Underground Energy Storage Program

1981 Annual Report

Volume I Progress Summary

June 1982

**Prepared for the U.S. Department of Energy
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**Pacific Northwest Laboratory
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UNDERGROUND ENERGY STORAGE PROGRAM

1981 ANNUAL REPORT

VOLUME I: PROGRESS SUMMARY

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

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PREFACE

This is the 1981 Annual Report for the Underground Energy Storage Program administered by the Pacific Northwest Laboratory for the U.S. Department of Energy. The two-volume document describes all of the major research funded under this program during the period March 1981 to March 1982.

Volume I summarizes the activities and notable progress toward program objectives in both Seasonal Thermal Energy Storage (STES) and Compressed Air Energy Storage (CAES). Major changes in program emphasis and structure are also documented.

Volume II 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
Program Manager
Underground Energy
Storage Program

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The efforts of many contributors are represented in the two volumes of this report. Progress achieved during the March 1981 to March 1982 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; Fluidyne Engineering Corporation, Minneapolis, Minnesota; S. W. Childs of Oregon State University, Corvallis; C.-F. Tsang of Lawrence Berkeley Laboratory, Berkeley, California; A. F. Fossum from RE/SPEC, Inc., Rapid City, South Dakota; J. Istvan of PB-KBB, Inc., Houston, Texas; R. L. Thoms of Louisiana State University, Baton Rouge; W. E. Soderberg, University of Minnesota, Minneapolis; and F. J. Molz, Auburn University, Auburn, Alabama.

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Credit for assembling the many contributions to, and typing the draft and final versions of this report goes to Sue 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.

This objective implicitly limits DOE efforts from preempting the action of free enterprise in the development of UES 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. The common use of underground formations for fluid storage and the 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. Although program management for CAES and STES has been consolidated, the technologies remain diverse.

PROGRAMMATIC CHANGES

The UES Program structure, scope, and direction underwent dramatic changes as a result of the redirection of energy research and development from near-term technology development and demonstration to longer term, high risk R&D. Severe budget rescissions at midyear and a projected 60% reduction in FY 1982 funding for UES activities forced termination of the Aquifer Thermal Energy Storage (ATES) Demonstration Projects and elimination of major elements of both STES and CAES technology development activities. Considerable technical and program staff dislocation occurred as a result of these budget actions.

The STES Program was the most affected by the change in direction and budget. Original planned expenditures totaled \$7.8 million in the STES Program in FY 1981. As a result of midyear funding rescissions, actual expenditures totaled less than \$6 million. The FY 1982 STES Program budget target is \$2.1 million. The STES Program structure prior to consolidation with CAES is illustrated in Figure 1. Program areas that were terminated or were being closed out at year-end are shown in the cross-hatched region. The remaining activities are being continued or redirected to meet new DOE policy. Termination activities on the ATES Demonstration Projects will continue well into FY 1982 due to the size and complexity of those subcontracts. Only the St. Paul, Minnesota Demonstration Project will continue. It is being converted from a demonstration project to a high-temperature field test facility (FTF) similar to the Auburn University low-temperature FTF near Mobile, Alabama.

FIGURE 1. Original Seasonal Thermal Energy Storage Program Structure

The CAES Program fared considerably better in the FY 1982 budget than did the STES Program. However, budgeted activities were still eliminated at midyear due to funding rescissions, and in FY 1982 as a result of budget reductions. The CAES Program structure is shown in Figure 2, again with terminated activities indicated by cross-hatching. The only areas significantly impacted by budget reductions were salt numerical studies (terminated) and solar-augmented adiabatic CAES (terminated). As with STES, other areas of the CAES Program were reduced in scope and redirected but not eliminated. Original funding for CAES in FY 1981 was \$3.5 million. Due to rescissions the actual expenditures totaled \$2.6 million. The CAES budget target for FY 1982 is \$1.9 million.

The UES Program structure, which will operate in FY 1982 and which consolidates both the STES and CAES Programs, is shown in Figure 3. The structure of the UES Program is little more than a joining of the STES and CAES Programs, in their reduced forms. Consolidation occurs at the administrative rather than the technical level, consistent with the desire of DOE to reduce management and administrative functions while preserving the technical programs as entities, each moving appropriately toward the program goal.

Programmatically, FY 1981 was a year of tumultuous change for both STES and CAES, and one that will continue to affect the scope and direction of technical and programmatic efforts for several years to come.

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

FIGURE 2. Original Compressed Air Energy Storage Technology Program Structure

FIGURE 3. Underground Energy Storage Program Structure

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 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.

Aquifer Thermal Energy Storage

Work on ATES, formulated under the former STES Program Office at PNL, continues in the Underground Energy Storage Program. Technology studies in reservoir analysis (numerical modeling and laboratory/field analysis) are continuing. The ATES Demonstration Projects were terminated at or before the end of FY 1981. No further work is contemplated under DOE auspices at the Bethel, Alaska site. However, some follow-on work is planned at the Stony Brook, New York site during FY 1982 to resolve a well-plugging problem that occurred during chilled water reinjection. The St. Paul, Minnesota Demonstration Project is currently being converted to a high-temperature ATES Field Test Facility (FTF). Work is continuing at the Mobile, Alabama low-temperature ATES FTF.

Numerical Modeling

Two documents were completed during the year on state-of-the-art modeling technology as applied to ATES. The first publication reviewed numerical simulation techniques for saturated porous media; the second reviewed heat and mass transport in the partially saturated regime.

Numerical model technology was applied by Lawrence Berkeley Laboratory (LBL) for simulation/prediction/optimization of the first and

second heat injection tests at the Mobile, Alabama FTF. The model-predicted temperature curves for recovered water, as well as the total energy recovery factor (efficiency), showed excellent agreement with the field-measured results for both tests. The model-generated recovery temperature curves were within a few degrees of the measured values for all points along the temperature versus time curve. Predicted and measured subsurface temperatures also showed good agreement. The model-predicted energy recovery factor for the first cycle test was 0.620, compared to the measured value of 0.552. Slight modification of the geohydrologic parameters used in the model revised the predicted recovery to 0.585. The model-predicted energy recovery factor was 0.434 for the second cycle test, and the measured value was 0.452. The successful prediction of the first and second cycle tests at the Mobile FTF demonstrates the applicability and value of numerical modeling technology to ATEs problems involving complex geohydrologic systems.

Laboratory/Field Analysis

During this reporting period, permeability/creep compaction tests were run on Massillon sandstone, Ottawa sand and a simulated sand pack using these two materials. Minor permeability impairment was shown in the current tests to be both temperature- and time-dependent in the generic reservoir materials and in the sand pack samples. Permanent permeability impairment (plugging) was caused by small amounts of corrosion products generated in the test apparatus flow loop; by flow-induced migration of internal fines in the samples; and by particulates generated from the mechanical breakdown of the sand-sandstone interface in the sand pack samples.

Construction of the laboratory Aquifer Properties Test Facility (APTF) was completed in September 1981 and installation, testing, and calibration were completed in March 1982. The Field Injectivity Test Stand (FITS) for in situ evaluation of ATEs fluid and media response was completed in August 1981 and installed at the St. Paul, Minnesota FTF injection well site in preparation for the short-cycle heat injection tests scheduled to begin there in April 1982.

Geochemical modeling work concentrated on model development, model applications, and the establishment of water sampling requirements. The original ion-speciation/solubility WATEQ model was improved by merging it with a model (MINEQL) capable of simulating mass transfer. The WATEQ model was used to evaluate possible solubility controls on the ground-water composition at the St. Paul FTF.

Field Test Facilities

Parallel field tests on ATES are in progress at both the Mobile and St. Paul sites. The experiments will assess the long-term effects of heat injection on the ground-water systems. In addition, ATES work was carried out at the site of the Stony Brook, New York Demonstration Project, although the project was terminated at the end of FY 1981.

Mobile Field Test Facility. The Mobile, Alabama FTF is the site of low-temperature (55°C to 90°C) ATES studies. Two heat injection/storage/recovery tests were completed at the Mobile FTF during this reporting period. In the first cycle heat injection test, 6.87×10^6 gallons of water, heated to 58°C, were injected into the aquifer over a 1-month period at an average rate of approximately 150 gpm. Water recovery was initiated at a rate of 200 gpm after a corresponding storage period of 1 month. At initial recovery, water temperature was 55°C, and the temperature fell linearly to 53°C after recovery of 6.9×10^6 gallons of water in 24 days of pumping. Recovery factor for this test was 0.553.

Fifteen million gallons of water at an average temperature of 82°C were injected into the aquifer over a period of about 4.5 months during the second cycle test. After a storage period of 34 days, water recovery was started at a rate of 200 gpm. Initial recovery temperature was only 56°C, and temperature data from the monitoring wells showed the influence of convective flow due to thermal buoyancy. The test was stopped after two weeks and the recovery well was modified to recover water from the upper half of the aquifer to increase efficiency. The test was continued, with an initial increase of 2.5°C in temperature of the recovered water. However, water temperature

decreased at the same rate as before well modification, and the final recovery factor was only 0.452. Work is underway to further change the configuration of the recovery well system to achieve greater efficiency. The numerical model is being used to assist in design optimization, and plans are in progress for the third cycle test (80°C) at the FTF.

St. Paul Field Test Facility. The St. Paul, Minnesota ATES Demonstration Project is being converted to a high-temperature ATES field test facility. The former Phase I demonstration project task of aquifer characterization and short-cycle heat injection tests will be completed, and FTF plans for longer-term tests are being made.

During this reporting period, all installation and testing of surface and subsurface systems were completed. The monitoring wells were finished and the production/injection doublet wells were drilled, screened, and completed. Problems with "running sand" were encountered while drilling through the St. Peter sandstone, delaying completion of the monitoring and production wells.

The above-ground equipment installation (including line-shaft turbine pumps in production wells A and B) was completed during November 1981. Cold water startup of the system was initially tested on December 9, 1981 and the system long-term continuous flow test was completed on March 1, 1982.

Work continued on aquifer characterization and modeling. A sensitivity analysis of aquifer anisotropy was completed, and the potential for hydrofracturing the aquifer during injection was evaluated. In addition, step-drawdown tests for production wells A and B and a continuous rate aquifer test for well A were analyzed. The study shows that anisotropy changes within the aquifer/aquicludes should not cause significant errors in model-generated head calculations. Also, the potential for hydrofracturing does not appear to be a serious problem, because the maximum water flow rate planned for injection using the existing well configuration during the short-cycle nonisothermal tests results in hydrostatic pressures well below the danger point.

Evaluation of the step-drawdown data shows an 80% efficiency for well A at a pumping rate of 300 gpm, and a 90% efficiency for well B at the same pumping rate. The lower efficiency computed for well A could be due to poor well development as less time was spent developing well A compared to well B. This efficiency may improve with testing. Regardless, total drawdown computed for both wells A and B are close and well efficiency of 80% is not expected to hinder either withdrawal or injection during testing. Evaluation of the continuous-rate aquifer test shows that the aquifer can provide adequate water flow rate for large-scale tests and that the aquifer appears nearly optimal for high-temperature aquifer thermal energy storage.

Evaluations of water chemistry and geochemistry continued at the St. Paul site. The chemical reactions most likely to influence the feasibility of ATEs are dissolution and precipitation. Precipitation of carbonates caused by heating saturated ground waters may cause scaling on heat exchanger surfaces or plugging in the aquifer. Dissolution of silica by hot water and reinjection of silica-rich water after heat recovery may also result in plugging of the aquifer by precipitated amorphous silica. Detailed petrologic analysis was made of rock recovered from the two core borings at the St. Paul site. Knowledge of site mineralogy and ground-water chemistry will allow prediction of system geochemistry under elevated temperatures and will define probability of aquifer/well/heat exchanger fouling and changes in ground-water quality.

Work continued on environmental assessment. Environmental data, particularly water quality and microbiological information, were reviewed and evaluated. These data form the basis of the project environmental assessment. Two major environmental reports were published concurrently in March 1981.

Stony Brook Demonstration Project. The ATEs chill demonstration project on the Stony Brook (Long Island) campus of the State University of New York was terminated at the end of FY 1981 due to funding reductions. However, some follow-on work was performed. During this reporting period, the limited nonisothermal chill injection test was

completed and the aquifer characterization report was issued. The cost estimate for aquifer thermal energy storage alternatives was completed under support of the New York State Energy Research and Development Authority (NYSERDA) and a draft report was issued. Plans were made to investigate and rectify the well-plugging problem that occurred during the chilled water reinjection test.

Based on the results of the field investigations, the nonisothermal injection tests, model studies and other available information, application of ATES for air conditioning of the Stony Brook campus is technically feasible. Although some difficulty was experienced with chilled water reinjection, it does not appear to be outside the scope of an engineering solution. Studies are tentatively planned to investigate and better define those factors affecting the performance of injection wells.

A cost estimate was made for chill aquifer thermal energy storage alternatives on the Stony Brook campus. Two options for developing thermal energy storage chill systems were evaluated:

- a small-scale demonstration on one or a few buildings
- a full-scale demonstration using the original demonstration project concept.

A preliminary economic analysis for the first option indicates a simple payback period of 7.7 years, based upon construction costs of \$656,000, a \$40,000 credit for existing chillers, and an annual energy savings of \$80,000.

Preliminary economic analysis of the second option indicates that the estimated payback period of 11 to 12 years is outside the range generally acceptable by SUNY. However, in reviewing the economic analysis, the operating advantages and indirect benefits should be considered, as should potential change in any cost comparison based upon current fuel price. The capital and operating cost of an additional 4500-ton chiller, which would be necessary to provide for current West Campus needs, should also be considered in the cost-benefit evaluation.

Seasonal Thermal Energy Storage Technology Assessment and Development

The purpose of this task is to 1) identify and assess technical, economic, environmental, institutional, and legal issues affecting STES implementation and 2) develop promising nonaquifer STES technologies. The primary activities during this reporting period were the preliminary evaluation and screening of nonaquifer STES technologies and the development and application of economic models to characterize the economic features of ATEs.

Technical assessment efforts concentrated on analyzing pond, lake, cavern, tank, earth, rock, and ice thermal storage systems. Results obtained from those efforts include:

- Thermal recoveries can be good for all concepts. However, earth and rock borehole concepts will provide good recovery at only relatively low temperatures.
- Site availability is best for tank, earth and pond stores.
- Most of these storage systems usually require a 50-home or larger capacity for cost-effectiveness. However, smaller capacities may be possible for tank stores, and size ranges from 1 to 50 homes and larger are probable for ice storage systems.
- Annual thermal inventory turnover is an important factor in economic justification for the storage system. High capital costs are acceptable only in systems having high numbers of inventory turnover, i.e., not strictly seasonal.
- STES systems with sensible energy storage can often benefit from use of heat pumps.
- Coupling solar thermal energy with small to intermediate STES has good potential and is being vigorously explored in European countries. Use of waste heat from power and industrial plants has very good potential.
- The recommended order of priority for further research is ice storage, followed by existing caverns, ponds, lakes, tanks, earth, rock borehole, and constructed caverns.

During this reporting period, a methodology for economic evaluation of ATES configurations was developed and applied. First, development and documentation of the computer model AQUASTOR was completed. 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. This model was then used to parametrically investigate factors that may influence the economics for point demand, residential development, and multidistrict ATES systems. Parameters found to substantially influence ATES costs were:

- purchased thermal energy cost
- capital cost
- source temperature
- system size
- transmission distance
- aquifer efficiency.

Aquifer thermal energy storage was found to be economic under a wide range of operating, system and financial conditions. However, because of economies of scale ATES systems will require large capital expenditures. The cost of purchased thermal energy from industrial and waste heat sources and the characterization of cost penalty for thermal energy degradation (i.e., temperature drop during storage) are significant uncertainties requiring further investigation.

COMPRESSED AIR ENERGY STORAGE PROGRESS

The compressed air energy storage (CAES) concept includes near- and mid-term technologies for central station electric utility applications. This concept greatly improves the effectiveness of a gas turbine using petroleum fuels and could reduce petroleum 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 has been 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 Concepts Studies. Because long-term reservoir stability is crucial to CAES system commercialization, the CAES Reservoir Stability Studies received major emphasis in the early phases of the program. 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 constitute the basic research projects within later periods. The Second-Generation CAES Concepts Studies include a number of oil conservation technologies suitable for wider application than the utility market.

Reservoir Stability Studies

The objective of the CAES Reservoir Stability Studies is to develop stability criteria for large underground reservoirs in salt domes, hard rock, and porous rock used for air storage in utility applications.

Porous Media Reservoirs

The major concerns in developing stability criteria for porous media reservoirs are 1) the performance of CAES wells in aquifers over a wide range of operating and geophysical conditions, 2) the geochemical stability of typical CAES porous rock and caprock, and 3) the structural stability of porous rock and caprock. The second and third concerns are primarily for injection of hot compressed air.

Numerical modeling during the reporting period focused on the application to the Pittsfield data base of one and two-dimensional, one and two-phase thermohydraulic flow models developed previously to evaluate bubble development processes, prediction for water coning, thermal development and desaturation processes. The models were applied to support the field test activity. Preliminary predictions of test performance based on exploration and development data bases were performed. This information was used to size equipment, select instrumentation and plan test cycles.

Porous media laboratory studies completed all separate effects evaluation including thermomechanical, geochemical, autoclave, and ventilation studies early in this reporting period. Primary effort for the remainder of the period was directed toward combined effects evaluation of aquifer materials in the porous media flow facility, which became operational at PNL during this time. Equipment capability allows elevated temperature/controlled saturation air to reversibly flow through triaxially confined samples. The facility was used primarily to evaluate St. Peter core from the aquifer field test site at Pittsfield, Illinois. Preliminary evaluation indicates good stability with a tendency toward permeability reduction at higher temperatures. The mechanism currently hypothesized is particle generation and plugging within the samples. Laboratory study is continuing to confirm this.

The porous media field study plan approved in early FY 1980 moved from exploration into construction during this reporting period. Exploration activities were completed, including leasing, preliminary and confirmatory drilling, seismic surveys, and final site selection. Environmental activities included acquiring a construction permit from the Illinois Environmental Protection Agency and preparing an injection permit for submittal in May 1982. The construction and operations contractor has completed development of the well field and characterized the structure and aquifer. PB-KBB of Houston, Texas, is currently designing and constructing equipment for the test's surface facilities and surface and subsurface instrumentation, with test startup scheduled for September 1982. Operations are planned to run through the period of FY 1983 under DOE and possibly private sponsorship.

Hard Rock Caverns

Major concerns related to compensated CAES in hard rock include 1) determination of rock properties and behavior under cyclic thermal, pore liquid saturation, and mechanical loading conditions, 2) determination of the effect of local rock failure on cavern stability, 3) evaluation of the relative value of rock structural improvement methods, and 4) determination of the impact of fracture networks on global air leakage.

RE/SPEC, Inc., the lead contractor in hard rock cavern studies, completed numerical and experimental studies and issued a series of reports. Primary effort during this reporting period was collaboration with PNL to issue the final stability criteria and guidelines document on this study area. This report was prepared in draft, reviewed by industry experts and is currently in press. The document will be available in May 1982 as PNL-4180.

No field studies in hard rock are planned at this time because of the site-specific nature of problems and the probability of satisfying general situations by examining field experience of similar geotechnical projects.

Salt Cavern Reservoirs

Major concerns related to CAES in underground salt caverns include 1) evaluation of long-term salt response to cyclic mechanical and thermal loads, 2) determination of the potential for and consequences of surficial air penetration of the cavern wall, and 3) resolution of the difference in the response of varying types of salt to CAES loadings.

Continued numerical modeling of salt during the reporting period was precluded because of budget rescission. However, elevated temperature and boundary deterioration due to air penetration are critical parameters analyzed prior to termination. The major conclusions of this and previous work were that 1) caverns that are well designed and constructed are very stable, 2) cyclic loading strains can be approximated conservatively by utilizing the strain resulting from the most severe deviatoric stress encountered during cycling, and 3) elevated temperatures increase closure strain in salt caverns but do not jeopardize cavern stability with currently planned operation ranges (less than 200°F).

Laboratory studies of salt response to CAES conditions during this period included laboratory-scale and in-mine, bench-scale testing. Triaxial cyclic thermal and mechanical testing has been performed in six triaxial cells with salt specimens from several Louisiana salt mines, the Huntorf site in West Germany, and Kansas and Nevada bedded salt.

Cyclic mechanical loading results in strain cycling that is very small in response to cyclic stress having a larger range, but much greater strain is exhibited during elevated temperature portions of thermal cycling. Acoustic emission patterns appear to trace cyclic strain very closely, showing potential as a technique for in-situ monitoring of salt cavern stability. Tests in boreholes in the pillars of the Cote Blanche salt mine in Louisiana, initiated during FY 1981, were continued to completion during this period. Slant boreholes in pillars provided data on in-situ modulus, fracturing phenomena, in-situ permeability measurement and acoustic response. The information reinforced the previous conclusions of the stability of salt for air containment.

The salt stability study area has completed its assigned task during this reporting period. Data, results, and conclusions from the above described studies were compiled in salt stability criteria and guidelines, primarily by PNL and Louisiana State University due to budget restrictions. This document (PNL-4242) is complete, cleared for publication, and will be available in May 1982.

Second-Generation Concepts Studies

The objective of the Second-Generation CAES Concepts Studies is to develop second-generation CAES technologies that require little or no petroleum fuel for operation. During this reporting period major results were obtained at Fluidyne Engineering Corporation and PNL on the suitability of proposed materials for thermal energy storage (TES) in adiabatic and hybrid CAES plants. These studies were supported by both DOE and the Electric Power Research Institute. Materials considered included:

- 3/8-in. sintered iron oxide pellets
- 1/2-in. Denstone balls
- 1-in. cast iron alloy balls
- crushed, tumbled and unwashed Dresser basalt, approximately 3/4-in. maximum dimension.

At Fluidyne, beds of these materials 3 ft in diameter and up to 15 ft high were thermal-cycled from 100 to 900°F for 100 or more times.

Particulate elutriation rates, particulate sizes, and the thermal, hydraulic and mechanical performance were measured. At PNL, smaller samples of TES materials were exposed for long time periods in autoclaves under the conditions of high temperature, high pressure, and in the presence of moisture and SO₂ contamination expected in actual service.

The results of this study indicated that Denstone, crushed Dresser basalt, and alloyed cast iron probably possess sufficient durability for use as a TES material. Gray cast iron was determined to be unsuitable because of excessive corrosion. The suitability of sintered iron oxide was uncertain, because samples obtained from one mill were found to suffer a dramatic loss of strength in the presence of moisture. Considering combined performance, durability and cost factors, it appears that crushed rock (Dresser basalt) may be the most desirable of the materials considered and should be given additional attention in future CAES studies.

SIGNIFICANT ACCOMPLISHMENTS

Despite the funding reductions and redirection from DOE there were many significant accomplishments during the reporting period. These accomplishments are identified below by technology.

Seasonal Thermal Energy Storage

The program plans formulated in FY 1980 were restructured. The number of Phase I demonstration contracts negotiated was limited to three by the available FY 1981 budget. Later in the fiscal year, further budget restrictions in FY 1981 and FY 1982, as well as reorientation of DOE's role in the commercialization of energy-related technologies, required the termination of two demonstration studies and modification of the third demonstration project to a Field Test Facility.

Work in FY 1981 established a sound planning base and progress toward development of operating systems using storage in aquifers; development of technical, environmental, and other information essential

to support application of ATES; and initial evaluation of alternative seasonal storage methods.

Significant STES accomplishments during the reporting period were:

- Planning documentation was completed for the three ATES demonstration projects.
- Aquifer characterization was in an advanced state of progress at all three ATES demonstration project sites when terminated.
- A preliminary report was completed on nonaquifer STES methodology.
- Draft numerical simulation model documentation including sample analyses was completed.
- Reports were issued on state-of-the-art of ATES simulation modeling and heat and mass transfer in unsaturated porous media.
- 55°C and 82°C true doublet cycle (injection/storage/recovery) tests were completed at the Mobile, Alabama FTF site.
- Numerical model simulation/prediction was completed for both Mobile FTF tests.
- Program plans were completed for converting the St. Paul, Minnesota ATES demonstration project to a high-temperature FTF.
- Construction of all surface and subsurface systems was completed at the St. Paul, Minnesota FTF and initial tests of the system were made.
- Although the Stony Brook ATES Demonstration Project was terminated at the end of FY 1981, aquifer characterization was completed and a final report issued. Also, a cost estimate was made on ATES alternatives at Stony Brook, and a draft report was issued.
- Installation of the STES Aquifer Properties Test Facility was completed.
- A report was issued on legal issues affecting end uses of energy from an ATES project.

- Development of the AQUASTOR code for simulating ATES cooling/heating systems was completed.
- The final Environmental Assessment for ATES (DOE programmatic) was completed and issued.
- Contacts were established with key personnel involved in storage work in countries participating in International Energy Agency (IEA) seasonal storage.

Compressed Air Energy Storage

During the reporting period, the Reservoir Stability Studies completed numerical and experimental work in all three reservoir types and completed the hard rock and salt components of the project. The porous media field study activity and its related numerical, experimental, and administrative support functions were the primary activities in this area. Its purpose is to resolve the remaining geotechnical issues with respect to porous media storage systems. All phases of planned hard rock and salt cavern study were completed and both stability criteria documents finalized by May 1982. Correlation of laboratory and in-mine experimental salt results was the only FY82 activity in either salt or hard rock. Generic numerical and experiment work on porous media are complete. The Pittsfield aquifer field test has completed its exploration, initial permitting, and well field development activities. All major design is finished and equipment procurements for the construction phase are being placed under the direction of the operations contractor.

The principal emphasis in the Second-Generation Concepts Studies during the reporting period was on completing and assessing the engineering studies of the four concepts identified early in the program as being particularly attractive for utility energy storage applications. These concepts include adiabatic CAES, hybrid CAES, CAES/fluidized bed combustion (FBC), and CAES/coal gasification (CG). Activities were initiated to develop thermal energy storage systems for the adiabatic CAES concept.

Significant CAES accomplishments during the reporting period were:

- Completed Potomac Electric Power Company (PEPCO) site-specific numerical design evaluation of hard rock cavern system using CAES developed models and finalized the stability criteria guidelines.
- Completed generic and site-specific experimental evaluations of hard rock materials (Sykesville gneiss).
- Concluded salt numerical analysis studies.
- Completed salt generic laboratory studies (further study terminated).
- Completed in-mine testing of in-situ salt response at the Cote Blanche mine and finalized the salt cavern stability criteria and guidelines document.
- Applied the porous media numerical models to the Pittsfield Aquifer Field Test to assist design and predict performance.
- Completed separate effects porous media experimental studies.
- Continued combined effects testing of Pittsfield core in the Porous Media Flow Facility to assess permeability response.
- Completed site exploration for the Pittsfield Aquifer Field Test.
- Completed leasing and construction permitting for the field test site.
- Prepared the application to the Illinois Environmental Protection Agency for a construction permit.
- Drilled and completed the injection/withdrawal well for the aquifer field test.
- Drilled the monitoring well field for the aquifer field test.
- Completed instrumentation and surface facility design and began placing major equipment procurements for the aquifer field test.
- Performed an independent assessment of the commercial availability of equipment and components for advanced CAES systems.

- Completed a comparative economic study to normalize and compare the costs of the second-generation concepts that have been considered in conceptual design studies.
- Performed an overall assessment of the candidate second-generation concepts and recommended the further development of adiabatic CAES because of its all-around attractiveness.
- Developed a methodology to assess and analyze the reliability of CAES plants.
- Awarded a contract for the thermal-mechanical testing of thermal energy storage (TES) materials for adiabatic CAES systems.
- Initiated a study to assess the thermal/chemical attack of high pressure, moist, polluted air on TES materials; completed the evaluation of two materials identified as most promising in engineering studies.

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UNDERGROUND ENERGY STORAGE PROGRAM
1981 ANNUAL REPORT
VOLUME I
PROGRESS SUMMARY

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 two-volume 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 1981 to March 1982. Work performed prior to March 1981 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). In Volume I, the Underground Energy Storage Program objectives, approach, structure, and milestones are described in Section 2.0. The important programmatic changes that occurred during this reporting period are also discussed here. Section 3.0 summarizes technical activities and progress in the STES component of the program. In Section 4.0, CAES efforts are similarly described. Volume II presents more detailed technical summaries of the separate projects conducted in support of the overall UES Program during this reporting period.

2.0 UNDERGROUND ENERGY STORAGE PROGRAM DESCRIPTION

Because of the potential benefits, the U.S. Department of Energy (DOE) (as well as other groups) has initiated activities to accelerate the successful introduction of the STES and CAES technologies. The strategy adopted by DOE was to identify factors inhibiting entrepreneurial 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 entrepreneurial 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 would 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 on 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 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 and operated separately 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.

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 such that entrepreneurial development is probable.

Pursuant to the principal factors identified as inhibiting entrepreneurial 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

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

- to develop advanced CAES technologies that would eliminate the dependence of CAES systems on petroleum fuels.

2.3 APPROACH AND STRUCTURE

The STES and CAES programs were not consolidated into the UES Program until late in FY 1981. Therefore, for much of this reporting period, two different approaches were followed to meet DOE programmatic needs and pursue the objectives identified above.

The STES Program strategy, originally adopted for meeting the objectives identified above, involved development and proof-of-principal testing. Rapid development and implementation of ATEs (the most promising STES technology) would be accomplished through small-scale demonstration projects at sites suitable for eventual commercial development. Technology required to conduct these small-scale demonstration projects would be obtained in a companion effort involving numerical modeling, laboratory, and field testing. A less extensive effort was initiated to identify alternative STES concepts that did not require aquifers. This approach was aggressively pursued at PNL until budget rescissions in April 1981. At that time, FY 1981 funding was reduced; additional funding reductions were projected for FY 1982. In addition, DOE abandoned the approach of using small-scale demonstration type projects. The new favored approach was one in which only high technology, high risk, technical R&D would be performed.

The impact on the STES Program was severe. Two of the three small-scale ATEs demonstration projects (Bethel, Alaska and Stony Brook, New York) were terminated; the third (St. Paul, Minnesota) was redirected toward conducting high-temperature tests. The ATEs technology studies were also reduced in scope and funding. More emphasis was to be placed on development of high technology nonaquifer STES systems, which are only now being thoroughly examined.

The original STES organizational structure is shown in Figure 2.2. The cross-hatched areas are those that were eliminated in response to severe budget reduction and redirection. The reorganized STES

FIGURE 2.2. Original Structure, Seasonal Thermal Energy Storage Program

activities are shown in Figure 2.3 as part of the UES Program organization. Generally, more emphasis is being placed on technical studies of STES at more extreme conditions than previously. Alternative methods of STES are also being examined. However, environmental, institutional, and legal studies have been terminated. The approach to the development of alternative STES systems will involve technical and economic screening followed by selective engineering development and testing.

The CAES Program approach developed to achieve the objectives identified above involved different strategies for reservoir stability studies and second-generation studies. Numerical modeling, laboratory testing, precedent experience, and field testing (if required) would be conducted on an ever-narrowing range of technical issues until reasonable confidence in resulting stability criteria was obtained. Second-generation technologies would be subjected to feasibility analyses, cost analyses, and successive levels of engineering screening and development, as appropriate.

The CAES Program was not as severely impacted in FY 1981 by budget cuts, or by redirection in FY 1981 and FY 1982, as was the STES Program. Although the structure of the CAES Program has not been dramatically altered, significant changes have occurred. Activities in underground pumped hydro (UPH), previously managed by PNL, were terminated as a result of funding reductions in FY 1981 and FY 1982. Continued activities in numerical modeling studies for salt reservoir stability were terminated. Several studies of second-generation technologies were indefinitely postponed as a result of funding reductions. The original structure of the CAES Program is illustrated in Figure 2.4. This can be contrasted with the FY 1982 structure following consolidation into the UES Program shown in Figure 2.3.

2.4 MAJOR MILESTONES

The financial and programmatic dislocation of STES and CAES in FY 1981 disrupted orderly progress toward major milestones. Nonetheless, significant progress was accomplished during this reporting period.

FIGURE 2.3. Underground Energy Storage Program Structure After Consolidation

FIGURE 2.4. Original Structure, Compressed Air Energy Storage Program

The original STES Program schedule and milestone chart is shown in Figure 2.5. Areas of the program that were terminated are so indicated. It should be noted that the reductions in funding also affected areas of the program that were not terminated. In many of these cases, effort was slowed such that the schedules indicated are not appropriate for FY 1982 activities. Progress toward milestones on these schedules is discussed in Section 3.0.

The principal milestones in the ATES Demonstration Program were the completion of aquifer characterization, preliminary environmental reports, and functional design criteria. Major milestones in the Seasonal Storage Technology Program included the completion of an analysis of legal issues affecting ATES; final programmatic environmental assessment (EA) for ATES; the 55°C test at Mobile, Alabama; installation of the aquifer properties test facility; and assessment of ATES modeling.

The original CAES Program schedule and milestone chart is shown in Figure 2.6. The principal milestones in the Reservoir Stability Studies were the completion of the numerical modeling studies and the laboratory studies. Major milestones for Second-Generation Concepts Studies included the completion of feasibility studies and the initiation of development of a selected second-generation concept. Progress toward these milestones is described in Section 4.0.

2.5 RESOURCE REQUIREMENTS

To achieve the program objectives, expenditures up to \$28.7 million may be required for the period 1980 through 1985. Figure 2.7 shows the annual funding requirements by the four major program elements from 1979 through 1985. Activities in ATES include the demonstration studies funded into FY 1981.

SEASONAL THERMAL ENERGY STORAGE PROGRAM

FIGURE 2.5. Seasonal Thermal Energy Storage Program Milestone Schedule

SEASONAL THERMAL ENERGY STORAGE PROGRAM

FIGURE 2.5. contd

FIGURE 2.6. Compressed Air Energy Storage Technology Program Milestones

Figure 2.7. Resource Requirements of the Underground Energy Storage Program

As can be seen, increased resources will be required for the growing program in alternative STES technology development. The Reservoir Stability Studies are expected to lose all DOE support in FY 1983. Therefore, it is anticipated that Second-Generation Studies tasks will be the only CAES activities to receive any continued support.

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 study scope encompasses concepts that utilize seasonally available heat or cold from waste sources or other surplus sources to reduce peak period energy demand, reduce electric utilities' peaking requirements, or 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 with 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 met.

Research beyond the reasonable scope of entrepreneurs is needed on aquifer characteristics and their interrelationship with and impact on aquifer thermal energy storage. Earth media thermal characteristics and behavior must be investigated for dry earth and rock thermal energy storage (TES). Studies of barrier and insulation materials are needed for wet earth and insulated pond TES. Economic and institutional studies are needed to encourage acceptance of all types of large-scale commercial STES methods. Modeling technology must be developed and

applied to simulate, optimize, and predict STES system performance. Modeling requirements range from system/distribution performance to geochemical, hydrologic, and heat transport simulation.

Initially, the STES Program was divided into an Aquifer Thermal Energy Storage (ATES) Demonstration Program and a parallel Seasonal Storage Technology Program. The ATES Demonstration Program was terminated at the close of FY 1981 because of funding rescissions for FY 1982, and reorientation of DOE's role in commercialization of energy-related technologies.

Research and development efforts required to meet program objectives are now being carried out in the ATES Technology Studies and the STES Technology Assessment and Development (STES/TAD) Studies. Activities include social, economic, and environmental assessment, as well as technical research and development studies to provide a sound base for technology implementation. The STES/TAD Studies and ATES Technology Studies replaced the earlier Seasonal Storage Technology Program.

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, formulated under the former STES Program office at PNL, continues in the Underground Energy Storage (UES) Program. The ATES Demonstration Projects were terminated at or before the end of FY 1981. No further work is contemplated under DOE auspices at the Bethel, Alaska site. However, some follow-on work is planned at the Stony Brook, New York site during FY 1982 to resolve a well-plugging problem that occurred during chilled water reinjection. The St. Paul, Minnesota Demonstration Project is now being converted to a high-temperature ATES Field Test Facility (FTF). Work is continuing at the Mobile, Alabama low-temperature ATES FTF.

3.1.1 Goal and Objective

The objective of the ATES Technology Studies is to establish guidelines and methods for cost-effective appraisal of ATES. The goal is to provide entrepreneurs with the tools to establish technical and economic feasibility for ATES.

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.

3.1.3 Project Descriptions

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

3.1.3.1 Numerical Modeling

The objective of the numerical modeling project is to develop new, or determine appropriate existing, simulation technologies capable of predicting the transport and retrieval of thermal energy resources within the ground-water environment. The resulting models would then be used in designing and evaluating ATES systems.

Two documents were completed in the review and assessment of state-of-the-art modeling technology during the year. In the first, GeoTrans Inc. reviewed simulation techniques for saturated environments (Mercer et al. 1981). A second effort completed by Stuart Childs of

TABLE 3.1. Aquifer Thermal Energy Storage Technology Studies
Tasks and Projects

<u>Task/Project</u>	<u>Contractor</u>	<u>Status as of March 1982</u>
Reservoir Analysis		
• Numerical Modeling		
- Hydrologic Model Development	LBL and PNL	On schedule
- Site Analysis	LBL	On schedule
- Design Assistance	LBL	On schedule
- Geochemical Modeling	PNL	On schedule
• Laboratory/Field Studies		
- Study Development	PNL	On schedule
- Critical Particulate Velocity Study	Terra Tek	On schedule
- Monitoring and Analysis of a Functioning Chill Storage Project	W.J. Schaetzle	One month behind
- Documentation of a Functioning Heat and Chill Storage System	To be determined	One month behind
Field Test Facility Testing		
• Mobile, Alabama FTF	Auburn University	On schedule
• St. Paul, Minnesota (Demo)	U. of Minnesota	Terminated
• St. Paul, Minnesota FTF	U. of Minnesota	One month behind
• Stony Brook, New York (Demo)	Dames & Moore	Terminated
- Well-Plugging Study	Dames & Moore	Two months behind
• Bethel, Alaska (Demo)	TRW	Terminated

Oregon State University reviewed the literature on heat and mass transport in the unsaturated porous media overlying an unconfined aquifer (Childs and Malstaff 1982).

Two activities were directed toward documenting verification of simulation capability. The first was to convert the Survey Waste Injection Program (SWIP) code (INTERCOMP 1976) to a short word length (e.g., IBM) computer and verify it against published solutions. The results of this effort were published by Washington State University (Ichimura 1982). The second activity completed verification of the Coupled Fluid, Energy and Solution Transport (CFEST) code. Primary documentation for CFEST will be published in May 1982 by PNL.

Lawrence Berkeley Laboratory (LBL) applied numerical modeling technology for simulation/prediction/optimization of the first and second heat injection tests at the Mobile, Alabama FTF. The model PT (formerly called CCC) was used to simulate both the first (59°C) and second cycle (82°C) Mobile FTF tests. Model calibration/verification had been essentially completed during previous application at the FTF site, although some additional modifications were made, based on refined geohydrologic data. Basic well-test, injection and recovery flow rate, and injection temperature data were provided to LBL. No information on field-measured subsurface temperature or water temperature of the recovered water was supplied to the modeling team. Hence, the simulation/prediction studies were done "blind" to preclude influence from the field-derived heat recovery data.

The model-predicted temperature curves for recovered water, as well as the total energy recovery factor (efficiency), showed excellent agreement with the field-measured results for both tests. The model-generated recovery temperature curves were within a few degrees of the measured values for all points along the temperature versus time curve. Predicted and measured subsurface temperatures also showed good agreement. The model-predicted energy recovery factor for the first cycle test was 0.620, compared to the measured value of 0.552. Slight

modification of the geohydrologic parameters used in the model revised the predicted recovery to 0.585. The model-predicted energy recovery factor was 0.434 for the second cycle test, and the measured value was 0.452.

The successful prediction of the first and second cycle test values at the Mobile FTF shows the applicability and value of numerical modeling technology to ATES problems involving complex geohydrologic regimes.

Work on geochemical modeling has been directed toward developing and applying models and establishing water sampling requirements. The original ion-speciation/solubility WATEQ model was improved by merging it with a model (MINEQL) capable of simulating mass transfer. A copy of the latest version of EQ3/EQ6, which includes both mass transfer and dissolution kinetics subroutine, was obtained for future modeling use. The WATEQ model was used to evaluate possible solubility controls on the ground-water composition at the St. Paul FTF. The data requirements for geochemical modeling studies are being used to produce sampling guidelines for FTFs and the APTF.

3.1.3.2 Laboratory/Field Studies

The laboratory/field studies objectives are to test the physicochemical properties and stability of aquifer materials under ATES conditions, to implement laboratory and field facilities for the tests, and to develop/apply geochemical models to ATES.

During this reporting period, permeability/creep compaction tests were run on Massilon sandstone, Ottawa sand, and a simulated sand pack using these two materials. Previous tests showed permeability reduction at elevated temperatures, but much of the reduction was attributed to particulate plugging from the test apparatus. Extreme measures were taken with the current tests to preclude this "artifact" through design and control of the materials used in the test facility flow system.

The current tests showed minor permeability impairment to be both temperature- and time-dependent in the generic reservoir materials

and in the sand pack samples. Repeated heating and cooling cycles were shown to not result in large-scale cumulative impairment of permeability in either Massillon sandstone or Ottawa silica sand. Simulated injection in the sand pack samples resulted in some time-dependent permanent impairment but essentially no permanent, temperature-induced impairment. Sources of permanent permeability impairment (plugging) were small amounts of corrosion products generated in the test apparatus flow loop, flow-induced migration of internal fines in the samples, and particulates generated from the mechanical breakdown of the sand-sandstone interface in the sand pack samples.

Construction of the laboratory Aquifer Properties Test Facility (APTF) was completed in August 1981 and installation, testing, and calibration were completed in March 1982. The Field Injectivity Test Stand (FITS) for in-situ evaluation of ATEs fluid and media response was completed in August 1981 and was installed at the St. Paul, Minnesota FTF injection well site in preparation for the short-cycle heat injection tests scheduled to begin there in April 1982.

3.1.3.3 Field Test Facility Testing

The objective of the field test facility work is 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 are planned for both the Mobile and St. Paul sites. The experiments will assess the long-term effects of heat injection on the ground-water systems. In addition,

ATES work was carried out at the site of the Stony Brook, New York Demonstration Project, although the project was terminated at the end of FY 1981. Research activities and results from the three sites are summarized in the next three subsections.

3.1.3.3.1 Mobile, Alabama Field Test Facility. The Mobile, Alabama FTF is the site of low-temperature (55°C to 90°C) ATES studies. Two heat injection/storage/recovery tests were completed at the Mobile FTF during this reporting period. Prior to the first test, the well field was altered to provide a true doublet test, with the supply/reinjection well and injection/recovery well completed in the same aquifer. The observation and monitoring well pattern was revised, and wells were placed to determine thermal plume movement within the aquifer through temperature and chemical tracer measurements.

In the first cycle heat injection test, 6.87×10^6 gallons of water, heated to 58°C, were injected into the aquifer over a one-month period, at an average rate of ~ 150 gpm. Water recovery was initiated at a rate of 200 gpm after a corresponding one-month storage period. At initial recovery, water temperature was 55°C, and the temperature fell linearly to 35°C after recovery of 6.9×10^6 gallons of water in 24 days of pumping. Recovery factor for this test was 0.553.

Fifteen million gallons of water at an average temperature of 82°C were injected into the aquifer over a 4.5-month period during the second cycle test. After a storage period of 34 days, water recovery was started at a rate of 200 gpm. Initial recovery temperature was only 56°C, and temperature data from the monitoring wells showed the influence of convective flow due to thermal buoyancy. The test was stopped after 2 weeks; to attempt increased efficiency, the recovery well was modified to recover water from the upper half of the aquifer. The test was continued, with an initial increase of 2.5°C in temperature of the recovered water. However, water temperature decreased at the same rate as before well modification, and the final recovery factor was only 0.452. Work is in progress to further change the configuration of

the recovery well system to achieve greater efficiency. The numerical model is being used to assist in design optimization, and plans are being made for the third cycle test (80°C) at the FTF.

3.1.3.3.2 St. Paul, Minnesota Field Test Facility. The St. Paul, Minnesota ATES Demonstration Project is now being converted to a high-temperature ATES field test facility. The former Phase I demonstration project task of aquifer characterization and short-cycle heat injection tests will be completed, and FTF plans for longer-term tests are in progress.

During this reporting period, all installation and testing of surface and subsurface systems were completed. The monitoring wells were finished and the production/injection doublet wells were drilled, screened, and completed. Problems with "running sand" were encountered while drilling through the St. Peter sandstone, delaying completion of the monitoring and production wells.

The above-ground equipment installation (including line-shaft turbine pumps in production wells A and B) was completed during November 1981. Cold water startup of the system was initially tested on December 9, 1981, and the system long-term continuous flow test was completed on March 1, 1982.

Work continued on aquifer characterization and modeling. A sensitivity analysis of aquifer anisotropy was completed, and the potential for hydrofracturing the aquifer during injection was evaluated. In addition, step-drawdown tests for production wells A and B, and a continuous rate aquifer test for well A, were analyzed.

Anisotropy values of the aquifer and confining layers were obtained for input to the transport model. To examine the sensitivity of anisotropy on computed head values for the isothermal flow system, a three-dimensional flow model was constructed. The computer program used for the anisotropy analysis was the three-dimensional finite difference model developed by Pinder and Bredehoeft (1968), and previously used to investigate the study area's isothermal flow system. Input parameters

for the model were derived from the numerous field and laboratory studies carried out at the St. Paul site. The Eau Claire formation appears to be the member most sensitive to changes in anisotropy. Anisotropic changes in this formation could cause errors in computed heads for all other formations from 0.5 to 3.25 ft. This range in values should not cause significant error in model results.

The nonisothermal radial flow model was used to examine the maximum injection rate based on the aquifer's potential for hydrofracturing. The hydrofracture pressure range is calculated to be approximately one-half the lithostatic pressure, or between 400 and 415 psi for the Franconia-Ironton-Galesville aquifer. Using 415 psi as the maximum allowable pressure, the model calculated a maximum injection rate of 660 gpm. The maximum pressure was first attained by the Galesville formation. The potential for hydrofracturing does not appear to be a serious problem, because 300 gpm is the maximum rate planned for injection using the existing well configuration during the short-cycle nonisothermal tests.

Step-drawdown tests were run on the injection/production doublet wells (wells A and B, respectively) to determine well efficiencies. The production well at Site B was developed by the pump and surge method for approximately 10 h. The maximum rate pumped during well development was 850 gpm for approximately 4.75 h; maximum drawdown was measured as approximately 409 ft below land surface. The well recovered for approximately 12 h and measured water levels were within 0.2 ft of predevelopment levels. This recovery was considered sufficient to conduct a step-drawdown test. Pumping duration and pumping rate were 220 gpm for 258 min, 380 gpm for 217 min, and 735 gpm for 190 min. The injection well at Site A was developed for approximately 8 h using the pump and surge method. The maximum rate pumped during development was approximately 900 gpm for 3.0 h. The well recovered for approximately 18 h and was within 0.3 ft of predevelopment water levels. This was considered sufficient recovery to conduct a step-drawdown test. Duration of step-drawdown test pumping and pumping rate were 182 min at

584 gpm, and 133 min at approximately 1000 gpm. Evaluation of the step-drawdown data shows an 80% efficiency for well A at a pumping rate of 300 gpm, and a 90% efficiency for well B at the same pumping rate. The lower efficiency computed for well A could be due to poor well development as less time was spent developing well A compared to well B. Nevertheless, total drawdown computed for both wells A and B are similar; and well efficiency of 80% is not expected to hinder either withdrawal or injection during testing.

A continuous rate aquifer test was performed at Site A. The well was pumped at an average 340 gpm for approximately 4.5 days. Drawdown measurements were taken in all observation wells located at Sites A, B, and C. Drawdown data were analyzed for transmissivity and storage coefficient. Because the well does not have continuous screen and the lower Franconia acts as a confining layer, the test data were treated similar to those for a multiaquifer well. Relative hydraulic conductivity values for the upper Franconia and Iron-ton-Galesville formations were used to proportion the pumping from the screened intervals within the aquifer. A total transmissivity of 1090 ft²/day and a storage coefficient of 2.55×10^{-5} is calculated for the upper Franconia and Iron-ton-Galesville aquifer. Previous estimates of transmissivity based on initial drill stem tests were 300 to 350 ft²/day, indicating that a full-scale ATEs project would be difficult to implement (considering water supply requirements) using this aquifer. The transmissivity of 1090 ft²/day derived from the more comprehensive tests assures adequate water flow rates and appears nearly optimal for high-temperature aquifer thermal energy storage.

Work continued on evaluation of water chemistry and geochemistry at the St. Paul site. The purpose of the water chemistry studies is to study those chemical reactions that may affect the project. Ground water from an array of monitor wells is being collected and analyzed. Characterizing the water chemistry before heat injection will allow prediction of the extent of carbonate precipitation, as well as establish baseline water quality values for comparison with samples collected after heat injection.

The chemical reactions most likely to influence the feasibility of ATEs are dissolution and precipitation. Precipitation of carbonates caused by heating saturated ground waters may cause scaling on heat exchanger surfaces or plugging in the aquifer. Dissolution of silica by hot water and reinjection of silica-rich water after heat recovery may also result in plugging of the aquifer by precipitated amorphous silica.

The dissolution rates of representative aquifer rocks at temperatures from 45° to 150°C have been measured. Because dissolution rates are proportional to interfacial area, measurement of specific surface areas of ground rocks used in dissolution experiments and natural aquifer rocks permits extrapolation of experimental results to in-situ conditions. Chemical equilibrium computations suggest that the maximum precipitation of calcium and magnesium carbonates and silicates occurs between 75° and 125°C. Silica and aluminum concentrations approach 10 mM and 0.1 mM, respectively, at high temperatures. Because these concentrations are orders of magnitude greater than saturation at 10°C, precipitation of amorphous silica and aluminum hydroxide can be expected after heat recovery and reinjection of ground water. Computations involving recent analytical results and inclusion of iron and manganese in computations are planned.

Rock recovered from the two core borings at the St. Paul site underwent detailed petrologic analysis. Measured porosities ranged from 9.1% in the St. Lawrence formation to 27% in the Ironston and Galesville formations.

Determination of the detailed mineralogy combined with knowledge of the ground-water chemistry will allow prediction of system geochemistry under elevated temperatures and will define probability of aquifer/well heat exchanger fouling and changes in ground-water quality.

Work continued on environmental assessment. Environmental data, particularly water quality and microbiological information, were reviewed and evaluated. These data form the basis of the project environmental assessment. They may also have significant environmental

implications for future ATES projects. The St. Paul project was monitored during construction and initial test phases for environmental quality assurance to ensure the accuracy and reliability of water chemistry, microbiology and thermal monitoring data for the project.

Two reports, published jointly in March 1981, addressed major environmental issues at the St. Paul site. Typical environmental concerns were investigated in the Phase I Preliminary Environmental Assessment. A preliminary assessment of probable impacts was given for each of the issues. This report also briefly assessed Phase II of the project for probable environmental impacts. The other report, Phase I Environmental and Institutional Monitoring Plan, defined the requirements and procedures for project surveillance to assure that environmental impacts are addressed and minimized.

3.1.3.3.3 Stony Brook Demonstration Project. The ATES chill demonstration project on the Stony Brook (Long Island) campus of the State University of New York was terminated at the end of FY 1981 due to DOE reduction of funds in support of the STES Program for FY 1982. However, some follow-on work was done, under support of the New York State Energy Research and Development Agency (NYSERDA), on a comprehensive cost estimate for ATES alternatives at Stony Brook. Also, a special project is planned for later in FY 1982 to resolve a well-plugging problem that occurred during the reinjection phase of the nonisothermal chill storage test.

During this reporting period, the limited nonisothermal chill injection test was completed and the aquifer characterization report was issued. The cost estimate for aquifer thermal energy storage alternatives was completed and a draft report was issued. Plans were made to investigate and rectify the well-plugging problem that occurred during the chilled water reinjection test.

The limited nonisothermal chilled water injection test, started in January 1981, was completed in July 1981. The test objective was to characterize aquifer response to chilled water injection as input to Phase I ATES conceptual design and implementation of larger-scale ATES demonstration.

Energy recovery for that test, in terms of total injected chill energy, was approximately 60%. Using a 1.6°C cutoff temperature rise, the chill energy recovery was approximately 30%. These figures are based upon a 1.6°C "round trip" heat gain in transmission through the chill injection/recovery system. Numerical simulation of recovery, in which the ground water flow was normalized (by the addition of wells with pumping designed to extract ground water upgradient and inject water downgradient), indicates that the total efficiency could be increased to more than 80%.

Aquifer characterization (including the chilled water injection test) was the sole task within the original demonstration project plan on which work continued during this reporting period. On March 24, 1981, because of the funding rescission, PNL directed Dames & Moore to suspend all work on the Stony Brook ATES Demonstration Project that was not directly associated with aquifer characterization. The suspension deferred all milestones except completion of aquifer characterization. This milestone was completed in September 1981, when the Comprehensive Aquifer Characterization Report was issued.

All geohydrologic data collected during the last reporting period from drilling, sampling and testing of the nine monitoring/test wells and injection/production wells were evaluated for the report. Three aquifers occur in the area; the Lloyd sand member of the Raritan formation; the Magothy aquifer, and the Upper Glacial aquifer (in ascending order), which is comprised of the saturated portion of the undifferentiated glacially derived sediments.

Based upon results of the field tests, model studies, and other available information, most portions of the Magothy aquifer under the Stony Brook campus can be considered satisfactory for an ATES storage zone. Final selection of storage zone limits would have to be based on results from additional test drilling. For the feasibility test, the storage zone was selected on the basis of the screen interval in an existing well. Subsequent drilling of 10 test borings (converted to nine monitoring wells and one pumping/injection well) at the test site indicated that, although this portion of the Magothy aquifer does

contain relatively few clayey zones, the overall gross character of this portion is not appreciably different from other portions of the Magothy formation. Application of ATES for air conditioning of the Stony Brook West Campus is technically feasible. The difficulty experienced with injection does not appear to be outside the scope of an engineering solution. Studies are tentatively planned to investigate and better define those factors affecting injection well performance.

Under funding from the New York State Energy Research and Development Agency (NYSERDA), a comprehensive cost estimate was made for chill aquifer thermal energy storage alternatives on the Stony Brook campus. Data collected during the terminated Stony Brook ATES Demonstration Project were used in this cost estimate.

Two options for developing thermal energy storage chill systems were evaluated:

- a small-scale demonstration on one or a few buildings, which would use a small cooling tower and the existing aquifer doublet field (installed as part of the completed aquifer characterization studies)
- a full-scale demonstration using the original concept with the Marley cooling tower and the complete campus distribution system.

The approach used in preparing these conceptual designs was to first define the seasonal recovery efficiency for various temperature differentials (injection temperature versus recovery temperature, based upon the results of the already completed test program). The second step was to evaluate user needs, based upon the operating characteristics of the existing system, the practical minimum temperature to which water could be chilled in a cooling tower, and the necessary quantity of chilled water for injection to provide sufficient recovery at a usable temperature. Then, based upon the required storage volume and recovery efficiency, an aquifer storage system was designed. All equipment, material and construction costs were then calculated using current (Fall 1981) prices and New York area contractors.

Operating costs for the conceptual ATES systems were then compared with current operating costs; savings were divided into the ATES capital costs to provide simple payback period estimates.

A preliminary economic analysis for the first (small-scale) option indicates a simple payback period of 7.7 years, based upon construction costs of \$656,000, a \$40,000 credit for the existing chillers in the retrofitted buildings, and an annual energy savings of \$80,000. Preliminary economic analysis of the second (full-scale) option indicates that the estimated payback of 11 to 12 years is outside the range considered acceptable by SUNY. However, in reviewing the economic analysis, the operating advantages and indirect benefits should be considered, as should potential change in any cost comparison based upon current fuel price. Such a cost-benefit evaluation should also consider the capital and the operating cost of an additional 4500-ton chiller, which would be necessary to provide for current West Campus needs.

Early in the chill recovery test, the reinjection well capacity deteriorated significantly. Plans were made to investigate and remedy this problem. This study was programmed to begin early in FY 1982, but funding and contractual problems have deferred start of the work until May 1982. The investigation will involve remedial work on production/injection well PI-2 to attempt recovery of original injectivity capacity through well surging, overpumping and, if necessary, chemical treatment. During this work, produced water will be analyzed to attempt identification of the factors causing the problem. If injectivity capacity is improved, the short-term reinjection test (isothermal or chill) will be conducted.

3.1.3.3.4 Bethel, Alaska Demonstration Project. The Bethel ATES project, under a stop work order since December 1980, was terminated on April 16, 1981. No work was done on the project during this reporting period. The project subcontractor, TRW, was directed to prepare a proposal for termination, including identification and disposition recommendations for all equipment purchased with Federal funds. Negotiations with TRW are proceeding with regard to allowable costs and fees.

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 economic, environmental, institutional, and legal issues 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 assessment and

development task primarily for alternative STES technologies and an economic analysis task. The latter task also includes the environmental, institutional, and legal assessment activities that have been terminated as a result of budget reductions but which will be reactivated as required.

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, detailed assessment of current energy costs in appropriate STES application sectors, estimation of STES market potential and penetration schedule, and economic assessment of alternative STES technologies. Environmental assessment is performed at various levels for ATES as well as promising alternative STES concepts. Legal and institutional assessments are made in conjunction with estimation of market penetration schedules.

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 Assessment

The main activity in this task has been to survey and evaluate nonaquifer STES concepts. The initial evaluation indicates that, in general, the most promising STES concepts use temperatures less than 95°C, low-cost storage media (water and rock), construction with earth, good insulation, impervious liners, and economies of large scale. The concepts exhibiting these characteristics include pond, lake, cavern,

tank, earth, rock, and ice thermal storage. Those seven concepts have received the most evaluation emphasis during the past year.

Thermal recoveries can be good; however, the earth and rock borehole concepts will achieve good thermal recovery only at lower temperatures. All of the concepts except ice utilize sensible heat and are therefore subject to declining temperatures; heat pump or booster heat (or chill) may be required to maintain efficient operation.

The best site availability occurs for tank, earth, and pond stores. To maximize the cost-effectiveness and thermal efficiency of these stores would usually require a minimum capacity of 50 homes. However, tank and pond storage may also be feasible for a less than 50-home capacity if multiple annual inventory turnovers are possible from use of solar or steady waste heat sources, or if such storage is used with heat pumps. A 1- to 50-home capacity may be possible for ice storage. When accompanied by heat pumps, earth storage may be used for one or more homes.

Annual thermal inventory turnover is an important factor when considering economic justification for a storage system. Use of heat pumps can also help the economics through increased capacity, improved coefficient of performance, and flexibility in operations.

Economics favor ice storage for small to large capacities, existing caverns for intermediate to large capacities and lake storage for large capacities. All of the concepts are capital intensive; therefore, their future implementation depends upon electricity and fuel costs escalating more rapidly than general inflation, and/or establishing a national policy to conserve energy resources.

Ice storage in certain parts of the country has good economic potential and should receive the highest priority for research funds. Existing caverns (abandoned mines and natural caverns) are also close to being economic and should be second in priority. The approximate order of priority for the remaining concepts would be ponds, lake, tanks, earth, rock borehole, and constructed caverns.

Additional research is needed to investigate lining and insulation materials, as well as construction design and methods. More accurate assessments of concept thermal, structural, cost, site, and market factors must be made. Heat pump technology requires further exploitation.

It appears that coupling solar energy with small to intermediate STES systems has good potential. On the large scale, use of waste heat from power and industrial plants has tremendous potential.

Activities in FY 1982 are directed primarily at assessing ice and existing cavern storage. Additional work on assessment of existing tankage for STES will also be performed.

3.2.3.2 Economic Assessment

The primary STES economic assessment activities during this reporting period consisted of three subtasks:

1. Develop a methodology for economic evaluation of ATES configurations.
2. Provide a detailed economic evaluation of ATES heat storage.
3. Coordinate with other STES tasks in providing preliminary economic and technical evaluation of alternative nonaquifer chill storage concepts.

Activity on the first subtask culminated in the development and documentation of the computer model AQUASTOR. An extensive manual for application of AQUASTOR, entitled User Manual for AQUASTOR: A Computer Model for Cost Analysis of Aquifer Thermal Energy Storage Coupled with District Heating or Cooling, was completed; publication is expected in April 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.

The second subtask involved economic analysis of heat storage with ATES systems. Results were issued in Aquifer Thermal Energy Storage Costs with a Seasonal Heat Source (Reilly, Brown, and Huber 1981).

Costs were estimated for point demand, residential development, and multidistrict city 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 ATES costs were:

- purchased thermal energy cost
- capital cost
- source temperature
- system size
- transmission distance
- aquifer efficiency.

Purchased thermal energy cost is the major cost component of ATES delivered energy at purchase prices as low as \$2/MBtu. The purchase price of thermal energy is magnified by price escalation and by thermal losses to the surroundings.

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 from 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 source temperature deliverable to an ATES system plays an important role in system economics. Higher storage temperatures are expected to yield poorer thermal efficiencies due to tilting of the thermocline within the aquifer and conductive losses at the "bubble" interface. Despite the poorer thermal efficiency, a higher source temperature ultimately allows a higher 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. Of course, higher temperature sources will probably command a higher purchase price.

Significant economies of scale are available for ATES systems. In fact, fairly large systems are required to achieve cost-effectiveness. For point demand systems, 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. Residential developments achieve the available economies of scale at larger system sizes due to the addition of extensive distribution piping networks.

Lengthy transmission distances can quickly result in prohibitive costs, especially for smaller (less than 5-MW) ATES systems. Extensive transmission systems can substantially increase system capital cost as well as increase the thermal loss to surroundings. Larger ATES systems are somewhat shielded from these cost effects due to large economies of scale available in piping systems.

Delivered energy costs for ATES systems are compared with the costs of hot water generated from more conventional fuel sources in Figure 3.1. Levelized costs for electrically-heated water (at 5¢/kWh and 7% annual escalation) and oil-heated water (at \$1/gal and 8% annual escalation) are compared to costs for an ATES point demand configuration with a 10-MW peak demand and 25% load factor. ATES costs are shown as a function of purchased thermal energy. Figure 3.1 shows both the potentially low delivered energy costs available from an ATES system and its strong cost dependence on the cost of purchased thermal energy.

FIGURE 3.1. Delivered Energy Cost Comparison: ATES Versus Conventional Fuel Sources

Further study is required to accurately characterize the purchased energy cost for typical industrial and waste heat sources and to characterize ATES economic status for chill storage and continuous or nonseasonal sources.

Activity is currently underway on the final subtask, and involves providing economic analysis of alternative STES systems (particularly chill storage systems) in support of Task 1 screening studies. System design and economic parameters have been identified and preliminary design/economic tradeoffs on such items as insulation (thermal barriers), piping materials and configuration, approach temperatures, and hydraulic flow regimes have been examined. A more detailed discussion of these parameters is provided in Section 6.0 of Volume II.

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 the proper power generation mix, economically viable. Compressed air energy storage systems offer several advantages over conventional systems used by utilities for meeting 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 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 savings of up to 100 million barrels of oil annually by the year 2000. The net annual oil saving could be greater in the future with growth in the demand for power. 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.

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

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, it was necessary to pursue a comprehensive technology research and development program on 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.

The CAES Technology Projects within the UES Program are charged with promoting development of 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, determine feasibility of, and develop second-generation CAES concepts that minimize the need for, or do not require, petroleum fuels for firing of the CAES plant turbines.

In response to these goals and needs of the CAES technology development, two major research and development projects were formulated. These are the Reservoir Stability Studies and Second-Generation Concepts Studies.

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 two-thirds of its major charter during this reporting period. Technical work in hard rock reservoirs and on solution-mined caverns is complete, and final stability criteria and guidelines for these two reservoir types are being issued concurrent with this report. Porous media studies have completed generic numerical and experimental work and all reservoir stability effort has now shifted to preparation for and support of operations of the Pittsfield Aquifer Field Test in Illinois. This major project activity is currently well into the construction phase; well field development is complete and instrumentation and facility construction are underway. Operations will begin during late FY 1982.

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 through detailed research and development of the concept. The specific objective of this multiphase project is to develop stability criteria and guidelines for CAES reservoirs from related technologies and the research data base. This information will allow engineers involved in CAES development to confidently propose the CAES option from a solid technical base.

4.1.2 Strategy

This project required detail 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. Therefore, four activity phases for each of these three major types of underground air storage reservoirs were initiated in 1977. These 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 corroborate numerical modeling and laboratory analyses to provide accurate estimates of reservoir response to CAES conditions; to examine geotechnical issues not amenable to evaluation with numerical modeling or laboratory testing; and to verify the existing reservoir stability criteria and amend them as necessary.

Stability criteria were formulated at the completion of Phase I. These criteria were used as the basis for prioritization of work in later phases, which was designed to confirm or refine the initial work. The end product of the research performed on each reservoir type is a final set of stability criteria.

Study on all three reservoir types has been completed through the stage of generic evaluation, including literature review and numerical and experimental study. Further geotechnical research of hard rock caverns is not planned, as it is deemed within the capability of engineering groups addressing specific applications.

Research on domal salt reservoirs for CAES is at completion with correlation between laboratory and in-mine experimental work. Field studies in salt and hard rock were precluded based on previous experience, data site-specificity, and budget restrictions. Both hard rock and salt stability criteria have been prepared and have undergone intensive internal and external review. The documents are currently being finalized and will be issued concurrent with this report.

Phases I through III of the porous media studies have been completed, with development of a numerical modeling capability and an experimental reservoir simulation capability, and a much reduced 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. It was deemed essential 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 resides 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 is responsible for design, construction, and operation of the field study. This portion of the project is currently in the construction phase.

The field study, with support from the numerical and experimental capabilities developed previously, is the only activity remaining in the Reservoir Stability Studies. It is scheduled for completion during 1983. At that time the final stability criteria and guidelines for porous media reservoirs will be issued.

4.1.3 Project Description

Summaries of all tasks within this project and their progress are presented below. The brief preliminary comments give perspective to the later project reports. More detailed summaries by project participants are presented in Volume II: Technical Summaries.

4.1.3.1 Stability Criteria Formulation

This task is the central receiving point for all information generated under the Reservoir Stability Studies Project. Data from numerical, experimental, and field studies projects are integrated

into the existing stability criteria generated during the state-of-the-art surveys, which have been completed. These documents, one each for solution-mined salt reservoirs, compensated excavated hard rock reservoirs, and porous media reservoirs, are the condensed final product of the Reservoir Stability Studies. Interim versions of the criteria were updated and revised during FY 1981. Final versions of the hard rock and salt criteria have been prepared as that work draws to a close, and are to be issued in mid-FY 1982. An interim version of the porous media criteria has been prepared but the final will not be issued until the completion of the porous media field study.

The hard rock and salt stability criteria are being issued as two reports:

- Geotechnical Factors and Guidelines for Storage of Compressed Air in Solution Mined Salt Cavities. PNL-4242. R. D. Allen, T. J. Doherty and R. L. Thoms.
- Geotechnical Issues and Guidelines for Storage of Compressed Air in Excavated Hard Rock Caverns. PNL-4180. R. D. Allen, T. J. Doherty and A. F. Fossum.

4.1.3.2 Porous Media Studies

Natural gas has been stored in porous rock formations for more than 50 years. The conditions required for natural gas storage are similar to those for CAES; however, CAES requires daily cycling, as compared to annual cycling for gas. Further, air has at least twice the viscosity of natural gas and air may require storage at elevated temperature. These differences result in a large number of unknowns regarding CAES in porous rock reservoirs.

The concerns related to CAES porous media reservoir stability have been examined through numerical and laboratory investigation and are now being addressed in the Pittsfield aquifer field test. These concerns include:

- low frequency fatigue caused by cyclic pressure, temperature, and humidity conditions on porous media and caprock

- reservoir material properties at nonambient conditions
- effects of reservoir morphology, anisotropy, and inhomogeneity
- response of wellbore casing and cementation materials
- wellbore desaturation and air-water interface movement
- the potential for geochemical reactions
- the generation and transport of fine particulate matter.

These concerns are addressed by a series of technical tasks described below.

4.1.3.2.1 Numerical Studies of Porous Rock Reservoirs. The objective of this modeling task is to characterize the fluid, thermal, and structural behavior of porous media reservoirs. Structural modeling and a series of thermal fluid models have been completed and previously reported. The series most recently included two-phase, two-dimensional isothermal models that evaluated the air-water interface of the reservoir, including capillary and gravity effects.

The numerical task efforts during this reporting period were devoted entirely to support of the Pittsfield field test. Predictive modeling of test performance has been provided to aid in test planning and to assist in design and specification preparation. Problem-solving modeling and technical support has been provided to establish cycle times with respect to water coning, to indicate laboratory testing requirements, and to support instrumentation selection and design. Modeling capabilities exercised have included one- and two-dimensional, thermohydraulic, and two-phase modeling of phase change processes and movement of the air-water interface. A final series of predictions has been formulated based on the facility design and the detailed geologic data base and will precede operation of the test.

4.1.3.2.2 Laboratory Studies of Porous Media. Laboratory studies in porous media have sought to identify and evaluate the effects of air injection on typical reservoir, caprock, and well materials. Dry air injection, the effect of moisture and moist air, and the geochemical and

thermomechanical response of porous media were investigated for varying temperature ranges anticipated for conventional and advanced CAES reservoirs. Facilities to do these sorts of tests simultaneously to determine total environmental response to CAES conditions did not exist. Therefore, the experimental program was structured to evaluate separately, under as close a simulation as possible, the responses of reservoir materials to temperature, ventilation, anticipated geochemical environment, and expected cyclic structural loadings. These separate effects studies were essentially completed at the end of FY 1981. Simultaneously, the need for full environmental response of the media resulted in the planning, design, and construction of the Porous Media Flow Facility. This facility has completed acceptance tests, and has been the primary experimental activity in this period. Its test plan is in support of the aquifer field test at Pittsfield and it will continue to be dedicated to that purpose until field test completion.

The facility, with a cell designed for standard core, has the capability to induce triaxial stresses with confining (radial) loads up to 10,000 psi (70 MPa) and axial loads up to 80,000 psi, fluid pore pressures up to 1500 psi (10 MPa), temperature up to 550°F (300°C), pore fluid relative humidities from 0 to 100%, and flow rates of up to 1.53 in.³/sec (25 ml/sec). Sample size is 2-1/8 in. (5.4 cm) in diameter and 4 in. (10 cm) long. A deformation jacket uses displacement transducers (LVDT) to measure each sample's axial and circumferential displacements. Additional instrumentation monitors and controls inlet temperature, pressure, mass flow rate, and humidity. These parameters are also measured and recorded at the outlet. The instrumentation and control system are connected to a data acquisition and system control computer to ensure test quality and data tracking.

Dehydration and permeability alteration experiments on Pittsfield core in prototypic CAES environments have been carried out. These experiments indicate good stability for the St. Peter sandstone from Pittsfield, but a decrease in permeability is noticeable at higher temperatures under confinement.

4.1.3.2.3 Pittsfield Aquifer Field Test. The goal of the field studies is to validate the numerical and laboratory methods and tools developed within the program by in-situ experiment. The objective is to design, construct and field-test a reduced-scale air reservoir system in a prototypic geologic medium. Two phases of this project--Phase I, Field Test Planning and Site Screening, and Phase II, Site Acquisition and Exploration--were completed previously. During this reporting period all activity has occurred in Phase III, Site Development. This phase includes leasing, permitting, designing, and constructing surface facilities, and developing the well field.

Early in this reporting period, leasing activities were completed and a construction permit for an injection well was obtained from the Illinois Environmental Protection Agency. This allowed major mobilization of the design, construction, and operations contractor, PB-KBB, Inc. of Houston, Texas to the Pittsfield site. Their initial task was to drill the injection withdrawal well and then subsequently develop the monitoring well field. These activities were performed expeditiously and were essentially complete at the end of FY81. The contractor then proceeded with surface equipment and facility design, data acquisition system selection, and subsurface instrumentation system design. This process was hampered somewhat by budget uncertainty and some contract uncertainty. The design process was also very strongly controlled by total project cost and value engineering.

As of the end of this reporting period, design is complete and final approvals are being sought for major procurement items. The compression system will be a lease package to minimize cash flow and maintenance. Other surface equipment will be handled through two purchases for mechanical and architectural requirements. Instrumentation is being provided by PB-KBB and some specialty subcontractors. Detail project planning administered by PNL has been instituted during construction. Air injection is scheduled for September 1982.

4.1.3.3 Salt Cavern Studies

Storage of hydrocarbons in salt dome caverns has been practiced in the U.S. Gulf Coast region for more than 25 years. However, this kind of storage has involved mainly liquids and relatively slowly varying pressure loadings. Salt caverns used in CAES plants will undergo daily cycling of pressure, temperature, and humidity. Possible deleterious effects due to cyclic loadings must be identified and controlled so that the CAES caverns remain stable and functional over 30- to 50-year periods. Some of the concerns related to CAES salt cavern stability and addressed by numerical and laboratory studies include:

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

Program activities in domal salt reservoirs have consisted of numerical and experimental studies. The laboratory studies included in-mine correlation of experimental data and testing of core from the Huntorf facility, and continued to completion during this reporting period. The numerical studies were completed during early FY81 and terminated prior to this reporting period. Also, due to funding limitations and the fact that there is operational experience in the Zechstein domal salt from the operation of the Huntorf CAES facility, it was decided that the project would forego field study activities in compressed air energy storage.

4.1.3.3.1 Experimental Studies of Domal Rock Salt. Robert Thoms and Louisiana State University (LSU) have been involved in numerical, geophysical, and laboratory studies of salt domes and domal rock salt for nearly as long as scientific and engineering principles have been

applied to their utilization. Experience ranging from petroleum storage to solution and mechanical mining to nuclear waste isolation evaluations provide a solid technical basis for extension of Gulf Coast salt dome usage to the unique situation of CAES.

This year's experimental program at LSU continued a project initiated in 1978. The work included both laboratory and in-mine evaluations of salt response. These activities, completed in FY 1982, provided the basis for finalization of the stability criteria and guidelines outlined in Section 4.1.3.1.

Laboratory studies included Brazilian, uniaxial, and triaxial testing over a range of temperatures. Alteration of permeability resulting from load cycling was evaluated. In addition, acoustic emission techniques were investigated for monitoring cavern response to cyclic loading. Salt materials from Gulf Coast domes, bedded deposits, and Huntorf were examined. The general conclusion is that Gulf Coast domal salts are more uniform, more predictable, and apparently more competent than the Huntorf Zechstein salts, which have adequately housed the first CAES cavern since 1978.

An in-mine borehole study at the Cote Blanche salt dome to evaluate in-situ salt response to pressurization and cycling was also completed during this reporting period. Diametral deformations and acoustic emissions were monitored during testing. Correlation of these in-situ tests with the laboratory studies provided solid validation of simple and straightforward laboratory techniques. In addition, in-mine activities included permeability evaluations to determine the effect of core drilling on core permeability versus in-situ permeability. Upon completion of correlation evaluation, hydrofrac experiments were also conducted to determine the maximum limit of the ability of in-situ salt to contain pressure. The general conclusion is that, within reasonable temperature and rock mechanical limitations, domal rock salt is an excellent candidate for CAES development and will be predictable and monitorable.

4.1.3.4 Hard Rock Studies

Hard rock caverns were first used for compressed air storage in 1916, in Norway. Since then there have been many instances of oil, gas, air storage, and accumulator experience in excavated hard rock chambers. In general, the performance of these caverns has been satisfactory. However, a number of questions arise when hard rock caverns are used for CAES plants.

Because of the large difference in volume requirements between compensated and uncompensated caverns, current economics dictate that CAES plants utilize water-compensated hard rock caverns. As a result, pressure cycling will be minimal and the studies of this project addressed only hard rock caverns that involve daily cycling of only temperature and cavern wall wetting.

Some of the concerns related to hard rock CAES cavern stability addressed by numerical and laboratory studies included:

- cavern geometry and size
- effects of temperature loading rates
- low-frequency fatigue caused by cyclic temperature and wetting conditions
- air penetration of hard rock mass
- hard rock properties at nonambient conditions
- residual strength of hard rock after failure
- weathering (geochemistry) of hard rocks at CAES conditions
- excavation techniques.

RE/SPEC, Inc., a highly qualified geotechnical research and engineering firm located in Rapid City, South Dakota, was the lead contractor in hard rock cavern studies. RE/SPEC, Inc. originally completed the state-of-the-art survey and issued preliminary stability criteria for hard rock CAES. Just prior to this reporting period they completed all generic numerical and experimental studies, along with associated methodology development. This included a confirmatory numerical evaluation of the Acres American design for hard rock CAES

caverns. Revision and updating of the stability criteria were the only activities related to hard rock studies performed during this period. The final hard rock stability criteria document was completed and submitted for publication.

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 employ a three-step strategy. In Step 1, new proposed concepts are subjected to a preliminary technical and economic screening to determine which have the best potential for economic and technical feasibility. In Step 2, conceptual designs and detailed cost estimates are 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 Step 3. In Step 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 Step 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 Step 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

Activities in the Second-Generation Concepts Studies are grouped into three principal tasks: 1) Second Generation CAES Concepts Support and Assessment, 2) Design Studies, and 3) Component Evaluation and Development. Major emphasis was placed on the Component Evaluation and Development task. Because adiabatic CAES was identified in FY 1981 as one of the most attractive concepts for early commercialization, much of this emphasis was specifically directed toward this concept.

4.2.3.1 Task 1. Second-Generation Concepts Support and Assessment

The overall objective of this task is to support and integrate the results of all Second-Generation Concepts Studies. These results will be used to develop recommendations to DOE on which concepts should be considered for further engineering and economic study and/or development. This task currently has only one subtask, Advanced Concepts Screening and Evaluation. The objective of this subtask is to collect, screen and evaluate information on new concepts and those concepts currently under study and to develop plans and recommendations regarding future program activities pertaining to these concepts.

New concepts and ideas will be evaluated and screened for potential engineering and economic competitiveness with other concepts currently under consideration. The concepts to be considered include both those received as unsolicited proposals and those received from program

participants and developed during the progress of funded CAES activities. Concepts showing potential promise will be recommended for additional, more detailed, engineering and economic attention.

Data on all projects related to CAES systems will be collected, compiled and evaluated. This information will be used to define the current economic and technical status of second-generation systems and will be used as a basis for plans and recommendations on future program activities.

4.2.3.2 Task 2. Design Studies

The overall objective of this task is to determine the technical and economic feasibility of second-generation CAES concepts identified in Task 1. Currently this task contains only one major subtask, Design Code Documentation. The objective of this subtask is to develop and describe analytic and computer methods employed to evaluate second-generation CAES cycle thermodynamics.

During FY 1979, a computer code, CYCLOPS MOD1, was developed to thermodynamically design and optimize various advanced CAES cycles. This code was subsequently used extensively in the Task 1 screening and evaluation of candidate CAES concepts. In this subtask, a document will be prepared fully describing this code and its application to CAES cycle analysis. This report will contain examples of the thermodynamic analysis of each type of second-generation concept considered in this program. Document publication is scheduled for near the end of FY 1982.

4.2.3.3 Task 3. Component Evaluation and Development

This task contains three subtasks that deal with the evaluation and development of second-generation CAES component technology. They are 1) Thermal/Mechanical Evaluation of Materials for Adiabatic CAES Thermal Energy Storage Beds; 2) Thermal/Chemical Evaluation of Materials for Adiabatic CAES Thermal Energy Storage Beds; and 3) Thermal Energy Storage Evaluation and Analysis. Activities in this task have been supported by both DOE and the Electric Power Research Institute.

The objective of subtask 1 is to evaluate durability of thermal energy storage (TES) materials during thermal cycling. One of the key

issues in the viability of adiabatic CAES is the ability of the selected TES material to survive many years or decades of daily thermal cycling without comminution. Such comminution will not only require the expensive premature replacement of TES beds, but will also cause turbine damage from damage by elutriated particulates. Comminution is caused by "ratcheting" induced by thermal cycling. In FY 1981, FluidDyne Engineering Corporation modified an existing DOE facility to simulate the ratcheting phenomenon in adiabatic CAES thermal energy storage beds. In this facility, beds of TES material can be thermal-cycled between 100 and 900°F at atmospheric pressure while subject to maximum static loads imposed by the bed overburden. Initially, iron oxide pellets, Denstone spheres, crushed granite, and cast iron balls were evaluated under separate DOE and EPRI programs. The experimental evaluation of these materials started during the last quarter of FY 1981 and was completed in early FY 1982.

The objective of subtask 2 is to evaluate the candidate TES materials for thermal/chemical attack that would limit service life or make them more susceptible to fracture from thermal ratcheting. The thermal/chemical attack of candidate TES materials is being investigated under static conditions in DOE-owned autoclaves at PNL. In these tests, the two most thermally aggressive conditions present in a CAES TES are being considered:

- 1215 psi, 290°F air contaminated with SO₂ and with the sample, under static stress, wetted by water to simulate the condensation of atmospheric moisture in the high pressure TES of an adiabatic CAES plant
- 1215 psi, 900°F to simulate approximately the maximum thermal condition present in a hybrid CAES plant.

In FY 1981, the evaluation of iron oxide pellets and crushed granite was completed. By the end of FY 1982, the evaluation of Denstone and cast iron balls will be completed under separate EPRI funding. A preliminary evaluation of those materials is given earlier for completeness.

The objective of subtask 3 is to integrate and evaluate the results of contributing TES materials and performance testing subtasks and to determine the effects of these results on TES system designs, CAES performance and power costs. The results of the experimental subtasks 1 and 2 will be collected, integrated and evaluated. This information will be analyzed to determine the influence of the observed performance on TES system lifetime, CAES system performance and power costs. Recommendations will be developed on which material or materials are most suitable for TES application and should be considered in extended lifetime testing. A report documenting the work performed to date and the results of that work and recommendations on further study will be prepared and issued by the end of FY 1982.

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