
3. coordinate with other STES tasks in providing preliminary economic and technical evaluation of alternative nonaquifer chill storage concepts.

#### Technical Progress

Task 1. Development of a Methodology for Economic Evaluation of ATES

Development and documentation of the computer model AQUASTOR was completed in April 1982 with the publication of User Manual for AQUASTOR: A

Computer Model for Cost Analysis of Aquifer Thermal Energy Storage Coupled with District Heating or Cooling (Huber, Brown, and Reilly 1982). The model optimizes system design and calculates the life-cycle cost of district heating (cooling) using thermal energy supplied by an ATES system coupled to a seasonal energy source. A detailed discussion of the model was included in last year's Annual Report (Kannberg et al. 1982) and will not be repeated here.

A technical paper describing the capabilities of AQUASTOR was presented at the Intersociety Energy Conversion Engineering Conference (Brown, Huber, and Reilly 1982). This work was also summarized at the Mid-Year and Annual Contractors' Review Meetings. A tape of the computer model was delivered to the National Energy Software Center at Argonne National Laboratory, completing the final obligation of this task.

### Task 2. Detailed Economic Evaluation of ATES Chill Storage

Economic analysis of chill storage with ATES systems resulted in the publication of Aquifer Thermal Energy Storage Costs with a Seasonal Chill Source (Brown 1983). This work parallels a previous investigation (Reilly, Brown, and Huber 1981) in which the cost of ATES-delivered heat was estimated. Chill storage costs were estimated for point demand and residential development ATES systems using the computer model AQUASTOR. In this analysis the cost effect of varying a wide range of technical and economic parameters was examined. Those parameters exhibiting a substantial influence on the costs of ATES delivered chill were:

- system size
- well flow rate
- transmission distance
- source temperature
- well depth
- cost of capital.

The primary constraint of ATES chill systems is the extremely low energy density of the storage fluid. The energy available for chilling in a pound of 35°F water is approximately 20 Btu, depending on the specific design characteristics of the system. By comparison, the energy available for heating in a pound of 325°F water is approximately 100 Btu, again depending on design conditions. Because of this much lower energy density, equipment for handling the chilled water must be substantially larger to deliver the same amount of energy. This relationship puts a premium on factors affecting wellfield and transmission system design. The cost effects of the parameters identified above are summarized below.

Significant economies-of-scale are available for ATES systems. In fact, fairly large systems are required to approach cost-effectiveness. Costs are fairly constant for peak demands (at 25% load factor) 8 to 10 MW and larger. Costs rise quickly for systems with peak demands less than 3 to 5 MW. These trends appear to hold regardless of source temperature of system type (point demand or residential district).

Well flow rate has a substantial impact on ATES chill costs. Due to the low energy density of cold water, voluminous amounts of water must be stored in the aquifer. Wellfields can be a substantial portion of ATES chill system capital costs. An increase in well productivity (flow rate) reduces the number of wells and pumps required. Fewer wells mean less interconnecting well manifolding and less pumping energy within the manifolding.

Lengthy transmission distances can quickly result in prohibitive costs, especially for smaller (less than 10 MW) ATES systems. Extensive transmission systems can become a major portion of system capital cost as well as increasing the thermal loss to surroundings. Larger ATES systems are somewhat shielded from these cost effects due to economies-of-scale available in piping systems and a decrease in thermal loss to the surroundings per pound of water transported.

The source temperature deliverable to an ATES system is an important determinant of system economics. A lower source temperature ultimately allows a lower deliverable temperature to the user, with more usable energy per pound of water. This higher energy density allows lower system fluid flow and directly reduces the amount of piping, pumping, and well drilling required. The load reject temperature influences costs in a similar manner. An increase in load reject temperature essentially increases the amount of delivered energy at no increase in cost. The important overall factor, then, is the difference between the maximum usable (reject) temperature and the source temperature.

Well depth can be an important factor in ATES chill system costs. Increasing well depth increases the capital cost of the well and its pump. Electrical energy required to pump water to the surface is also increased. Because the low energy density of chilled water necessitates the transportation and storage of large quantities of water, the cost effect of well depth is more pronounced than for hot water storage systems. Electrical pumping energy is a significant part of the delivered cost of chill and well pumping is a major portion of the electrical consumption.

Aquifer thermal energy storage systems are generally capital-intensive projects. Thus, the cost of financing is important in determining a system's cost-effectiveness. Municipalities offer financing possibilities at substantially lower interest than is available for private entities. For this reason a municipality can consider a broader range of other system parameters as part of a potentially cost-effective ATES system.

The availability of a suitable aquifer is obviously of prime concern when considering an ATES installation. Potential site-specific availability of aquifers was not addressed in this task. This analysis assumed that a (more or less) suitable aquifer exists and examines the cost effect of a range of possible thermal efficiencies. Aquifer thermal efficiency is an important ATES cost parameter, but no more so than the other parameters noted above.

The cost of ATES-delivered chill for a 5-MW system with a 35°F source temperature was estimated to be \$22.80/MBtu. The comparable cost of chilled water from a compressive chiller device would be \$8.96/MBtu. Both levelized energy costs were calculated based on an electrical energy cost of 5¢/kWh with 1% real escalation per year. As compared to ATES-delivered heat, ATES-delivered chill suffers from two major disadvantages when competing with conventional energy systems. First, the low energy density of the cold water requires an expensive investment to deliver a relatively small amount of energy. Second, the competing technology, electrically driven compressive chillers, is highly efficient. Therefore, cost-effective ATES chill systems will be limited to special situations with design conditions more advantageous than those considered here.

Of the cost components for a 5-MW point demand system with a 35°F source temperature, capital costs dominate. However, O&M and electricity charges are significant portions of the total levelized energy cost. Electricity charges are more important for ATES chill systems than for ATES heat systems due to the absence of purchased thermal energy costs and the pumping of large quantities of water. As system size increases, the proportion of levelized energy cost attributable to electricity increases because capital equipment shows economies-of-scale, while pumping energy is directly proportional to water flow rate (system size).

### Task 3. Nonaquifer Chill Storage Analysis

Six seasonal ice generation and storage concepts were evaluated at the conceptual design level. The analysis included both technical and economic assessment of the concepts with a specific cost comparison to conventional air conditioning systems. A report, Comparative Analysis of Seasonal Ice Storage Concepts (Blahnik and Brown), has been issued in a "working copy" format. The results of this analysis were also presented at both the Mid-Year and Annual Review Meetings (Brown, Blahnik, and Huber 1982).

The six concepts selected for comparison with conventional air conditioning were:

- frozen earth with horizontal tube heat exchanger (HX)
- ice pond with horizontal tube HX
- ice tank with vertical tube HX
- ice tank with heat pipe HX
- incrementally filled ice pond
- artificial snow pond.

The first three concepts use an outdoor fan coil to generate the ice in the store. The next uses a heat pipe to generate ice. The incrementally filled ice pond uses direct chill by ambient winter air to freeze water as it is gradually added to the store. The last concept employs a snow-making machine to add ice to a pond.

The procedural steps of the concept analysis were 1) establish design assumptions and criteria, 2) select the simplest concepts from past development work, 3) size the store and equipment, 4) select materials for construction, 5) briefly evaluate the structural considerations, and 6) briefly evaluate the technical/economic tradeoffs. Conceptual designs were developed in an iterative process based upon what was learned during these analytical steps. Among the design/cost tradeoffs considered were insulation material and thickness, piping material and configuration, and heat exchanger flow rates, tubing spacing, and approach temperatures.

The final conceptual designs were the basis for estimating capital and annual operating and maintenance costs for comparison with conventional air conditioning. These costs served as inputs for the calculation of life-cycle costs, levelized energy costs, and simple payback periods. The economic analysis indicated clearly that two concepts, the incrementally filled ice pond and artificial snow pond, would be competitive with conventional air conditioning. When life-cycle costs were compared, the remaining four concepts did not appear to be competitive.

Based upon information obtained during the iterative conceptual design phase, a comparative technical assessment was also made. The technical assessment of the six concepts also indicated that the incrementally filled ice pond and artificial snow pond are superior because of their simplicity. Considerable development work is required for the other four concepts.

# 4.0 COMPRESSED AIR ENERGY STORAGE TECHNOLOGY

Compressed air energy storage (CAES) is a technique that transfers energy from off-peak to peak demand time for electric utility systems. It incorporates modified state-of-the-art gas turbines and underground reservoirs---aquifers, salt cavities, or mined hard rock caverns. The compressor and turbine sections of the gas turbine are alternately coupled to a motor/generator for operation during different time periods. During nocturnal and weekend off-peak periods, base load plants not using petroleum fuels provide energy to compress air, which is stored in the underground reservoirs. During the subsequent diurnal peak-load periods the compressed air is withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. Because the turbine is not required to drive a compressor, this concept reduces peaking plant consumption of petroleum fuel by more than 60%. Some second-generation CAES concepts require no petroleum fuels.

Studies have shown that the CAES concept is technically feasible and, for utilities with sufficiently large daily peak-to-daily average load ratios and inexpensive baseload power resources, economically viable. Compressed air energy storage systems offer several advantages over conventional systems used by utilities for meeting such peak load requirements. Energy storage offers a degree of flexibility and control in system operation (e.g., frequency stabilization). It can be considered as a spinning reserve. It can be started rapidly and/or blackstarted, and is thus available as supplemental generation in times of emergency. The Electric Power Research Institute (EPRI) has estimated that probable market penetration of CAES could result in annual savings of up to 100 million barrels of oil by the year 2000. Compressed air energy storage plants can also be sited in many more areas with less environmental impact than conventional pumped hydro plants. Finally, a well-designed CAES plant should have a smaller adverse impact on air quality, in terms of emissions, than its direct competition, the conventional gas turbine peaking plant.

For conventional CAES systems, a key question is related to long-term cavern stability. To provide the utilities with a high degree of confidence in the CAES concept, a comprehensive technology research and development program on stability was pursued to generate guidelines for design of CAES reservoirs. Another key question to CAES technology commercialization is the dependence of CAES plants on petroleum fuels. The technology dependence on petroleum fuels could become a major barrier to large-scale implementation of CAES technology. Thus, second-generation CAES concepts must be identified and examined.

In view of the overall CAES concept's potential benefits, the U.S. Department of Energy undertook comprehensive research and development projects to accelerate commercialization of this technology.

The purpose of the CAES Technology Projects within the UES Program is to develop CAES technology for electric utility applications. The primary motivation is the annual conservation of more than 100 million barrels of oil. There is significant potential for rate reductions due to this conservation. Two major project goals have therefore been established:

- determine long-term reservoir stability criteria for CAES operating conditions
- identify and develop second-generation CAES concepts that minimize the use of petroleum fuels.

In response to these identified needs in CAES technology development, two primary research and development projects were formulated. These are the Reservoir Stability Studies and Second-Generation Concepts Studies. Task breakdowns within these projects are outlined in Table 4.1.

## 4.1 RESERVOIR STABILITY STUDIES

The Reservoir Stability Studies is a long-term project directed toward establishing criteria and guidelines for use by the engineering community to ensure stable operation of underground air storage reservoirs. The study has completed its major charter during this reporting period.

TABLE 4.1. Compressed Air Energy Storage Projects and Tasks

| Project/Task | Contractor | Status |
|---|---|---|
| Reservoir Stability Studies Project | | |
| Task 1. Stability criteria formulation | PNL | Complete |
| Task 2. Aquifer field test support | | |
| -Numerical modeling support | PNL | On schedule |
| -Experimental studies support | PNL | On schedule |
| Task 3. Pittsfield aquifer test (Construction, initial operations) | PNL, PB-KBB | Complete - Transferred to EPRI |
| Second-Generation Concepts Studies | | |
| Task 1. Thermodynamic analysis of CAES cycles | PNL | Complete |
| Task 2. Evaluation of TES materials | PNL<br>FluiDyne | Complete |

Technical work in hard rock reservoirs and on solution-mined caverns is complete, and final stability criteria and guidelines for these two reservoir types were issued early in this reporting period. Porous media studies completed generic numerical and experimental work; all reservoir stability effort during this reporting period was then shifted to construction and operation of the Pittsfield Aquifer Field Test in Illinois. Concurrent with this activity, an interim version of the porous media criteria was prepared. Bubble development operations were conducted for 4 months after completion of construction at the Pittsfield test site. At that point, DOE-PNL management and ownership of the project was transferred to the Electric Power Research Institute.

### 4.1.1 Goal and Objective

The goal of the Reservoir Stability Studies Project is to ensure long-term stable geologic containment of air in CAES reservoirs by thorough examination and resolution of the critical technical issues surrounding the concept. The specific objective of this multiphase project is to develop stability criteria and guidelines for CAES reservoirs from the research data base and from related technologies. This information will allow engineers involved in CAES development to confidently propose the CAES option.

### 4.1.2 Strategy

This project required detailed geotechnical investigation of the effects of compressed air energy storage on three major types of geologic air storage reservoirs--solution-mined salt caverns, excavated hard rock caverns, and porous media or aquifer structure reservoirs. The investigation, initiated in 1977, had four activity phases for each of these three major types of underground air storage reservoirs. The phases are:

- Phase I. State-of-the-Art Survey: to establish preliminary reservoir stability criteria and identify areas requiring research and development
- Phase II. Numerical Modeling: to parametrically evaluate the response and stability of CAES reservoirs under a wide variety of CAES operating and geotechnical conditions. These results will be used to guide activities in other phases of the program.
- Phase III. Laboratory Testing: to examine issues not currently amenable or appropriate to numerical modeling; provide data for use in numerical models; and investigate fundamental rock mechanics, thermal, fluid, and geochemical phenomena as appropriate to CAES.
- Phase IV. Field Studies: to examine geotechnical issues not amenable to evaluation with numerical modeling or laboratory testing; to validate the existing reservoir stability criteria and amend them as necessary; and to corroborate numerical modeling and laboratory analyses to provide accurate estimates of reservoir response to CAES conditions.

Preliminary stability criteria were formulated at the completion of Phase I for all three reservoir types. These criteria were used as the basis for prioritization of research work in later phases. The end product of this research on each reservoir type is a final set of stability criteria.

Study on all three reservoir types was completed through the stage of generic evaluation, including literature review and numerical and experimental study prior to this reporting period. Further geotechnical research of hard rock caverns was not planned, as the site-specific aspects of the critical technical concerns were deemed within the capability of the industry.

Research on domal salt reservoirs for CAES was completed early this reporting period with correlation between laboratory and in-mine experimental work. Field studies in both salt and hard rock were precluded based on previous experience, data site-specificity, and budget restrictions. Both hard rock and salt stability criteria were prepared and then underwent intensive internal and external review. The documents, listed below, were published early this reporting period, and have been well received by industry, requiring some reprinting.

- PNL-4180, Geotechnical Issues and Guidelines for Storage of Compressed Air in Excavated Hard Rock Caverns
- PNL-4242, Geotechnical Factors and Guidelines for Storage of Compressed Air in Solution Mined Salt Cavities

Phases I through III of the porous media studies were complete last reporting period, with development of a numerical modeling capability and an experimental reservoir simulation capability. The wide-ranging research conducted in the porous media study has much reduced the uncertainty matrix on the performance of porous media air storage reservoirs. This reservoir type is the only one to proceed into the Phase IV field study area. This is due partially to uncertainty about applicability of research results to field conditions and partially to the utility industry's stated concern that aquifer air storage must be field demonstrated prior to commercialization. The objectives of the test were to validate the concept of cyclic air storage in a "prototypic" reservoir, and to verify the adequacy and accuracy of the conclusions and engineering tools resulting from the preceding work.

The strategy for field study development was for PNL to plan the test, select the site, and conduct the detail exploration (with subcontractor assistance). Leasing, permitting and licensing responsibility resided with PNL to ensure maximum responsiveness both to and from regulatory bodies. Conceptual design, initiated by PNL, was carried out through detail design by the major subcontractor, PB-KBB, Inc., of Houston, Texas. Under PNL direction, PB-KBB was responsible for design, construction and operation of the field study. Design, procurement and construction activities were underway at the beginning of this reporting period, but no major site mobilization was as yet begun. Well drilling activity was completed the previous year. Construction activity began onsite early in this reporting period. By the end of Fiscal Year 1982, all equipment had been fabricated, shipped and installed at the site, and all site construction was complete. Air injection was initiated on October 2, 1982. Four months of bubble development were then carried out on the remaining DOE funding available to the project. Under the terms of a previous agreement, the project was transferred by DOE to the Electric Power Research Institute for continued testing near the end of this reporting period. Pacific Northwest Laboratory is continuing an advisory and support role under this agreement until testing is complete. To complete the four-phase study, PNL also issued an interim version of the stability criteria and guidelines for porous media CAES reservoirs. This marked an end of the active DOE involvement in the porous media reservoir stability study. The final stability criteria document will be published after completion of the field test activity by EPRI.

### 4.1.3 Project Description

The Reservoir Stability Studies projects for 1983 are significantly reduced from prior years and consist of those elements necessary to bring about an orderly closeout of the DOE-supported work, responsible reporting of the work to date, and transfer of responsibility to private industry the work meriting continued support. Both the hard rock and salt studies were completed during earlier reporting periods. The final criteria and guidelines documents were published early this reporting period. All active project elements were in the porous media study area. All tasks within the project were directed toward conduct and support of the Pittsfield Aquifer Field Test in Pike County, Illinois.

The following subsections provide detailed summaries of project activity for this reporting period in each of the task elements shown in Table 4.1.

#### 4.1.3.1 Stability Criteria Formulation

R. D. Allen (Pacific Northwest Laboratory)

#### Objective

The objective is to assemble and integrate the research results of the Reservoir Stability Studies into stability criteria for underground reservoirs that will focus the CAES geotechnical data base and provide a resource for groups responsible for CAES development and implementation.

#### Tasks

The project comprises formulations of stability criteria according to the three types of geologic compressed air storage reservoir: hard rock cavern, salt cavity, and aquifer. The three tasks are:

- Subtask 1 - Publish stability criteria for hard rock caverns
- Subtask 2 - Publish stability criteria for salt cavities
- Subtask 3 - Publish stability criteria for aquifers.

## Technical Progress

All subtasks have involved assemblage of data from the literature, from laboratory and numerical modeling studies funded by the CAES program, and from field experience or specific field studies funded by the CAES program. Both hard rock and salt stability criteria have been published as final PNL reports (Allen, Doherty and Fossum 1982; Allen, Doherty and Thoms 1982). The results are summarized in the following sections.

Stability criteria for aquifers are being published as an interim PNL report (Allen, Doherty, Erikson and Wiles 1983). These are summarized later in this report. Final criteria for aquifers, which will be published during 1984, will integrate the results of the Pittsfield Aquifer Field Test.

### Stability Criteria for Hard Rock Caverns

The primary objective of this study was to develop and present geotechnical criteria for the design and stability of CAES caverns in hard rock formations. These criteria involve geologic, hydrologic, geochemical, geothermal, and in situ stress state characteristics of generic rock masses. The design criteria must be established from the viewpoint of 1) the type of CAES system, 2) the desired air volume and pressure, and 3) the thermal/rock mechanics/hydrologic constraints appropriate to the rock mass. These constraints must be used to determine optimal cavern shape, cavern orientation, dimensions and spacing, and excavation methods.

Because of the high excavation costs associated with the larger volumes required by other storage schemes, a CAES reservoir in hard rock would probably be a constant pressure, water-compensated cavern. The daily temperature cycling and wall wetting occurring during the operation of a CAES reservoir, having never been encountered before in rock masses, lead to the following design concerns:

- cavern geometry and size
- cavern orientiation

- thermal response
- low frequency fatigue, coupled with temperature cycling and wetting
- air penetration of rock mass
- hard rock properties at nonambient conditions
- residual strength of hard rock after failure
- mineralogical alteration of hard rock under CAES conditions.

The following conclusions regarding air storage in hard rock masses have been identified:

- Rocks must be competent (with high structural strength and stability), and capable of sustaining openings with minimal support and rock improvement measures. Candidate rock types include granite/granodiorite, quartzite, massive gneiss, dolomite and limestone.
- Rock masses must be characterized by overall hydraulic conductivities less than $10^{-8}$ m/sec for water.
- Long-term containment of stored air may not be possible in tightly folded, heavily fractured, jointed, or faulted rocks.
- Cavity geometry and orientation must be selected for minimal support requirements. Important geologic parameters include extent of fracturing, nature of joint surfaces, permeability in zones of weakness, and hydrologic conditions.
- Storage cavern design and construction must minimize slaking, spalling and loss of ground water above the cavern.
- Cyclic temperature and humidity variations must not significantly decrease rock strength by fatigue.
- Geologic formations with high horizontal in situ stress are unfavorable. Maximum horizontal stress should not exceed vertical stress by more than a factor of 1.5.

- The construction cost of CAES caverns can be seriously impacted by conditions such as degree of jointing and faulting and incompetence of the overburden. Access shafts for CAES caverns should not be sunk in areas with more than 50 m of incompetent, water-bearing overburden.

Additional guidelines that should be considered when constructing a CAES reservoir in hard rock include:

- Hydrostatic pressure within the host rock must balance the pressure of stored air (and the equal pressure of the water-compensating column).
- Surface water must be available for pressure compensation.
- The "champagne effect", rapid evolution of air in the water column connecting the cavern to the surface lake, must be considered in the design of CAES plants with compensated caverns.
- Unconfined compressive strength should exceed 25 MPa over the cycling life.
- The nearest dissimilar geologic formation contact should not be closer than 100 m.
- Areas of active volcanism, faulting, seismic activity, excessive subsurface solution and subsidence are to be avoided as cavern sites.
- Long axes of caverns should be oriented with respect to structural discontinuities and in situ stress fields to maximize stability and minimize construction costs.
- The most likely cavern depth is 750 to 850 m due to operating requirements.
- Air loss should not exceed 1% during the storage period.
- Operating pressures, essentially constant, will fluctuate within a very narrow range with differences attributable to variations in the effective height of the water-compensating column. The most likely design range for operating pressures is 7.35 to 8.33 MPa. Maximum charging pressure will be 12.0 kPa/m of depth.

- Compressed air will enter the cavern at 30 to 80°C.
- Compensating water temperature may fluctuate between 0 and 30°C.
- Cavern depressurization should be gradual, not exceeding 1 MPa per hour.

In sum, this study concludes that the chief geotechnical issues for the development and operation of CAES caverns in hard rock are impermeability for containment, stability for sound openings, and hydrostatic balance.

## Stability Criteria for Salt Cavities

The state of knowledge about utilization of solution-mined salt cavities for CAES includes laboratory results, numerical modeling, field characterization, solution mining experience, and practical operating parameters. Salt caverns for CAES systems undergo daily cycles of pressure, temperature, and humidity. Effects that could damage the cavern must be controlled. Germane topics include:

- cavern geometry and size
- long-term creep and creep rupture of rock salt
- effects of pressure and temperature loading rates
- low frequency fatigue, coupled with cyclic pressure, temperature, and wetting conditions
- progressive deterioration of salt fabric with possible air penetration
- cavern monitoring methods
- salt properties at nonambient conditions.

The following design criteria serve as guidelines for long-term stability of salt cavities:

- Cavity floor depths to 1500 m may be acceptable depending on site conditions. For the anticipated maximum operating pressures of 9.0 MPa or less, optimal depth to cavern roof is about 800 m. (Maximum air pressure is to be 1.6 MPa per 100 m of depth.)

- Cavity wall temperatures should not exceed 80°C.
- Cavity separation (center-to-center)-to-diameter ratio (S/D) should be at least 4. Salt thickness between a cavern wall and the lateral salt dome boundary should be at least 3 times the cavern diameter.
- Minimum thickness of salt above a solution cavity should be 150 m. The ratio of overburden salt thickness to cavity span is to be at least 2.5. Cavern span should not exceed 60 m.
- Cavity height-to-diameter ratio (H/D) should be in the range of 1 to 5.
- Octahedral shear strength of salt should lie between 3.8 and 5.2 MPa.
- In situ horizontal stress should not exceed 120% of overburden pressure.
- Depressurization should not exceed 1 MPa/hr.
- Salt cavities must be protected against ground-water encroachment.
- Surface subsidence in the region overlying a CAES cavity must not be significant.
- Accessory minerals in salt reduce self-healing of fractures and contribute to irregular cavern shapes. Site selection should take this into consideration.

### Stability Criteria for Aquifers

Although most of the experience derived from natural gas storage can be applied to aquifer compressed air storage, several differences exist between the two systems. The storage of air for CAES involves daily or weekly, rather than seasonal, cycling. Moist air is more viscous than natural gas; and air storage at elevated temperatures may be desirable to increase cycle efficiency. Frequent pressure, temperature, and humidity cycles may have detrimental impacts on the aquifer matrix. In addition, the chemical environment produced by air storage may cause formation problems by oxidation of inorganic and organic substances.

Aquifers are suitable sites for compressed air storage because of low construction costs and widespread availability. The storage volume of interest consists of interconnecting pores, microcracks, channelways, permeable bedding planes, and joints that characterize the porous medium. An impermeable caprock and some form of structural trap are required to contain the air. Target aquifers must be deep enough to provide air withdrawal pressure suitable for turbine operation.

Issues related to the stability of porous rock reservoirs include:

- low frequency fatigue, coupled with cyclic pressure, temperature, and humidity influences on porous media and caprock
- reservoir and caprock material properties under CAES conditions
- effects of reservoir morphology, anisotropy and inhomogeneity
- response of wellbore casing and cementation materials
- wellbore desaturation and reversible air-water interface movements
- potential for geochemical reactions
- generation, transport and deposition of fine particulate matter.

Studies of these concerns and operational requirements have yielded the following guidelines and precautions for CAES reservoir selection, design, and operation:

- A doubly plunging anticlinal or domed sandstone aquifer conformably overlain by impervious shale, dolomite or limestone caprock represents the most desirable geology for a porous rock CAES reservoir.
- The range of parameters includes injection temperature from formation temperature to 200°C, reservoir closure 10 m or more, permeability 300 md or more, porosity 10% or more, depth 200 to 1500 m, storage pressure 2.0 to 15.0 MPa, primary caprock thickness 6 to 10 m, dehydrated wellbore, maximum charging pressure of 18.1 kPa/m of depth, and maximum storage pressure of 11.32 kPa/m of depth.

- Disaggregation of the porous medium may occur as a result of differential thermal expansion, cement dissolution, hydrolytic weakening of silicon-oxygen bonds, and/or other chemical reactions.
- Thermomechanical permeability changes may take place if air is injected at very high temperatures.
- Leakage of air through caprock due to drying or fracture should be unimportant if CAES excess pressure over discovery pressure is 0.5 of caprock threshold pressure or less.
- Regional ground-water flow gradients should be insufficient to significantly distort or displace the air bubble within an aquifer.
- Injection of air at formation discovery temperatures will present virtually no problems in most air storage operations.
- Corrosion of well casings is not regarded as a serious problem.
- Rock matrix disaggregation and other geochemical effects could restrict maximum injection temperatures to about 300°C. The absolute upper temperature limit remains to be identified.
- At least one redundant overlying caprock formation is desirable.
- Air cycling is to involve not more than 10% of the mass of the air bubble.
- In bottom drive reservoirs with thin storage zones, water coning must not inhibit air withdrawal.
- Injection well completions within the reservoir rock must provide for an adequate area of stable sandface to avert high air velocities and degeneration due to particulate plugging or geochemical reactions.

### 4.1.3.2 Aquifer Field Test Support

L. E. Wiles, R. A. McCann, and R. L. Erikson (Pacific Northwest Laboratory)

The Phase 2 and Phase 3 portions of the reservoir stability study evaluating porous media aquifer structures resulted in unique and extensive capability for numerical and laboratory simulation of CAES operational conditions. Numerical models developed to answer specific technical concerns on pressure losses, transient performance, water displacement, thermal response and phase change effects provided a resource capable of modeling the response of the Pittsfield field test aquifer as well as full-scale reservoir performance. Experimental studies conducted at many laboratories to select and evaluate reservoir and caprock materials indicated a need to satisfy a very specific set of test conditions for thorough and comprehensive evaluation of CAES reservoir rocks. This resulted in the construction of the porous media flow facility at PNL to precisely simulate the thermal, flow, and structural conditions typical of the CAES reservoir environment. This facility is a unique reservoir simulator that is capable of comprehensive evaluation of Pittsfield field test reservoir materials.

Both of these capabilities have been utilized to provide support to the design, construction and operation of the Pittsfield Aquifer Field Test during this reporting period. Subtask reports on these activities are summarized below.

### 4.1.3.2.1 Prediction of the Thermohydraulic Performance of Porous Media Reservoirs for CAES in Support of the Field Test at Pittsfield, Illinois

L. E. Wiles and R. A. McCann (Pacific Northwest Laboratory)

#### Objective

The objective of this task was to use numerical computer models to predict the thermohydraulic performance of the CAES field test reservoir at Pittsfield, Illinois. These predictions were used to verify equipment and instrumentation specifications and to assist in planning the injection and withdrawal schedule.

The prediction of reservoir performance was based on application of a series of numerical computer models developed within the CAES program at PNL. These models were applied to four basic reservoir problems at the Pittsfield site: bubble development, water coning, thermal development, and near-wellbore dehydration. Predictions related to all four of these problems were reported previously (Kannberg et al. 1982). In the current reporting period, the analytical efforts emphasized the isothermal two-phase flow problems, i.e., bubble development and water coning. Results for similar applications of the two-phase flow model were reported previously. The current results are based on a unique description of the permeability in the reservoir. This reservoir description represented the most current description available prior to initiation of air injection.

Bubble development involves the injection of air into a fully saturated porous zone, thereby displacing the aquifer water. For the computational simulation of the field test, the bubble development was considered complete when the air-water interface was depressed far enough below the wellbore so that water coning was avoided or minimized in subsequent air cycling.

Water coning is illustrated in Figure 4.1. During an air discharge cycle the depressurization around the wellbore causes mobile water in the vicinity of the wellbore to move toward the wellbore. The intrusion of water into the near-wellbore region could adversely affect reservoir operation by reducing the effective permeability. The presence of water will reduce the relative permeability to the air. Also, during the thermal cycling tests, the presence of water in the near-wellbore could enhance geochemical reactions that may reduce the absolute permeability. This could generally occur in an oxidizing environment when the temperature exceeds about 75°C (Stottlemyre and Erikson 1980).

Because most of the reservoir pressure loss occurs in the convergent region near the wellbore, decreasing the permeability in that area will require greater pressure losses to maintain a given air mass flow rate. In the most severe case, total communication with the reservoir could be lost due to near-wellbore pore plugging. Because of these potential adverse effects, the results of the analysis of isothermal two-phase flow during air cycling are reported with specific attention given to the problem of water coning.

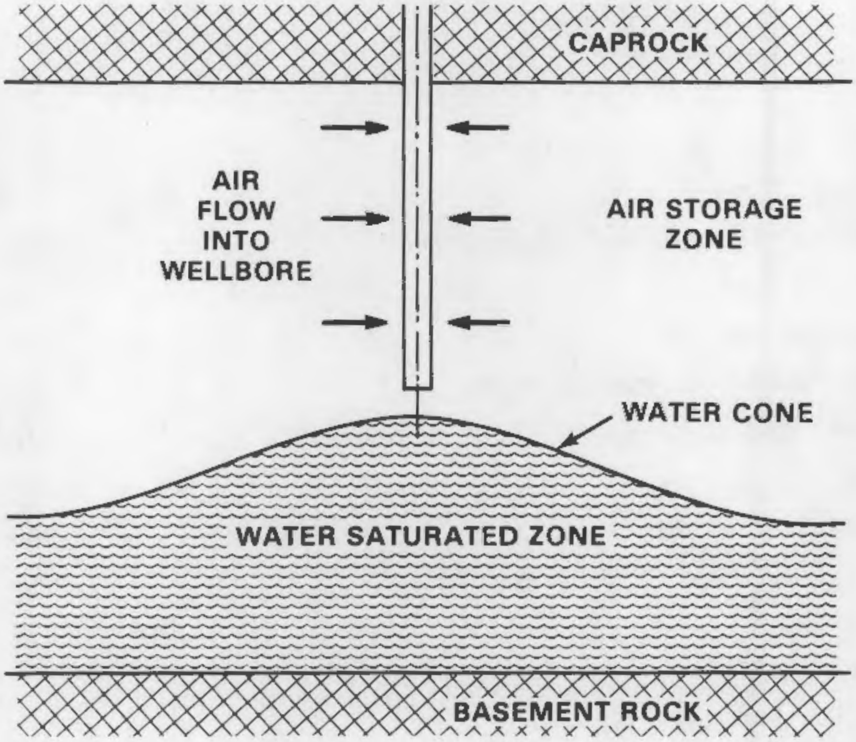

FIGURE 4.1. Water Coning During Reservoir Extraction Cycle

The bubble development and water coning analysis was done using the two-phase, two-dimensional, isothermal flow model described by Wiles and McCann (1981).

### Reservoir Description

The Pittsfield reservoir is a domal trap that has been modeled in the codes with a two-dimensional, cylindrical geometry. The structure has been modeled as a right circular cone with an impermeable caprock having a slope of 1/80. The impermeable basement rock is considered to be flat. The porous rock composing the air storage zone is characterized as a St. Peter sandstone.

The conditions applied to the analysis are defined in Table 4.2. The relative permeability and capillary pressure functions are shown in Figures 4.2 and 4.3, respectively. The unique feature of the current reservoir

TABLE 4.2. Reservoir Description

| | |
|---|---|
| Geometry | |
| Depth to top of structure | 215 m |
| Caprock slope | 1/80 |
| Vertical thickness of storage zone | 68 m |
| Well diameter | 15 cm |
| Producing length | 2.7 m |
| Outer radius of modeled region | 760 m |
| Assumed radius to hydrostatic pressure | $10^4$ m |
| Properties | |
| Permeability (horizontal) | 700 md |
| (vertical average) | 135 md |
| Porosity | 20% |
| Saturation functions | |
| Relative permeability | |
| (air) $k_r^g = (S_{c,g}-S)^2 \left[2.34-1.37(S_{c,g}-S)^2\right]$ | |
| (water) $k_r^\ell = (S-S_{c,\ell})^3 \left[4.93 - 3.72(S-S_{c,\ell})\right]$ | |
| Critical saturation for gas mobility, $S_{c,g}$ | 0.90 |
| Critical saturation for liquid mobility, $S_{c,\ell}$ | 0.20 |
| Capillary pressure | |
| $p^c = \left(\frac{0.05525}{S-0.15}\right) - 0.65$ atm | |
| Operating conditions | |
| Discovery pressure | 10 atm |
| Maximum injection pressure | 19.7 atm |
| Maximum injection air flow rate | 1250 scfm |
| Discovery temperature | 15°C |

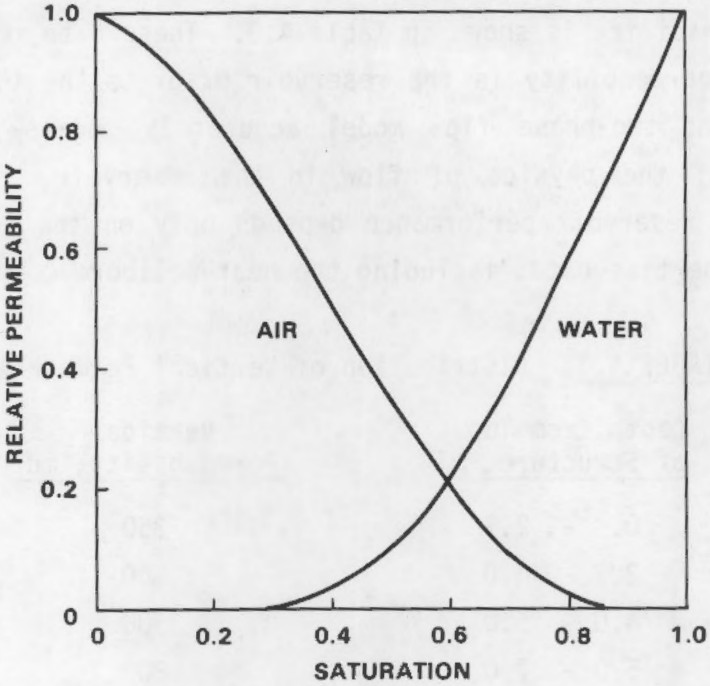

FIGURE 4.2. Reference Relative Permeability Functions

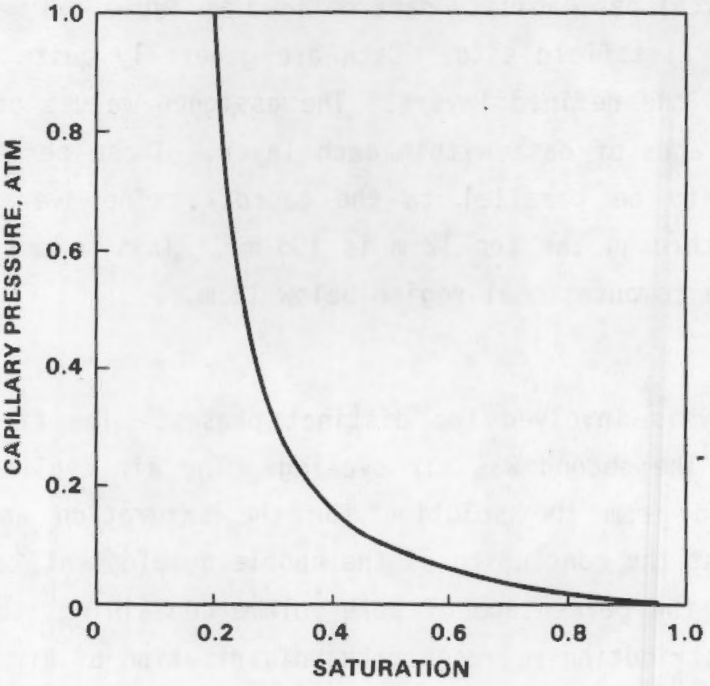

FIGURE 4.3. Reference Capillary Pressure Function

description involves the vertical permeability. The distribution of vertical permeability is shown in Table 4.3. These data represent our best knowledge of permeability in the reservoir prior to the initiation of air injection. The two-phase flow model accurately models an adequate description of the physics of flow in the reservoir. An accurate prediction of reservoir performance depends only on the accuracy of the reservoir properties data, including the near-wellbore completion effects.

TABLE 4.3. Distribution of Vertical Permeability

| Depth from Top of Structure, m | Vertical Permeability, md |
|---|---|
| 0. - 2.7 | 350 |
| 2.7 - 4.0 | 60 |
| 4.0 - 5.0 | 3500 |
| 5.0 - 7.0 | 800 |
| 7.0 - 12.0 | 80 |
| Below 12.0 | 135 |

The vertical permeability data defined in Table 4.3 were based on core data from the Pittsfield site. Data are generally quite variable, even within one of the defined layers. The assigned values of permeability represent averages of data within each layer. These permeability layers were defined to be parallel to the caprock. The average vertical permeability through the top 12 m is 135 md. This value is maintained throughout the computational region below 12 m.

### Analysis

The analysis involved two distinct phases. The first was bubble development. The second was air cycling. The air cycling calculations were initiated from the solution for the saturation and pressure distribution at the conclusion of the bubble development calculation. The saturation is the percentage of pore volume containing liquid water. The saturation distribution represents the distribution of air and water in the reservoir.

### Bubble Development

Bubble development was initiated by injecting air into the fully saturated reservoir, thereby displacing the aquifer water. The bottomhole pressure, i.e., the pressure in the wellbore at reservoir depth, was increased linearly with time during the first 24 hours. The pressure was increased from 10 to 19.7 atm. Thereafter, the bottomhole pressure was held constant. This ramp simulates the stepwise pressure increases that will be applied in the field test as a precaution against potential fracturing of the reservoir caprock (Katz et al. 1963).

The bubble development simulation was terminated after 60 days of continuous air injection. The predicted air injection rate over this period is shown in Figure 4.4. Previous results indicated that the flow rate decreased somewhat when the bottomhole pressure stabilized at 24 hours. In Figure 4.4 there is a slight inflection in the curve. When the bottomhole pressure stabilizes, the gravitational and capillary force equilibrate with the imposed bubble pressure, effecting a decline in the downward growth of the bubble. Further bubble growth occurs primarily by radial flow. The effect of this equilibration on the total injection flow rate depends on the contribution of vertical bubble growth to the flow rate. Previous results were based on a vertical permeability of 700 md. For the current results using a vertical permeability of 135 md, the vertical component would be considerably smaller by comparison. Thus, when the pressure ramp ends at 24 hours, the effect on the total injection flow rate is not as significant.

The advance of the 50% saturation front is shown in Figure 4.5. This value of saturation was chosen because it represents significant displacement of water and significant mobilities of both air and water. The bubble growth is initially both downward and horizontal. The downward growth slows appreciably as gravitational and capillary forces approach an equilibrium with the bubble pressure. Further bubble growth is primarily horizontal.

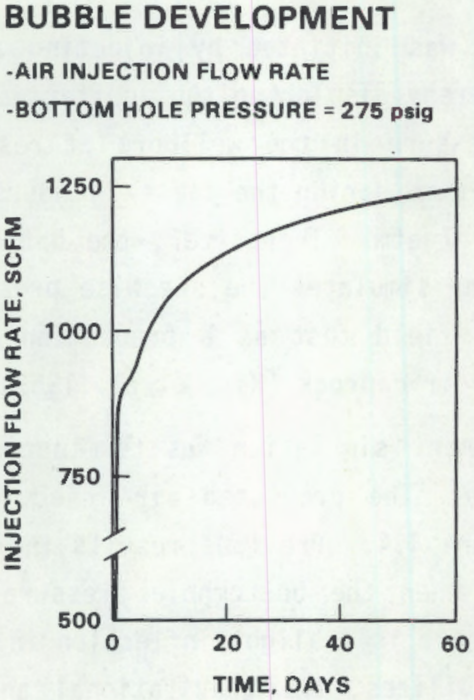

FIGURE 4.4. Predicted Air Injection Rate After 60 Days of Bubble Development

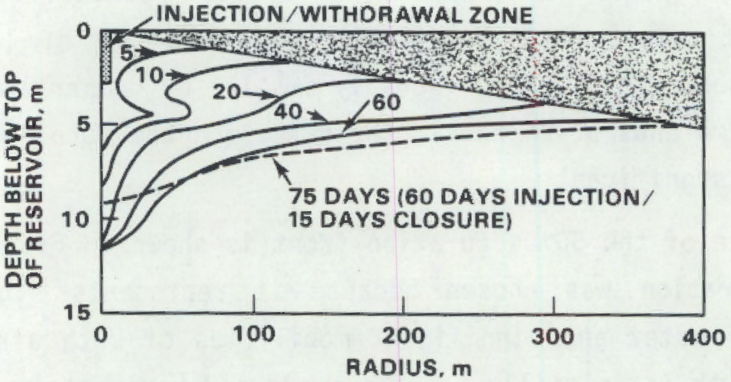

FIGURE 4.5. Advance of 50% Saturation Front During Bubble Development

In the early phase of bubble development, fingering of air into the high permeability layer below the wellbore is observed. The fingering disappears because of gravity drainage from the regions of higher saturation above the air layer.

After 60 days of air injection, a period of closure was computed for 15 days. During this closure the air-water interface approached the horizontal. The most notable effect is a resaturation of the region directly below the wellbore. Also during closure, the bubble continued to expand to approach a hydrostatic equilibrium. The average bubble pressure decreased from about 17 atm to about 13 atm during this time. The rate of equilibration depends strongly on the applied capillary pressure function and less dramatically on the assumed radius to a hydrostatic sink. According to the capillary pressure function used in the analysis, the entire vertical thickness of the resultant bubble is within the transition zone. As a result, gravity drainage is incomplete and the entire air storage zone will contain mobile water. This is a unique feature of the field test reservoir and would not be expected for a commercial facility. A smaller radius to a hydrostatic sink would effect more rapid bubble growth.

## Air Cycling

Air cycling begins with the bubble development solution after 15 days of reservoir closure. The injection/withdrawal cycle was designed to preserve the bubble air mass, although some overinjection may be practiced in the field to depress the air-water interface and make up any leakage. For the description of the field test reservoir applied in this analysis, the cyclic air injection flow rate is limited by the imposed flow rate capacity of the compressor.

The current results for air cycling calculations emphasize the problem of water coning. Water coning in the cyclic injection/withdrawal operation occurs due to an imbalance in the flow potentials and water mobilities between the two sides of the cycle. Water moves toward the wellbore during withdrawal. During the subsequent injection the water is not depressed to its original level. This results in a "ratchet" effect that provides a net increase with time in the saturation at a given elevation.

The first step to limiting this ratchet effect is to balance the pressure differential on both sides of the injection/withdrawal cycle.

This requires that the withdrawal period be longer than the injection period. A reservoir mass balance is obtained by proportioning the flow rates. The extent that the cycle can be skewed in this fashion is limited by the resultant effects that may occur on other aspects of the field test. A cycle skewed enough to balance pressures was considered to approach this limit. This approximates a similar volume flow rate at the reservoir wellbore sandface, where most of the pressure loss is concentrated.

The cycle that was chosen for final analysis was 7 hours of injection, 11 hours of withdrawal and 6 hours of reservoir closure. This 24-hour cycle was repeated 5 days per week. The reservoir was closed on weekends. The air cycling calculations simulated 10 weeks of operation.

The pressure response during air cycling is shown in Figure 4.6. The pressure differential of significance is the difference between the bottomhole pressures and the closure pressures. For the specified cycle the pressure differentials are approximately balanced.

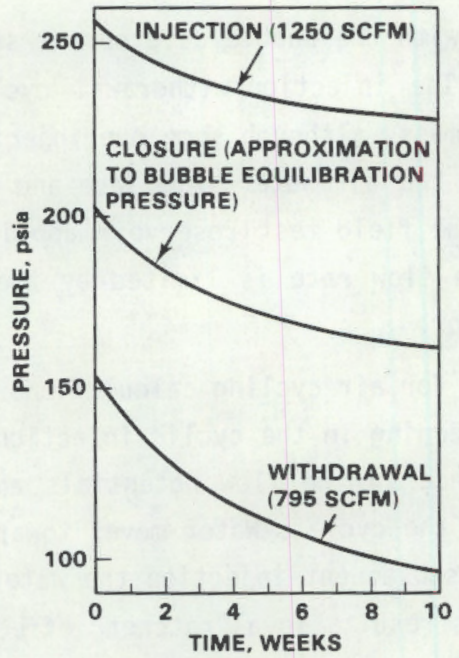

FIGURE 4.6. Bottomhole Pressure During Cycling

The movement of the 50% saturation front during this period of air cycling is shown in Figure 4.7. The initial condition is based on the bubble development solution after 15 days of reservoir closure. In 10 weeks the front advances more than 2 m toward the wellbore. Much of this advance is due to continued equilibration of the bubble. Saturation changes in the injection/withdrawal zone are minimal, a result of the low permeability layer below that zone. Thus, with the refined injection/ withdrawal cycle and the given reservoir description, there is a minimal potential for water coning to adversely affect the field test.

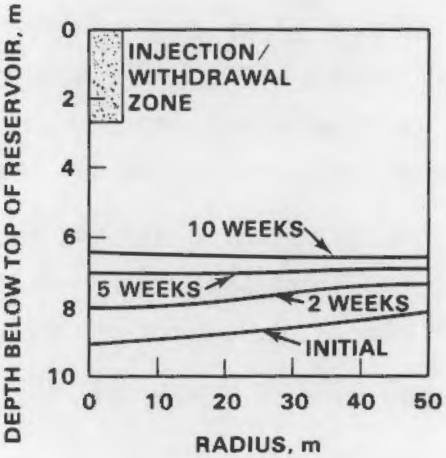

FIGURE 4.7. Movement of the 50% Saturation Front During Bubble Development

## Other Activities

During this reporting period the primary activity was the final simulation of the isothermal two-phase flow in the field test reservoir. In this section, other activities are briefly discussed.

### Video Presentation

A video presentation was created. It briefly outlines the purpose of the CAES program, followed by a description of the porous media CAES research at PNL. The thrust of the presentation is to visually demonstrate the predictions of two-phase flow in the field test reservoir. This is accomplished with a motion picture showing the change of saturation in the reservoir as time progresses.

Creating the data for the motion picture revealed a potentially important aspect of the field test. At the conclusion of the field test the air will be discharged from the reservoir as part of a plan to return the site to its original condition. Continuous withdrawal of air can lead to complete plugging of the wellbore if appropriate attention is not given to the discharge flow rate.

### Evaluation of Transient Test Data

Steady-state and transient shutdown and startup data were obtained from the field test. The data include the pressure at the bottom of well G, the injection/withdrawal (I/W)-well wellhead pressure, and the air flow rate. The field test reservoir is taking air at about one-third of the predicted rate. The data were evaluated to suggest possible reasons for this discrepancy between predicted and actual performance.

Two permeabilities were adjusted to attempt to match the predictions with the actual performance. These were the permeability of the entire reservoir and the permeability of the perforated section of the wellbore.

The following data were obtained from the field test operator on January 18, 1983:

- wellhead pressure = 315 psia
- well G pressure = 261 psia
- injection flow rate = 390 scfm

The steady-state pressure drop and flow rate are approximately matched computationally with an effective permeability through the perforated wellbore of 30 md and with an absolute reservoir permeability of 700 md. For these permeabilities the predicted total pressure drop between the wellhead and the well G location is about 51 psi, with about 80% of the drop occurring across the perforated wellbore.

The decay of the wellhead pressure during shutdown was approximately matched with a permeability through the perforated wellbore of 1.5 md.

About 50% of the total pressure decay occurs in the first half hour after shutdown.

The modeling could not match what appeared to be a significant delay in the pressure response at well G during startup. The results of this analysis strongly suggest the possibility that the deliverability to the reservoir has been significantly affected by the well completion.

### Summary

The analysis described in this section includes our final predictions of the isothermal two-phase flow in the field test reservoir. These predictions are based on our best knowledge of reservoir properties prior to the initiation of air injection. For these conditions and no well completion flow restriction, an adequate bubble size could be achieved with 60 to 90 days of continuous air injection with a bottomhole pressure of 19.7 atm. Water production should not be a problem with a pressure balanced injection/withdrawal cycle (7 hours injection/11 hours withdrawal/6 hours closure, 5 days a week with weekend closure). Other activities led to the importance of controlled air discharge to return the field test site to its original condition. Interactive modeling to match predictions with reservoir performance suggests that well completion effects may have reduced reservoir deliverability. This modeling also amplifies the importance of reliable field test data.

## 4.1.3.2.2 Porous Media Experimental Studies

R. L. Erikson (Pacific Northwest Laboratory)

Laboratory experiments were conducted in the CAES Porous Media Flow Loop (PMFL). The experiments were designed to investigate physical properties of reservoir rock under simulated field conditions.

### Objective

The objective of the experimental work during this reporting period has been to evaluate the physical properties of Pittsfield St. Peter sandstone reservoir rock under simulated field conditions.

## Tasks

The primary subtask for this reporting period involved experiments on the permeability stability of St. Peter sandstone. A minor subtask involved management of the CAES PMFL.

### 1. Subtask 1. Porous Media Flow Loop Management

The task encompasses the management duties that are part of this work, including planning and report preparation.

### 2. Subtask 2. Porous Media Experimentation

This major task includes the experimental work conducted in the CAES PMFL pertinent to the Pittsfield Aquifer Field Test. The experiments conducted were designed to investigate the effects of thermal and stress cycling on the permeability of St. Peter sandstone. All resevoir materials tested were obtained from boreholes on the field test site in Pittsfield, Illinois.

## Technical Progress

### Subtask 2. Porous Media Experimentation

The experiments conducted during this reporting period were performed exclusively using the CAES Porous Media Flow Loop (PMFL) to obtain data. The experiments completed have involved short- and long-term testing of borehole samples of St. Peter sandstone obtained from the Pittsfield site. Most of the tests sought to determine the effects of temperature, pore pressure, and confining pressure on the vertical permeability of St. Peter sandstone.

Short-Term Experiments. The results of the short-term experiments are summarized in Figure 4.8. In these experiments, the instantaneous permeability was measured as a function of temperature for two samples of St. Peter sandstone. The sample designations used throughout this section consist of letter and number identifications indicating the well location and depth from the surface (in feet) of each sample. In these instantaneous permeability measurements, the permeability was first measured at room temperature at constant confining pressure (Pc) and pore pressure (Pp). The sample was subsequently heated at <1°C/min to temperatures between 50° to 100°C at constant effective pressure (Pc - Pp) while the computer logged values of the dependent variables needed to calculate permeability (i.e., flow rate, differential pressure). These instantaneous permeability measurements represent values obtained during a temperature transient and, therefore, should be differentiated from steady-state permeability measurements which will be discussed later in this report.

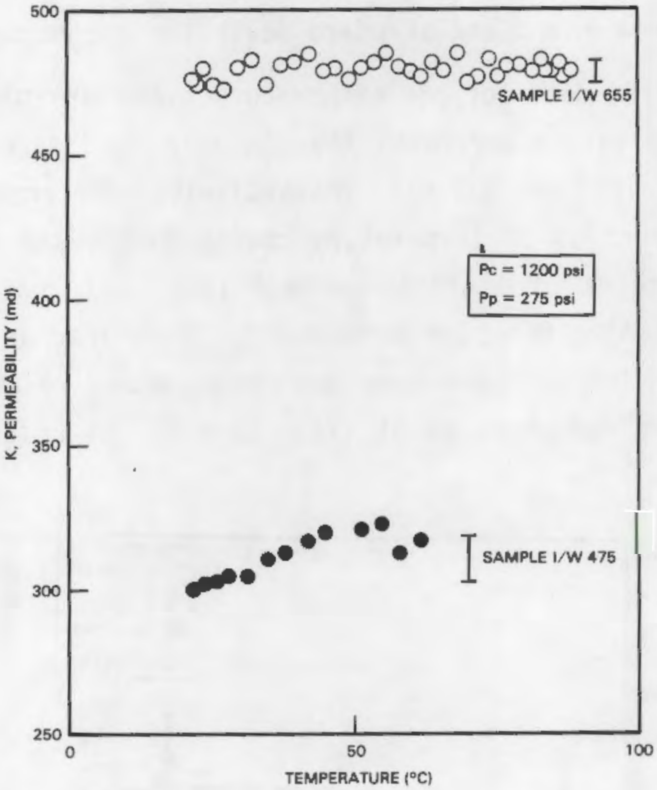

FIGURE 4.8. Instantaneous Permeability Versus Temperature at 1200 psi Confining Stress

The data from the short-term tests imply the permeability of each sample did not change appreciably during the transients at temperatures up to 100°C. The error bars plotted on Figure 4.8 indicate one standard deviation of the mean of all instantaneous permeabilities for each sample. These error bars essentially indicate the amount of uncertainty in the permeabilities typically measured using the PMFL.

Long-Term Experiments. In the long-term tests, experiments were designed to investigate the effects of temperature and stress cycling on the vertical permeability of St. Peter sandstone. All long-term tests involved measurement of steady-state permeability where permeability was measured over long periods of time (3 to 24 hours) at constant pressure-temperature conditions. In all the subsequent experiments, the permeability measured at constant P-T conditions was averaged over the time interval and the mean and one standard deviation are reported.

In Figure 4.9, data for one temperature cycle are plotted for sample I/W 657. During this experiment, the confining and pore pressures were held constant at 1200 and 275 psi, respectively. The arrows on the curves indicate the direction of temperature change during the cycle. The data are plotted in terms of absolute permeability (md) and also relative permeability (K/Ko). Relative permeability is defined as the ratio of the permeability (K) at any pressure and temperature relative to the permeability at a reference point (Ko), usually T = 20°C, Pc = 1200 psi, Pp = 275 psi.

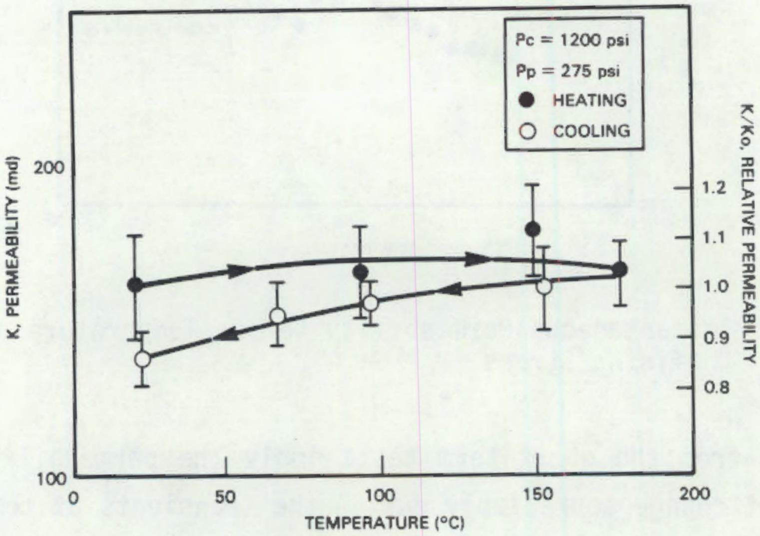

FIGURE 4.9. Permeability Versus Temperature at 1200 psi Confining Stress for Sample I/W 657

The averaged data from this sample imply that, during the heating cycle, the permeability increased only slightly (<10%). During the cooling cycle, averaged permeabilities decreased but did not reproduce the heating curve. After cooling, the permeability at room temperature was approximately 15% lower than the value before the sample was heated, indicating a permeability hysteresis effect. However, within the uncertainty of the measurements, it appears the permeability was not altered appreciably. This experiment ended prematurely due to experimental difficulties but the results indicate that multiple temperature cycles are needed to describe the behavior of samples of this sandstone.

Temperature-cycling experiments continued using sample I/W 703. In addition, the permeability of this sample was also measured as a function of pore pressure between 20 and 300 psi, which could simulate, for example, a change of injection pressure during a field test. The effect of variable pore pressure at constant confining pressure (1200 psi) and temperature (20°C) on permeability is illustrated in Figure 4.10. The data suggest the effect of pore pressure changes in the effective pressure ($P_e$) range 900 to 1180 psi is insignificant. However, at higher effective pressures (obtained by increasing the confining pressure), permeability may vary with effective stress. This problem will be discussed for a subsequent experiment later in this report.

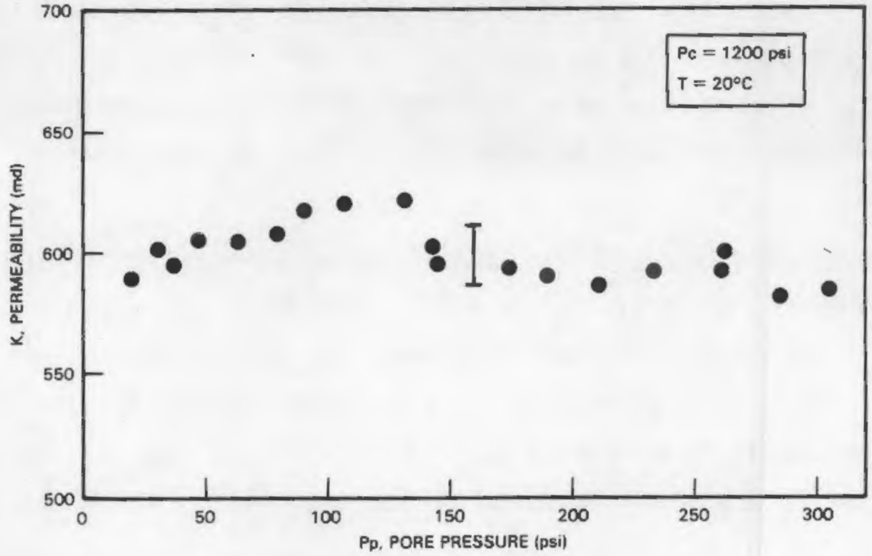

FIGURE 4.10. Permeability Versus Pore Pressure at 1200 psi Confining Stress for Sample I/W 703

A series of temperature cycling tests was completed after evaluating the effect of pore pressure on the permeability of sample I/W 703. Before cycling the sample with respect to temperature, the permeability was first measured at constant confining and pore pressures of 1200 and 275 psi, respectively. During each temperature cycle, these pressures remained unchanged so that the effective pressure was held constant at 925 psi. Experimental data for three cycles are illustrated in Figure 4.11. Each data point and error bracket represent the mean permeability and one standard deviation of a minimum of 25 measurements obtained at each temperature. The data suggest 1) a small permeability increase ($\sim$ 5%) as the sample is heated, 2) a greater permeability decrease as the sample is cooled, and 3) a permeability hysteresis effect that changes in magnitude depending on the cycle. It is evident that the largest hysteresis occurred during the first cycle in which the room temperature permeability after one cycle decreased by approximately 11%. In each of the two subsequent cycles, this value is approximately 5% or less.

The effects of varying the confining stress at constant pore pressure on the permeability of St. Peter sandstone were evaluated in a series of tests on sample I/W 664. In this experiment, the temperature and pore pressure were held constant at 20°C and 300 psi, respectively. The confining pressure, however, was varied from 1000 to 7000 psi in 1000-psi increments. Therefore, the effective pressure range covered in this experiment varies from 700 to 6700 psi. At each isobar, a minimum of 25 permeability measurements were recorded. Results are reported as an average permeability plus or minus one standard deviation of the measurements.

The measured permeabilities and relative permeabilities are plotted versus confining stress in Figure 4.12. The data indicate that the mean permeability of sample I/W 664 decreased as the effective pressure increased. There also appears to be a permeability hysteresis effect that decreases in magnitude with each subsequent cycle. From the initial mean permeability ($K_0$ = 469 md) measured at the beginning of cycle 1, mean

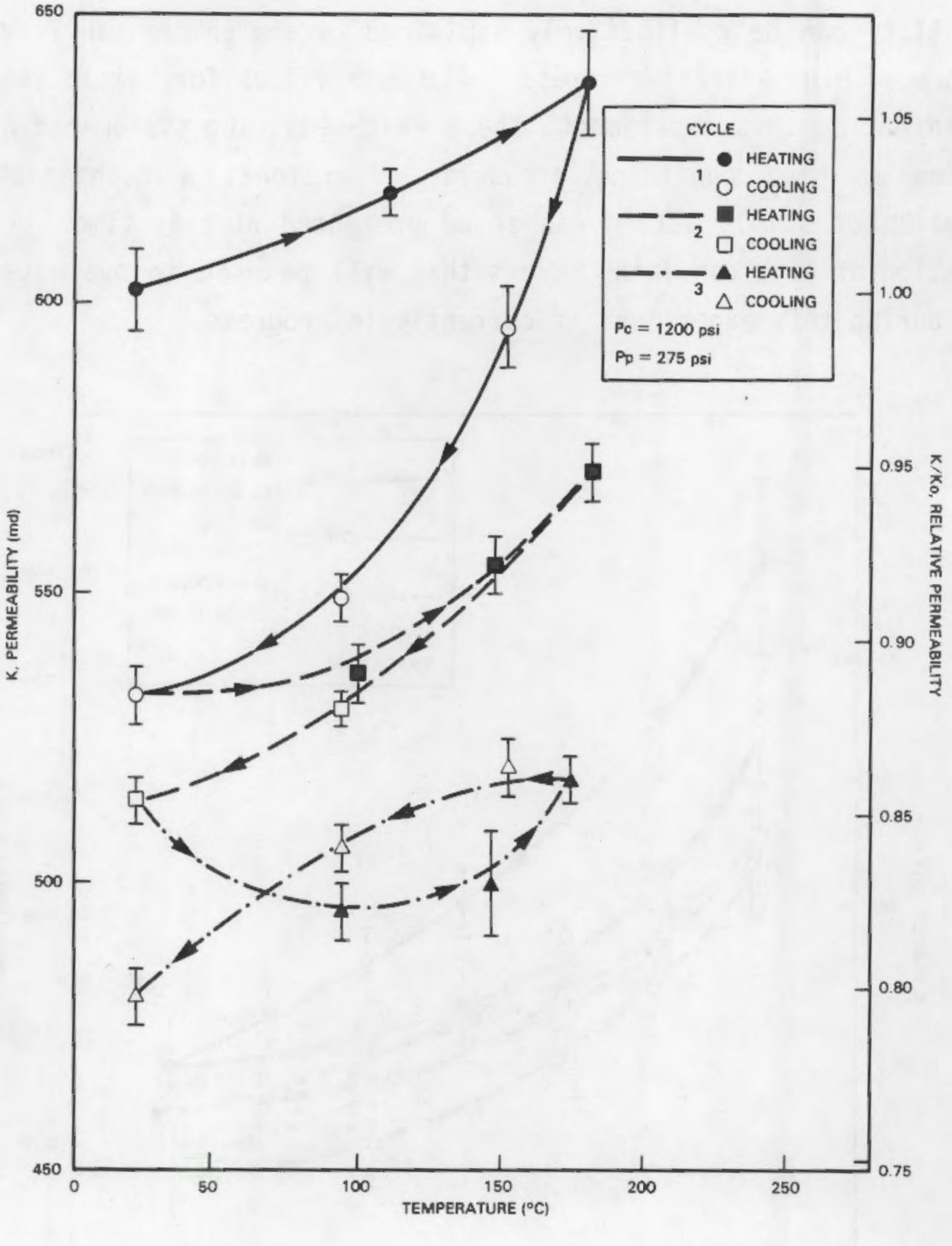

FIGURE 4.11. Permeability Versus Cyclic Temperature at 1200 psi Confining Stress for Sample I/W 703

sample permeability decreased approximately 7%, 12%, and 13% for cycles 1, 2, and 3, respectively. The decrease in magnitude of the permeability hysteresis for each cycle is similar to that observed in the temperature cycling experiment described previously (Figure 4.11). The decrease in permeability can be qualitatively explained by the compressibility of the sandstone at high effective stress. Although values for sample strain were obtained during this experiment, the strain-measuring system had not been calibated at high confining pressure. Therefore, a quantitative description of sample strain cannot be presented at this time. A strain calibration at high confining stress that will be used to evaluate sample strain during this experiment is currently in progress.

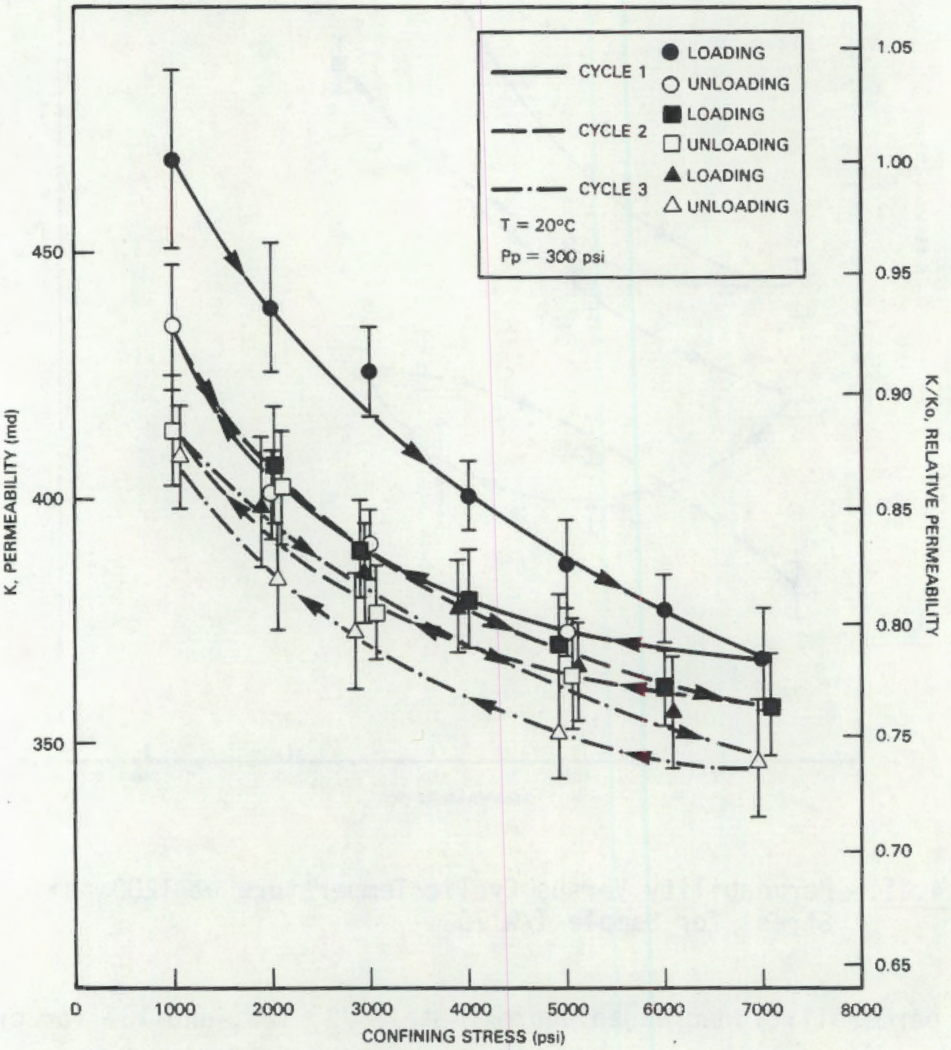

FIGURE 4.12. Permeability Versus Confining Stress at 20°C for Sample I/W 664

The temperature-effective stress cycling experiments described here suggest the absolute permeability of a reservoir sandstone at 0% water saturation can decrease during cycling. The data also imply the permeability loss is not recoverable. However, even under the somewhat extreme conditions of these experiments, the loss in permeability never exceeded 20 to 25%. The thermophysical behavior of a particular reservoir sandstone should, therefore, be evaluated when choosing a site to develop the CAES technology. However, the most important criterion to be used should be verification of the reservoir behavior in properly designed field tests.

### 4.1.3.2.3 Aquifer Field Study at Pittsfield, Illinois

R. D. Allen and T. J. Doherty (Pacific Northwest Laboratory)
J. Istvan (PB-KBB, Inc.)

The aquifer field study underway at Pittsfield, Illinois, serves a dual purpose. It is both a proof-of-principle demonstration of feasibility and a carefully instrumented field laboratory designed to promote basic understanding of the complex physical and chemical responses within an aquifer air storage system. It is designed to promote utility industry confidence in aquifer CAES reservoirs and to provide solid data to scientists and engineers involved in research, development, construction, and operation of such aquifer air storage systems.

#### Objectives

Field studies of porous rock reservoirs were conceived to fulfill four technical objectives:

- Demonstrate the feasibility of storage and cyclic injection/ retrieval of warm compressed air in using an aquifer reservoir.
- Investigate physical, chemical and mineralogical effects of CAES on reservoir rock, caprock, and wellbore, and compare with laboratory results.

- Verify and evaluate numerical modeling of bubble formation, dehydration and water displacement, thermal growth, and cyclic thermal performance.
- Evaluate system performance with respect to bubble growth rate, mass transfer rates, thermal development and recovery, water production, and entrainment of mineral particulates.

Tasks

The aquifer field study was originally divided into twelve tasks which were allocated between the Pacific Northwest Laboratory (PNL) as project manager, and PB-KBB, Inc., of Houston, Texas, as design, construction and operations contractor. Because of curtailed DOE support in FY 1983, ownership and project management were transferred to the Electric Power Research Institute (EPRI) in February 1983. The tasks and responsible organizations are listed below.

- Task 1 - Project management and technical support (PNL-1, EPRI-2)
- Task 2 - Permitting (PNL)
- Task 3 - Geologic exploration (PNL)
- Task 4 - Surface facility development (PB-KBB)
- Task 5 - Well field development (PB-KBB)
- Task 6 - Water sampling (PB-KBB)
- Task 7 - Subsurface instrumentation (PB-KBB)
- Task 8 - Air injection to develop storage bubble (PB-KBB)
- Task 9 - Cyclic air injection and withdrawal (PB-KBB)
- Task 10 - Post-test coring, core analysis, and disposition (PB-KBB)
- Task 11 - Decommissioning and site restoration (PB-KBB)
- Task 12 - Technical reporting, interpretation and data transmittal (PNL, EPRI, PB-KBB).

Work performed from March 1982 to March 1983 has been confined to Tasks 1, 2, 4, 7, 8, and 12. The scopes of these tasks are described in the following paragraphs.

Task 1. Project management and technical support provides overall project direction and integrates numerical modeling, laboratory experimentation, and field study results. During the design, construction, and operations phases, this task included contract negotiation with PB-KBB, project administration and review, and technical guidance of contractor activities.

Task 2. Permitting involved acquiring the Construction Permit (Form A) in June 1981. During this reporting period it consisted of acquiring the Operations Permit (Form B) from the Illinois Environmental Protection Agency under Interim Underground Injection Code rules to allow initiation of the field test activities including bubble development injection and subsequent cyclic testing.

Task 4. Surface facility development comprised the design, procurement, and construction of a facility capable of injecting, withdrawing, and monitoring air at the chosen CAES site. It included civil engineering, mechanical and electrical subsystems, and a structure sufficient to allow continuous all-weather testing. The facility comprises an air compression plant; heating and filtering equipment; instrumentation for monitoring flow, pressure, temperature and humidity; and semi-automatic control equipment allowing flexibility of operation. The facility also provides operators' office space, data acquisition system housing, and services for both surface and subsurface instrumentation.

Task 7. Subsurface instrumentation provided for design, calibration and installation of sensors capable of continuously measuring temperature, pressure, formation water content, and humidity. The task also included creation of an integrated data acquisition system to provide records of near-wellbore response.

Task 8. Air injection to develop storage bubble is the first stage of field testing. Initially, a 3-month period was specified to develop an air bubble with sufficient volume for daily cycling. Bubble development data from surface volumetric measurements and subsurface logging were to be compared with numerical predictions of reservoir response.

Task 12. Technical reporting, interpretation and data transmittal covers all aspects of data reduction, storage, transmission and interpretation. Periodic and technical reports are required for:

- annual report and annual contractors' review
- monthly management
- well field development
- surface facility design
- test plan
- instrument system
- test facility description
- operation and maintenance manual
- bubble development
- temperature cycling
- final report.

## Technical Progress

Installation of the surface plant and subsurface instrumentation was completed in September 1982. Injection of the air bubble was started in October. The compressor plant has functioned with minimal maintenance problems. The mass rate of air injection is approximately one-third of the computed rate probably because of the well completion method used, i.e., cemented in casing with perforations. Three acid treatments have improved the original transmissivity of the sandface from about 100 scfm to 430 scfm. No further acid treatments are planned. Many subsurface sensors in wells F and G have been permanently lost to the field experiment. Details are presented under the Task 7 discussion.

The task descriptions below briefly cover field study activity during this period. This document will be the concluding formal report to the Department of Energy on the Pittsfield Aquifer Test activities.

Task 1. Project Management and Technical Support

This task is the focal point for integration of knowledge from previous studies of aquifer CAES into the specific requirement of this limited field study. This requires translation of theoretical concerns into understandable forms, such as scopes of work and specific direction.

The project management aspects of this task changed as the project made the transition from the exploration to the design and construction phase. Exploration required PNL to administer many small subcontracts for activities such as geologic assistance, site leasing, legal assistance, drilling, coring, seismic exploration, and core evaluation, in addition to integrating this work with PNL technical administration and reporting to the sponsor. The design and construction phase began when PB-KBB was selected as the main contractor on a single, much larger subcontract. The management role with respect to integration with other technical contributors and reporting to the sponsor remained relatively unchanged. However, PNL's administration and technical support role with respect to the PB-KBB subcontract during the well field development phase became more of a review and approval function under the defined work scope rather than direct management. Facility design, construction, and instrumentation work has required more direct management, more control of subcontractor activity and careful review of second-tier subcontractor procurements because of budget considerations. The project has been hindered by budget uncertainty and some contracting difficulties.

In February 1983 the Pittsfield Aquifer Test was transferred from the Department of Energy to the Electric Power Research Institute (EPRI). All management functions performed by PNL have also been transferred to EPRI.

### Task 2. Permitting

The Illinois Environmental Protection Agency (IEPA) granted an Operation Permit to PNL on September 29, 1982. The permit was the last item required to initiate air injection at the site. The permit was based upon the PNL Form B application and well completion report. The two-year Operation Permit is conditional upon monthly reporting to the Illinois Environmental Protection Agency of normal and exceptional surface and subsurface events. Excursions beyond the agreed-upon operating limits are to be avoided. The final activity in this task was application to the IEPA for transfer of the operating permit to EPRI as part of the project transfer activity under the DOE/EPRI Field Study Agreement. The Operation Permit was transferred to EPRI by the IEPA in March 1983.

### Task 3. Geologic Exploration

The exploration task was completed during 1981. Figure 4.13 is a top of formation contour indicating the location of the selected field test site on the small second-order dome at the peak of the Pittsfield anticline. Dames & Moore of Park Ridge, Illinois, published the results of the exploration phase in an extensive two-volume report. Topics covered included regional environmental and geologic data, drilling and coring records for the 11 structural test wells sunk during this activity, lithologic and geophysical logs from the holes, and a summary of the seismic exploration and interpretation work performed on the Pittsfield structure.

### Task 4. Surface Facility Design, Procurement, and Construction

The surface facility consists of the air compression plant, the process and surface instrumentation equipment, and the civil engineering work and structure necessary to site and house this equipment, as well as the surface equipment and data acquisition system associated with the downhole instrumentation. Figure 4.14 illustrates schematically the basic elements of this equipment.

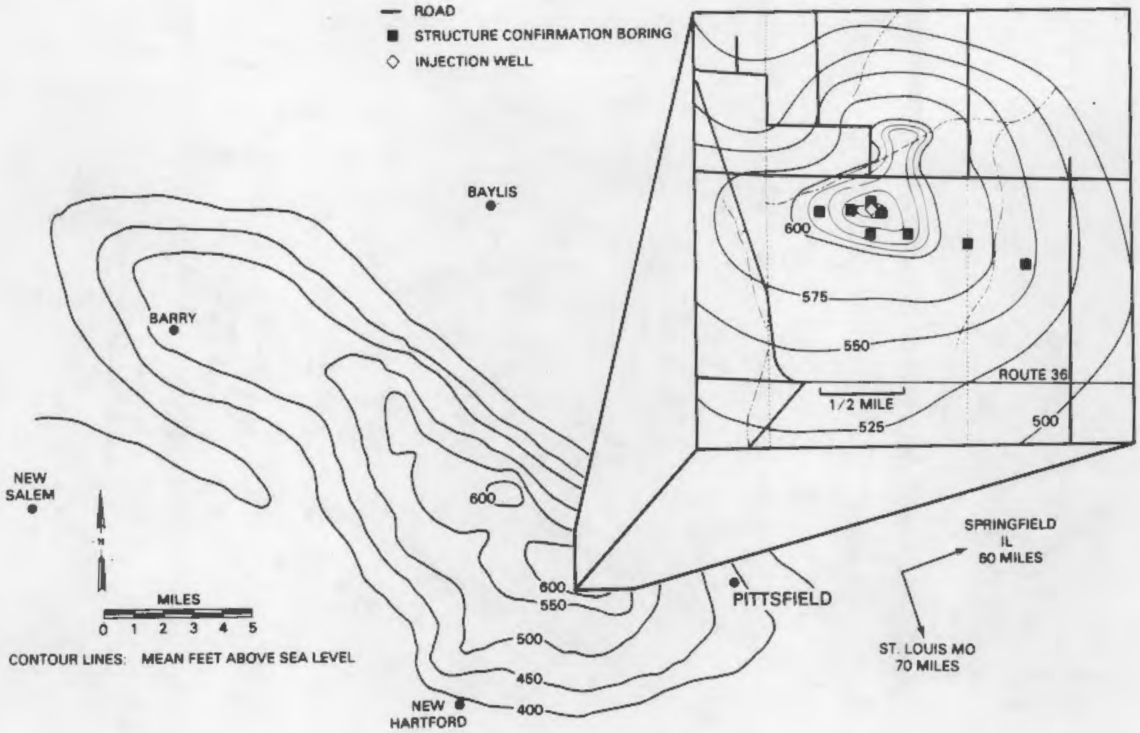

FIGURE 4.13. Test Site Location on the Pittsfield Anticline

The air compression plant was originally planned to be an electric powered 1250-scfm, 300-psi package system purchased for the field test. Investigation of prime mover power sources indicated that natural gas was an economic alternative because of local high electric rates.

BCC Engineering of Midland, Texas was selected by PB-KBB to provide a skid-mounted air compression plant under lease. The prime mover is a naturally aspirated natural gas-fired 400-hp diesel engine driving a four-stage intercooled and aftercooled reciprocating compressor. The compressor is of balanced force design to minimize foundation problems, and has adjustable clearance pockets to allow significant variations in pressure ratios. This feature and throttle control allow the operational flexibility necessary to match the compressor output to the reservoir

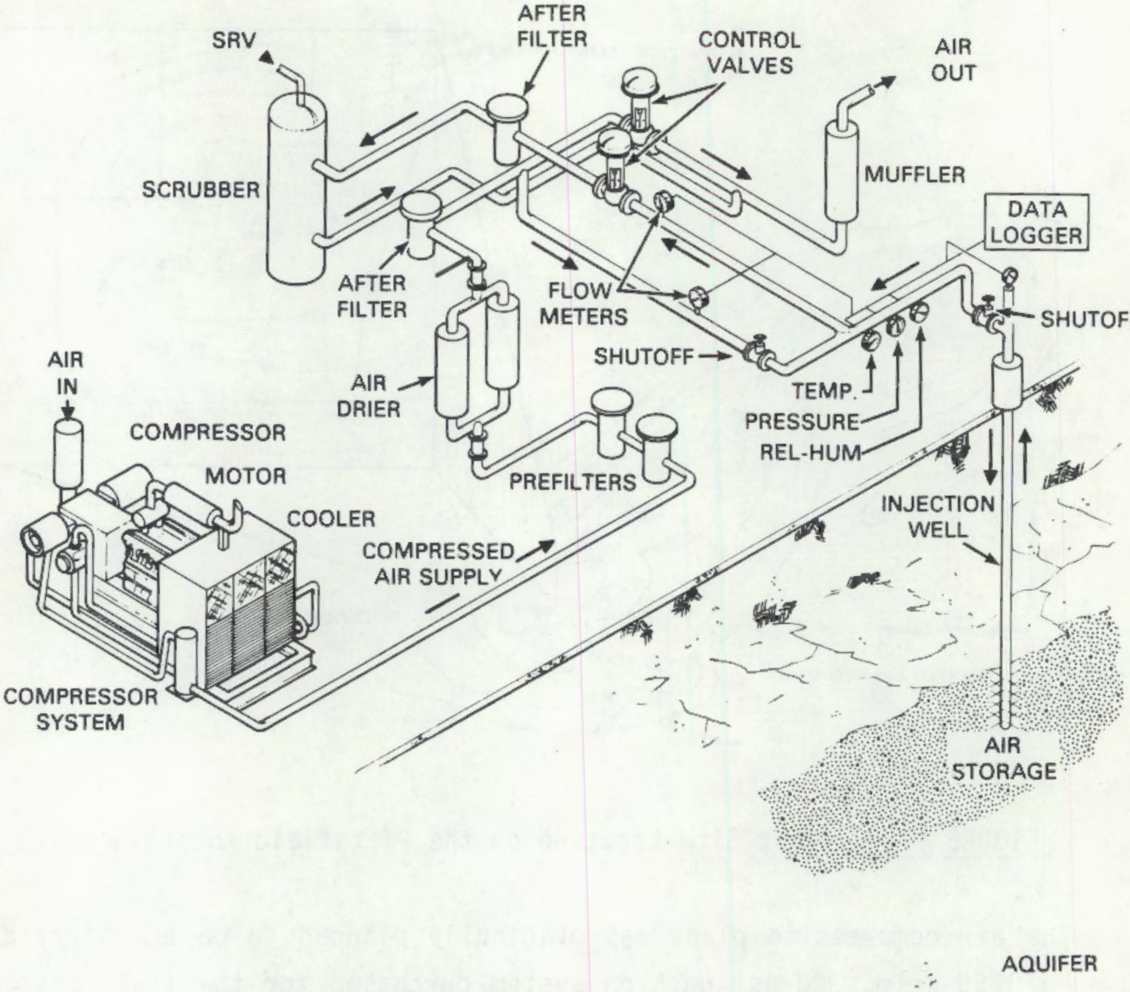

FIGURE 4.14. Simplified Schematic of the Surface Facility Operating Equipment

response. The skid contains a radiator type air cooling system that provides for engine cooling, interstage cooling, and aftercooling. The lease agreement also provides for inclusion of a full-time operator/ maintainance man. The lessor is thus fully responsible for compressor operation and maintenance. The compressor skid was delivered in August 1982.

BCC Engineering was also the fabricator and installer of the surface process and instrumentation equipment. The equipment is primarily skid-mounted. Processing of compressed air includes filtration to remove oil and solid particles, drying to reduce water content, and optional heating. Processing of withdrawn air includes scrubbing to remove liquid water. Instrumentation stations measure pressure, temperature, mass flow rate and humidity on both compressed and withdrawn air. Signals from the physical sensors are routed to a data logging system that processes data and provides operational and test data to both the operator and to diskette storage. Other instrumentation information is routed to power-operated valves or to self-contained packages such as the heater and dryer to control their operation. The control system is designed to operate at constant pressure for either injection or withdrawal with flow rate then measured to determine reservoir response. The system is flexible and pressure can be quickly adjusted to alter flow rates.

Civil engineering aspects of the surface facility include access road, foundations, drainage, and sewage systems. A building provides shelter for the operators, process equipment, and the injection and close-in monitoring wells, and provides a controlled environment for both the surface instrumentation and the data acquisition and processing systems. Utilities for the facility include 200-amp electrical service from the Illinois Rural Electric Cooperative and water routed from the adjacent Pike County water district. Natural gas, the primary power source, is provided by the City of Pittsfield through a new gas line laid for this project from the western end of Pittsfield.

All elements of this task were complete and the installed equipment and facilities were fully acceptance-tested and ready to initiate operations by September 30, 1982. Operation of the facility commenced on October 2, 1982. All of the equipment and instrumentation associated with the surface facility has performed well and reliably, except for minor maintenance problems, through the first 6 months of full-time 3-shift operation.

### Task 5. Well Field Development

Well field development took place from June to October 1981. The injection/withdrawal well, located at the peak of a small second-order dome on the highest point of the larger Pittsfield anticline, was drilled into the Ordovician St. Peter sandstone. Figure 4.15 is a schematic of the well location within the geology. Six monitoring wells were drilled to complete the preinjection well field (see Figure 4.16). Well E, a post-injection well, will be drilled after CAES test completion to acquire core for comparative evaluation. Wells A, B, C, and D are sampling and logging wells, drilled at 90 to 210 m north, east and south of the injection well. Their purpose during the test is to monitor bubble thickness but, because of their locations, they also provided valuable additional data to confirm the structure. Wells F and G are close-in monitoring wells to provide instrumentation locations near the injection/withdrawal well. Bottomhole separation was maintained within 1% of the surface separation, with well F at 3 m from the injection/withdrawal well and well G at 8 m. These wells were instrumented, gravel-packed and cemented closed prior to testing.

### Task 6. Water Sampling

Limited pump testing was performed on the injection/withdrawal well in February 1982 to provide water samples for the Illinois Environmental Protection Agency Form B (operation) permitting. This testing was to characterize the hydraulic conductivity of the formation, but the injection/withdrawal well did not expose sufficient surface to the formation in its current condition. Another small pump test was conducted in May 1982 to acquire extra formation water for analysis. Pump test results of this test were not reported. Water samples were analyzed by the State Water Survey of the Illinois Institute of Natural Resources. Results were similar to those previously reported by Dames & Moore, but the more recent samples were slightly higher in alkalinity and total dissolved solids.

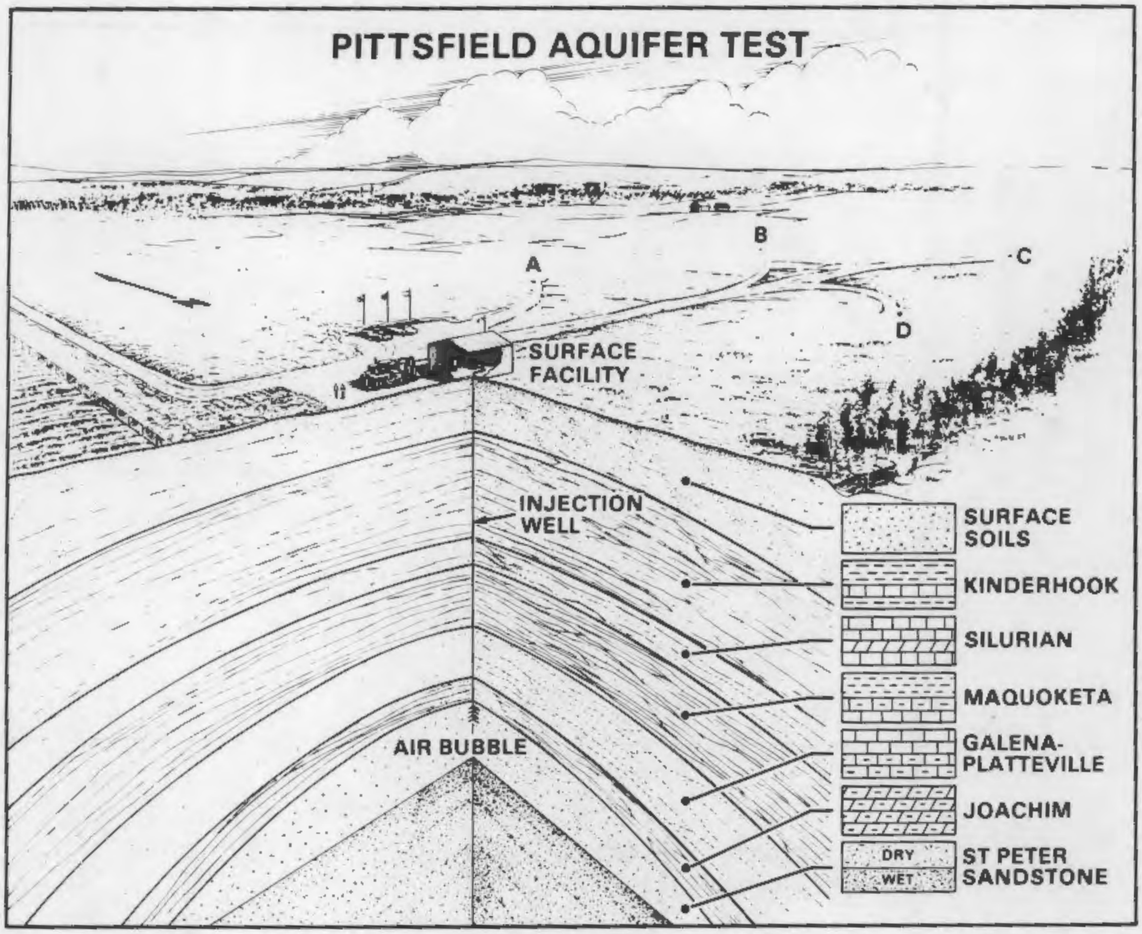

FIGURE 4.15. Schmatic of Section of the Pittsfield Aquifer Test Geology

### Task 7. Subsurface Instrumentation

Design of the subsurface instrumentation system consisted of sensor selection and calibration, lead routing, and installation method determination and integration of sensors with the data acquisition system. Permanent downhole instrumentation was provided only in the near wellbore region where continuous recording is necessary. More distant monitoring wells have surface pressure sensors and are used for neutron logging to determine air/water interface location. The close-in wells F and G were designed to have multilevel measurement stations at different distances and

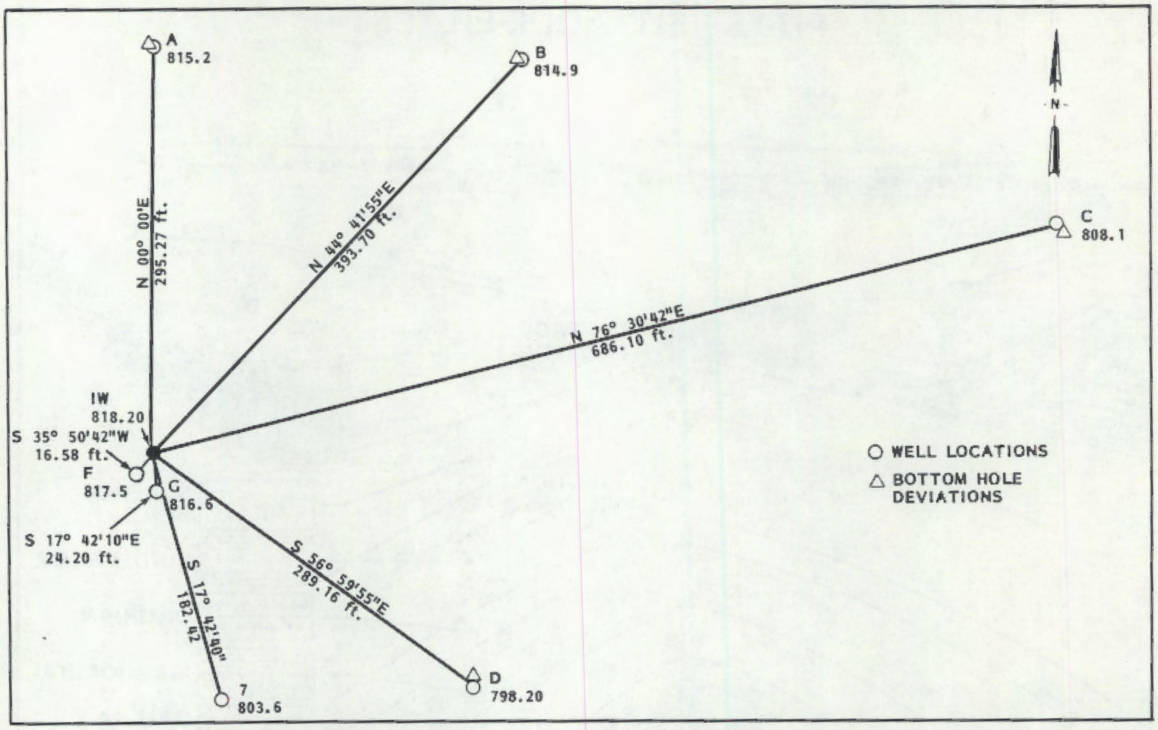

FIGURE 4.16. Locations, Elevations, and Bottomhole Deviations of Pittsfield Wells

azimuths from the injection well to measure three-dimensional reservoir response. The instruments were selected for measurement in three different environments: relatively dry rock with warm to hot air flow; partially saturated cool rock with both air and water flow; and fully saturated rock at ambient or flow induced pressure levels. Sensors were embedded in Ottawa sand packs within the open boreholes to simulate actual in situ conditions. Sensors in wells F and G are as follows:

- temperature - platinum resistance elements
  - thermocouple psychrometers
- pressure - diaphragm, strain gauge
- humidity - thermocouple psychrometers
  - cellulose crystal strain gauge

- water content - thermocouple psychrometer
  - nylon resistance block.

Well G was designed to have four monitoring levels and well F two levels. All leads were bound into a single cable, prechecked and calibrated as a unit. These instrumented cables were run into the holes along with a cementing pipe gravel-packed in place. The wells were cemented back to the surface to preclude leakage and abandonment paperwork was filed on them. They will require only removal of the wellheads and cutoff of leads for demobilization.

Unfortunately, of the nearly 50 gauges run in wells F and G, only 15 sensors survived, including 1 pressure transducer. Some sensors were lost due to ground potentials or bad lead splices. However, most were apparently lost during installation by abrasion damage to unarmored lead wires during the installation.

Wells A, B, C, and D are the sampling/logging wells, which primarily provided access for neutron logging. Wells A and C are provided with surface pressure transmitters to continuously monitor pressure. These wells are beyond the thermal region, where pressure response and air storage bubble thickness are the measurable quantities of interest. Bubble thickness is determined directly by neutron logging, the standard bubble measuring tool used by the natural gas storage industry. Some of these wells will also be perforated to allow for air and water sampling.

The surface components of the data acquisition system consist of signal conditioning and digitizing equipment, a computer for conversion and processing, and paper printout and disk storage for data filing, recording, digitization, processing, and storage.

There were problems with sensors, sensor conditioning, and with the data acquisition computer at the time injection was scheduled for initiation. It was decided to take manual readings of the surviving sensors until problems with the surface data acquisition components were resolved. Correction of the problems prior to startup was estimated at around a 2-month delay, with unacceptable budget impacts. As bubble development is a gradual, monotonic process in the near-wellbore region, a "fix-while-operating" philosophy was deemed reasonable.

By December, the sensor and conditioning problems had been defined and resolved. Chronic problems with the data acquisition computer did not appear reparable. Plans were underway to transfer all sensor readings to the surface data logger when the project was transferred to EPRI.

Task 8. Bubble Development

Calculations of bubble growth, based upon numerical methods similar to those used to compute natural gas storage volumes, were used to provide guidance on expected bubble volume versus time. Models predicted 60 days of injection into a reservoir with a permeability of 700 md; the "50% saturation front" had a computed radius of more than 350 m and computed thickness of 14 m. The total volume of injected air was calculated at over $100 \times 10^6$ scf. The projected bubble dimensions at equilibrium are radius 500 m and center thickness 20 m. These calculations were used as a guide in monitoring well layout and scheduling injection. Final bubble dimensions of this size were judged sufficiently large to enable short-term cyclic withdrawal and injection without causing significant variations in the bubble's areal extent or thickness.

Air injection for bubble development began October 1982. Dry air with relative humidity of less than 5% and temperature close to that of the natural reservoir was being injected near the top of the St. Peter sandstone over an approximately 2.5-m interval. The air injection pressure is 2070 kPa (300 psi) with an upper flow rate limit of 35.4 scmm (1250 scfm) based upon the IEPA operations permit. This pressure enables displacement of ground water within the aquifer because the discovery pressure is 1035 to 1104 kPa (150 to 160 psia). The injected air is monitored for relative humidity, temperature, pressure, and mass flow rate at the surface. The actual flow rate has never exceeded 35% of the calculated upper limit so that bubble development time had to be extended to about 5 months.

Approximately 110 days of air injection took place from October 1, 1982, through January 26, 1983, the end of the DOE-funded operational period. After initial pressurization the injection pressure was maintained at 275 to 300 psig through October. The injection flow rate varied between 107 and 130 scfm, only about 10% of the calculated flow rate. On October 19 the casing of the I/W well was reperforated with a 2-1/8 in. gun at 4 shots per foot over the original perforation depth interval from 653 to 661 feet. On October 21 the I/W well was acidized with 2 bbl of 15% hydrochloric acid. After treatment the well was "air-flowed" to the atmosphere. On October 22 the well was reacidized with 2 bbl of 15% HCl. The well was swabbed, found to be near neutrality, and air-flowed to the atmosphere.

Gamma ray-neutron logs were conducted in wells A and C before air injection to characterize both wells. Logging in the I/W well on October 19 divulged an air peak at 654 feet mean depth (uppermost St. Peter formation). The breadth of the peak was from 648 to 660 feet, indicating some air in the Joachim dolomite/St. Peter sandstone transition zone and excellent retention of air below the Joachim proper. About 3.2 MMscf were injected in October.

Operation during November showed a gradual but significant increase in the injection rate from about 120 scfm to near 340 scfm. The large increase was attributed to a brief overpressurization excursion to about 365 psig. During shutdown for Thanksgiving the I/W well was shut in and wellhead pressure equilibrated at 185 psi. The total volume injected in November was 10.7 MMscf.

In December the injection flow rate averaged about 350 scfm under a pressure of 300 psig. Thus, air injection occurred at 28% of the system capacity of 1250 scfm. Three significant shutdowns occurred in December: one for 8 hours to provide data for a short-term transient test, and two shutdowns for Christmas and New Year's. The transient test provided data for numerical modeling to match the steady-state and transient responses of the reservoir with a congruent permeability distribution. This determined whether the low injectability is caused by low formation permeability or a relatively impervious well completion. A reduced permeability region of only 75 to 100 md between the I/W and G wells contrasts with 200 md outward from well G. The data are consistent with throttled permeability in the near-wellbore region. Residual cement fines or silica flour were considered to be potential pore plugging agents. The total volume injected in December was 13.1 MMscf. After the month-end shutdown, the wellhead pressure was about 195 psi.

A final well acid treatment using both HF and HCl was employed as the last workover to improve near-wellbore injectivity. On January 6, the well was shut in and 428 gallons of acid were slowly injected into the formation. Careful control was exercised to allow significant near-wellbore-acid contact time and also to control downhole pressure levels. The acid injected was the standard workover mix of 3% HF and 12% HCl. As the acid drained into the formation, injection pressure was brought back up to the 300 psig operating pressure; flow recovered gradually as the spent acid/water cleared from the immediate wellbore region. By January 9, flow had risen to 400 to 420 scfm. The injection rate subsequently increased very gradually to over 430 scfm on January 26 when the facility was shut down for lack of operating funds. Operating funds on the project were depleted earlier than anticipated due to instrumentation problems and extension of the bubble development period because of low injectivity. Figure 4.17 indicates the mass flow rate and pressure histories for the entire bubble development period.

Pacific Northwest Laboratory had planned to develop a bubble of around 100 MMscf during a 2-month injection period (50 MMscf each month at the 1250-scf design rate), with injection proceeding 24 hours a day. During January, 13.42 MMscf of air were injected, bringing cumulative bubble volume to 40.75 MMscf. A minimum operable bubble volume of 75 to 80 MMscf was proposed as an alternative. Total bubble volume for both the DOE and EPRI portions of bubble development is indicated in Figure 4.18. A cumulative air volume of about 75 MMscf was injected over 6 months. The bubble development stage had to continue through to the end of March.

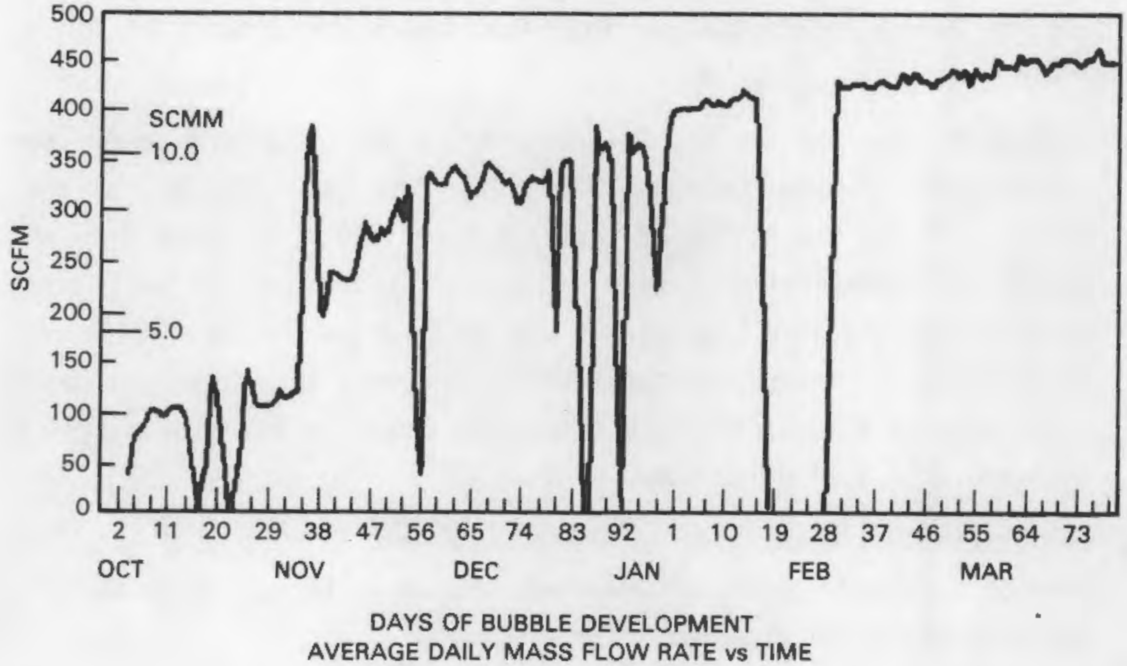

FIGURE 4.17. Pittsfield Aquifer Test Mass Flow Rate

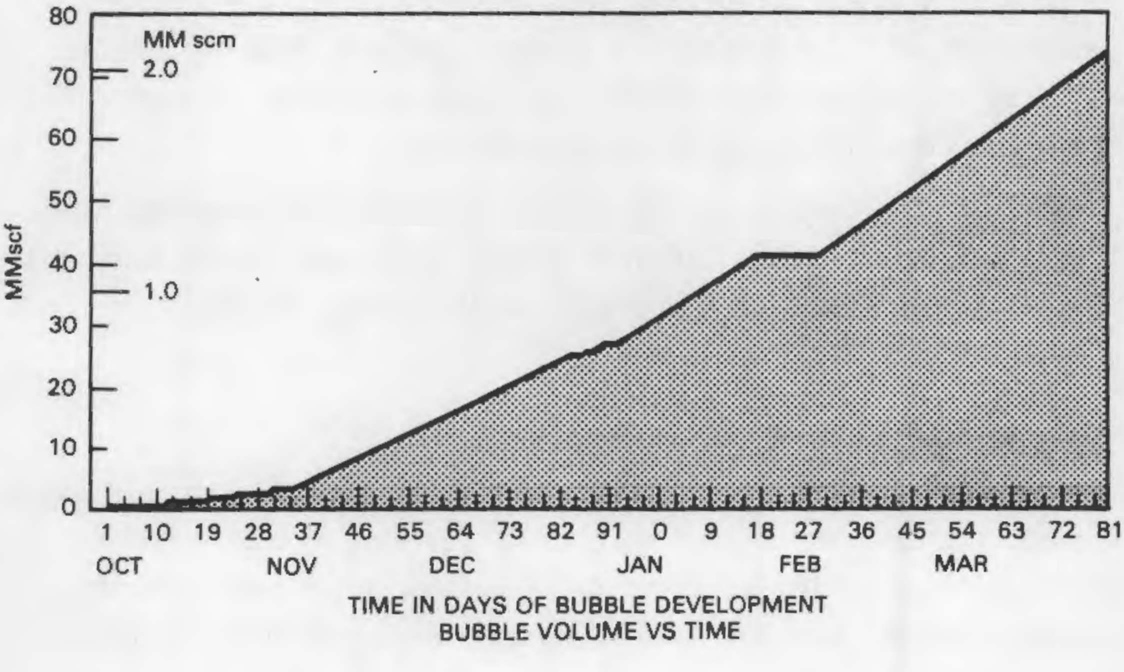

FIGURE 4.18. Pittsfield Aquifer Test Bubble Development

The following points sum up experience with air injection at Pittsfield:

- On January 26, 1983 the St. Peter sandstone was accepting compressed air at 430 scfm mean rate and 300 psia. The lower boundary of the bubble is below the bottom of the injection well. Pressure from the bubble is evidenced by a rise in closed-in pressure at well A. Neutron logs disclose significant air thicknesses in the I/W, A, C, and D wells. Although the total bubble geometry is unknown, it may be substantially thicker and less extensive laterally than the same air mass would be at equilibrium.
- Subsurface instrumentation in wells F, G, and Y did not initially provide useful recorded information. However, 15 out of 50 sensors are potentially servicable.
- The data logger is accurately recording surface parameters of injection rate, temperature, pressure, and dewpoint of the dehydrated compressed air.
- Even with limited useful data from wells F and G, the Pittsfield experiment will contribute to current concepts with respect to predictions of air injectivity, air recoverability, effects of dehumidifying, water coning and geochemistry.
- Despite frustrations, the Pittsfield experiment has generated useful injection data. Valuable design lessons are being learned at a small fraction of the cost of a full-scale aquifer CAES facility.

### Task 9. Air Cycling

This task is scheduled for initiation in the Spring of 1983.

Air cycling is prescribed to simulate the operation of the unit length of a producing section of one well of a full-scale CAES aquifer installation. Definition of exact cycle period, injection temperature, injection pressures, mass flow rates, air humidity, and number of cycles at each temperature depends on numerical modeling using the specific characteristics of the reservoir. The anticipated frequency is one cycle per day with approximately 7 hr injection followed by 11 hr withdrawal, a 6-hr rest period, and equal air masses injected and withdrawn. The injection pressure will not exceed 50% of the minimum laboratory-measured threshold pressure integrated for the total caprock thickness.

The baseline test matrix consists of injection at four temperatures varying from 50°C (122°F) to 200°C (392°F) in steps of 50°C (122°F). On the basis of 2 months of cycling per step, this cyclic testing matrix requires 8 months.

Cycling data will be compared with analytical and laboratory predictions of physical reservoir relationships and petrologic response to determine predictability of reservoir response. Subsurface and surface measurements of temperature and saturation during cycling will yield information on thermal energy recovery, radial extent of thermal cycling, dehydration versus time and temperature, and radial temperature distribution in the near wellbore region.

Work in the air cycling task and all subsequent effort will be supported by the Electric Power Research Institute. At this writing, EPRI and PB-KBB are testing the reservoir withdrawal response. Preliminary cycling completed to date indicates 0.26 to 0.32 kg/s (450 to 550 scfm) injection for 5 to 6 hr and 10 to 12 hr of withdrawal. Test withdrawal of mass flow rates of 0.09 to 0.15 kg/s (150 to 250 scfm) with back pressure of 0.65 to 1 MPa (100 to 150 psi) have been recorded. After these preliminary tests, it has been decided that the frequency will be one cycle per day with injection followed by withdrawal, a 6-hr rest period, and equal air masses injected and withdrawn each day. The withdrawal back pressure will be approximately equal to or greater than the discovery pressure minus the maximum overpressure used during injection.

### Task 10. Post-Test Coring and Core Disposition

Core from the well field development was distributed to David K. Davies and Associates, a PB-KBB subcontractor, and to PNL aquifer experimental tasks. The Davies work was reported as *Pre-Test Geological and Geochemical Evaluation of the Caprock, St. Peter Sandstone and Formation Fluids Yakley Field, Pike County, Illinois* (PNL-4564); the report on the PNL work is currently under preparation. After analysis, all core will be given to the Illinois Geological Survey for final disposition.

Post-test coring of the reservoir rock and caprock is also required to obtain petrologic specimens for comparing pre-test and post-test lithology. The near-wellbore zone is most likely to be impacted by geochemical and mechanical changes because highest temperatures, highest pressures, and greatest cyclic thermal stress effects will occur near the injection point. Hence, post-test coring is to be done as near the wellbore as possible. Core analysis will include mineralogical, chemical, physical, and mechanical characterization.

### Task 11. Decommissioning

This task will begin when all testing is completed. This is currently scheduled for early 1984. Responsibility for this activity has been wholly transferred to EPRI.

### Task 12. Technical Reporting, Interpretation and Data Transmittal

Reporting inputs have been received for monthly requirements, annual reports, and contractors' review; presentations have been made as required. In addition, presentations and papers have been given at other conferences and reviews including IECEC, the PSI Review and the CAES/STES conference by either PNL or PB-KBB as appropriate. The status of other report deliverables is summarized in Table 4.4.

Transmittal and storage procedures for data from the operations phase of the test have been designed to ensure that both PNL and PB-KBB have continual data access according to the contractor QA Plan. Both hard copy and diskette data files are to be maintained.

TABLE 4.4. Aquifer Field Test Documentation Status

| Document | Completion Date | Status |
|---|---|---|
| QA Plan | February 1982 | Received |
| Well Field Development Report | March 1982 | Received |
| Surface Facility Design | April 1982 | Received |
| Test Plan Report (draft finalized September 1982) | May 1982 | Received |
| Instrumentation System Report | June 1982 | Received |
| Test Facility Description Report | August 1982 | Deferred to EPRI |
| Facility Operation Manuals | September 1982 | Received |
| Bubble Development Report | April 1983 | Deferred to EPRI |
| 50°C Cycling Report | June 1983 | Deferred to EPRI |
| 100°C Cycling Report | August 1983 | Deferred to EPRI |
| 150°C Cycling Report | October 1983 | Deferred to EPRI |
| 200°C Cycling Report | December 1983 | Deferred to EPRI |
| Final Report | March 1984 | Deferred to EPRI |

## Conclusions

The Pittsfield, Illinois CAES aquifer field test involves simulation of full-scale air storage with a shallow confined and dome-shaped aquifer. Direct evaluations of geochemical and mechanical effects upon the sandstone reservoir formation and the overlying dolomitic caprock will be made. System operability with respect to input and output mass flow rates, thermal energy recovery, and water and solid particulate discharges will be studied at temperature levels from 50 to 200°C. The applicability of numerical modeling to prediction of physical reservoir behavior with time during both bubble growth and air cycling will be tested. The existing technology of air compression, injection, storage and recovery will be enhanced by the addition of direct field information. This proof-of-principle test is intended to provide a basis for confident development of CAES using aquifer air storage systems.

### Publications

Major publications describing aspects of the field study include:

Allen, R. D. and T. J. Doherty. 1982. "The Aquifer Compressed Air Field Experiment at Pittsfield Illinois." In Proceedings International Conference on Underground Pumped Hydro and Compressed Air Energy Storage, pp. 215-222, AIAA CP 826, American Institute of Aeronautics and Astronautics, New York, New York.

Hostetler, D. D., S. W. Childs, and S. J. Phillips. 1983. Design Report - Subsurface Monitoring of Reservoir Pressure, Temperature, Relative Humidity, and Water Content at the CAES Field Experiment, Pittsfield, Illinois: System Design. PNL-4687, Pacific Northwest Laboratory, Richland, Washington.

Istvan, J. A. 1982. "CAES in an Aquifer, Pittsfield, Illinois." In Proceedings of the DOE Physical and Chemical Energy Storage Annual Contractors' Review Meeting, pp. 163-168, CONF-820827, National Technical Information Service, Springfield, Virginia.

PB-KBB, Inc., and David K. Davies & Associates. 1983. Pre-Test Geological and Geochemical Evaluation of the Caprock, St. Peter Sandstone and Formation Fluids Yakley Field, Pike County, Illinois. PNL-4564, Pacific Northwest Laboratory, Richland, Washington.

## 4.2 SECOND-GENERATION CONCEPTS STUDIES

In the conventional CAES system, the air extracted from storage is heated by the combustion of petroleum fuel. This dependence of conventional CAES systems on petroleum fuels could become a disadvantage in an era of uncertain fuel supplies and increasing costs. Therefore, the Second-Generation Concepts Studies were established to identify and develop new CAES systems to reduce this disadvantage by minimizing or eliminating the use of petroleum fuels.

### 4.2.1 Goal and Objective

The objective of the Second-Generation Concepts Studies is to develop advanced CAES technologies that could reduce the cost of stored energy and reduce the dependence of CAES systems on petroleum fuels. The principal goal is to develop one or more concepts sufficiently to allow the utility industry to undertake the further development and construction of a plant sometime after 1985.

### 4.2.2 Strategy

The Second-Generation Concepts Studies employed a three-phase strategy. In Phase 1, new proposed concepts were subjected to a preliminary technical and economic screening to determine which have the best potential for economic and technical feasibility. In Phase 2, conceptual designs and detailed cost estimates were developed for only the most promising concepts. These designs and cost estimates are used to decide which concepts should be considered for hardware development in Phase 3. In Phase 3, key hardware items unique to the most viable concepts will be developed and tested in sufficient detail to provide a technological data base for further development by the private sector.

Concepts already evaluated in Phase 2 have included:

- CAES/fluidized bed combustion (FBC)
- CAES/coal gasification (CG)
- adiabatic CAES
- hybrid CAES.

The adiabatic CAES concept appeared to be the most attractive candidate for utility application in the near future. Subsequent Phase 3 studies have focussed on the principal outstanding development problem with this concept, i.e., the thermal energy storage system design.

### 4.2.3 Project Description

Completion and closeout of this project was accomplished during this reporting period. Two activities remained to be completed. Final reports on both elements were issued. The last Phase 3 activity, evaluation of thermal energy storage bed materials, was completed in conjunction with EPRI. The other activity consisted of documentation of the cycle analysis program that was used in earlier cycle evaluation phases of the project and reporting of some of the results from use of the code. The task reports summarizing this work follow.

### 4.2.3.1 Thermodynamic Analysis of Compressed Air Energy Storage Cycles

J. A. Fort (Pacific Northwest Laboratory)

#### Objective

The objective of this task is to perform thermodynamic cycle analyses on five alternative designs for second-generation CAES plants using the Compressed Air Energy Storage Cycle Analysis Program (CAESCAP). The resulting availability and energy flow diagrams for each plant cycle are intended to increase understanding of the overall thermodynamic performance characteristics of the five plant configurations.

#### Task

The CAESCAP computer code is used to analyze thermodynamic performance of five CAES plant designs. These designs are:

- conventional CAES
- adiabatic CAES
- hybrid CAES
- pressurized fluidized bed CAES
- direct coupled steam-CAES.

#### Technical Progress

During 1982, a computer code, CAESCAP, was developed at Pacific Northwest Laboratory (Fort 1982). This code was designed specifically to calculate overall thermodynamic performance of proposed CAES system configurations. This code was then applied to five specific CAES plant designs (Fort 1983). Inputs to the code were based on published reports describing each plant cycle. For each cycle analyzed, CAESCAP calculated the thermodynamic station conditions and individual component efficiencies, as well as overall cycle performance parameter values. These data were then used to diagram the availability and energy flow for each of the five cycles. Examples of these availability and energy flow diagrams are provided in Figures 4.19 and 4.20. The resulting diagrams for each plant design graphically illustrate the overall thermodynamic performance inherent in each plant configuration, and enable a more accurate and complete understanding of each design.

### 4.2.3.2 Evaluation of Thermal Energy Storage Materials for Advanced Compressed Air Energy Storage Systems

F. R. Zaloudek and K. R. Wheeler (Pacific Northwest Laboratory)
L. Marksberry (FluiDyne Engineering Corporation)

#### Objective

The objective of this study is to screen several thermal energy storage (TES) materials to determine which have the best chance of providing suitable long-term service in advanced CAES systems and which should be considered in subsequent developmental activities.

#### Tasks

Four heat storage materials, proposed for use in advanced CAES plants, were evaluated for performance and durability. The materials included:

- 3/8-in. sintered iron oxide pellets
- 1/2-in. Denstone pellets
- 1-in. cast-iron alloy balls
- crushed Dresser basalt.

Specific concerns addressed included particle formation and thermal ratcheting of the materials during thermal cycling and the chemical attack on the materials by the high temperature and moist environment in an adiabatic or hybrid CAES storage bed.

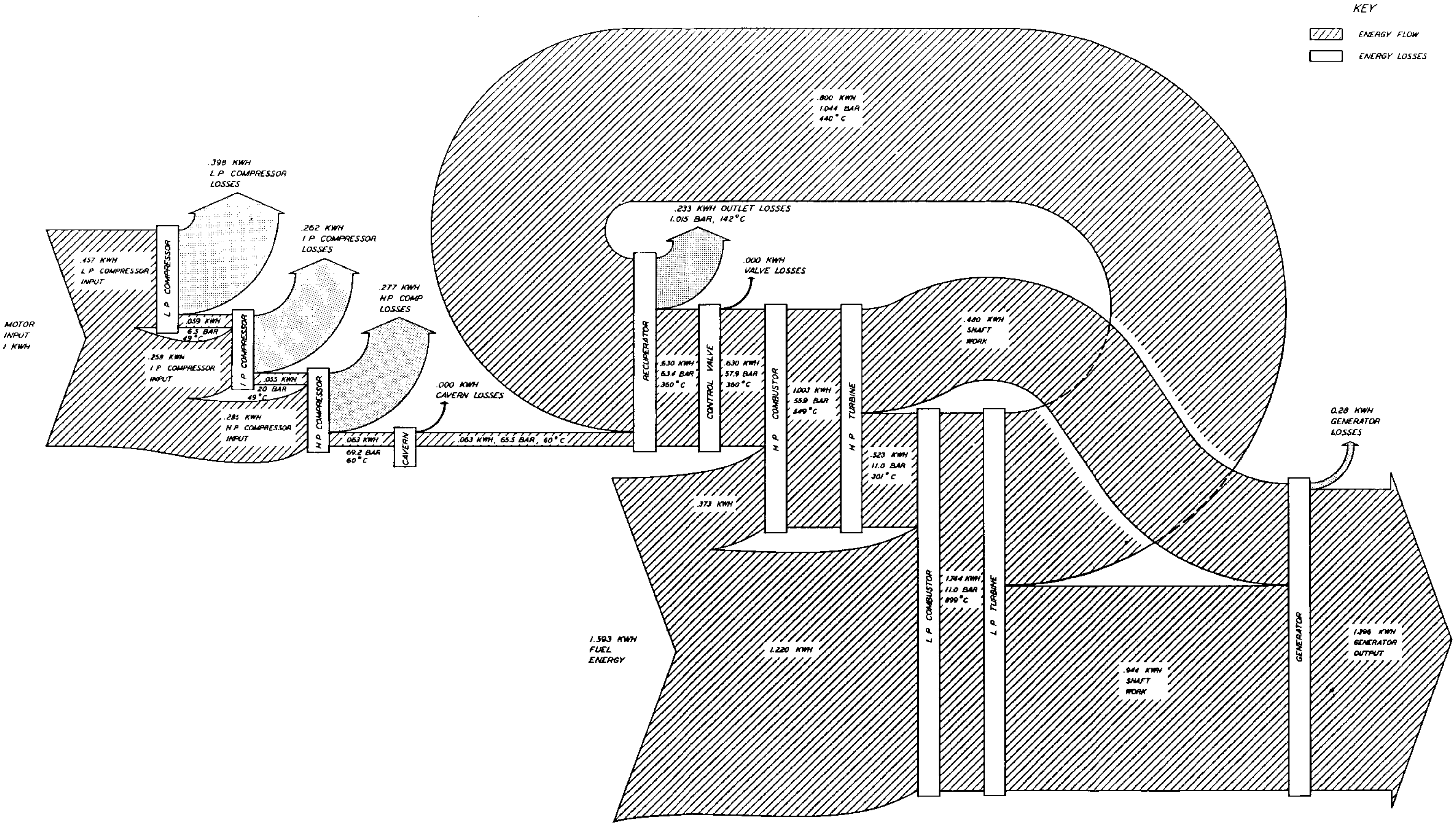

FIGURE 19. ENERGY FLOWS FOR A CONVENTIONAL CAES PLANT

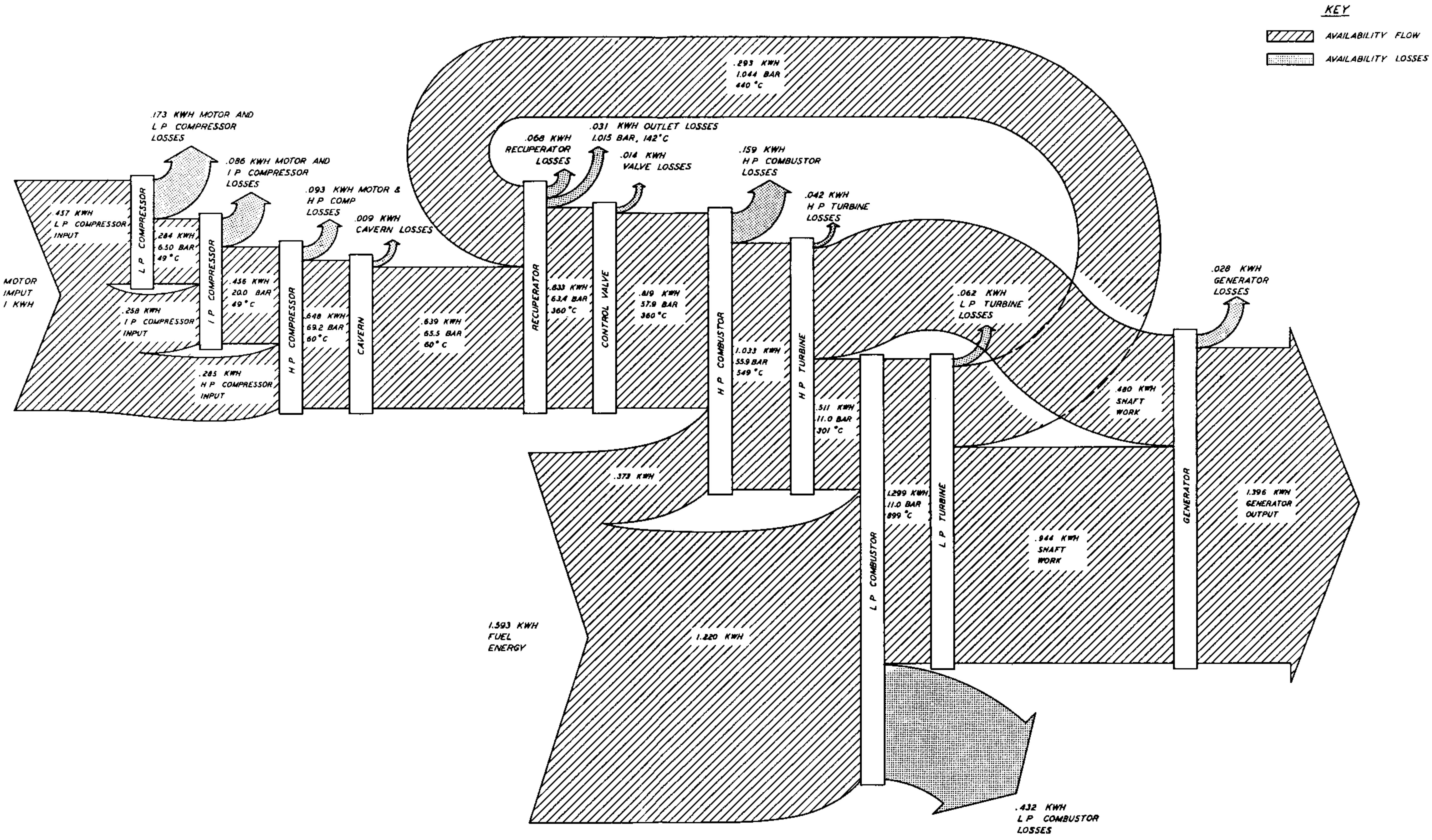

FIGURE 20. AVAILABILITY FLOWS FOR A CONVENTIONAL CAES PLANT

## Technical Progress

Recent engineering and economic studies of advanced CAES plant designs have identified two concepts offering sufficient technical and economic benefits that U.S. electric utilities might build such plants in the near future. These concepts include the adiabatic CAES and the hybrid CAES plant designs. Both plant concepts use sensible heat storage systems to store the heat of compression during the energy storage phase for subsequent use during the power production phase. By using the heat of compression, it is possible to reduce or completely eliminate the use of a fuel in these concepts. However, several developmental problems remain with both concepts. The most important problem is the development of durable and reliable regenerative heat exchangers that could endure for a 30-year plant lifetime under the thermally and chemically aggressive conditions expected in an advanced CAES system. A joint DOE/EPRI study was performed by Pacific Northwest Laboratory and FluiDyne Engineering Corporation to experimentally screen four materials to determine their performance and durability (Zaloudek, Wheeler, and Marksberry 1983).

The materials considered included 3/8-in. iron oxide pellets, 1/2-in. OD Denstone pebbles, 1-in. OD cast-iron balls, and crushed Dresser basalt. The iron oxide pellets are an intermediate product in the production of steel from ore and are available in large quantities. Denstone, a product of the Norton Company, is commonly used as a catalyst bed support in the petroleum processing industry. The cast-iron balls are commercially produced for tumbling and grinding processes. The principal alloy considered in this study contained 32% chromium for corrosion resistance; in addition, small test samples containing from 0 to 32% chromium were considered to determine minimum chromium content for corrosion resistance. The crushed Dresser basalt rock selected for evaluation was 0.5- to 2-in. in diameter. This material was processed by autogenous grinding, screening, and washing before being tested.

The experimental approach used in evaluating these materials was strongly influenced by capabilities of available testing facilities. Two types of tests were performed. In one type, the particulate formation characteristics and thermal ratcheting of these materials during thermal cycling was investigated. These tests were performed at a maximum temperature of 900°F, with temperature oscillation from 100 to 900°F and mechanical loads equivalent to a 65-ft high TES bed. However, dry, approximately atmospheric pressure air was used because of equipment limitations. This test was expected to produce realistic information on particulate formation and ratcheting, and conservative information on particulate carryout rates and sizes. Each sample was subjected to approximately 100 thermal cycles.

In the second type of test, the chemical attack of the TES system environment on these materials was investigated. This investigation was performed under static conditions for 30 days in autoclaves. Two types of autoclave tests were performed. The first considered the oxidation of the materials at approximately the maximum temperature (860°F) and pressure (1215 psia) expected in service. The second type considered the chemical attack of mechanically-loaded TES samples (simulating the loads from a 65-ft high TES bed) by air contaminated with 0.5 to 1.0 ppm $SO_2$, in the presence of liquid water simulating the condensation of atmospheric moisture. Temperatures were limited in these autoclave tests to the maximum dewpoint condition (280°F and 1215 psia) expected in advanced CAES service.

The results indicated that the iron oxide pellets produced large quantities of large particulates that could potentially damage advanced CAES turbomachinery. Furthermore, the effect of moisture was observed to significantly lower the crush strength of the material, making it more susceptible to particle formation and particulate carryout. Therefore, iron oxide is not recommended as a satisfactory advanced CAES thermal energy storage material.

The cast iron tests showed evidence of thermal ratcheting, which is a buildup of internal stresses that could lead to material failure or rupture of the TES bed. However, this material performed satisfactorily in all other respects.

The Denstone also performed satisfactorily, except for a 30% loss of crush strength when subjected to repeated thermal shock. This loss of crush strength was not apparently reflected in increased particulate formation rates or breakage in regions of the bed so affected. This material would require further testing before its suitability for advanced CAES plant TES service could be determined.

The crushed Dresser basalt appeared to perform satisfactorily in all respects in all of the tests. The acceptable performance, along with its comparatively low cost ($4/ton in large quantities), led to the recommendation that Oresser basalt should be the preferred material in future advanced CAES plant TES system developmental activities.

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# APPENDIX

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The documents listed in this section describe research, development, and technology transfer activities conducted earlier in support of the STES and CAES programs under Pacific Northwest Laboratory (PNL) direction. Those designated by a PNL-XXXX or a CONF-XXXXXX number are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22151. Reports issued by specific program subcontractors may be obtained either directly from the subcontracting firm or from the Underground Energy Storage Program Office, Pacific Northwest Laboratory, P.O. Box 999, Richland, Washington 99352. Copies of papers designated by a PNL-SA-XXXX number may also be obtained from the UES Program Office at PNL.

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