**Seasonal Thermal Energy
Storage
Program Progress Report
April 1979 - December 1979**

J. E. Minor

March 1980

**Prepared for the
U.S. Department of Energy
Office of Advanced Conservation
Technologies
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
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EXECUTIVE SUMMARY

The Seasonal Thermal Energy Storage (STES) Program, managed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy, Division of Energy Storage Systems (STOR), is one element of the Thermal Energy Storage Program.

The objective of the STES Program is to demonstrate the economic storage and retrieval of thermal energy on a seasonal basis, using heat or cold available from waste sources or other sources during a surplus period to reduce peak period demand, reduce electric utilities peaking problems, and contribute to the establishment of favorable economics for district heating and cooling systems for commercialization of the technology. The initial thrust of the STES Program is toward utilization of ground-water systems (aquifers) for thermal energy storage. The program has the further objective of evaluating other methods of seasonal storage, both from existing literature and by following current work in other countries.

The STES Program is divided into an Aquifer Thermal Energy Storage (ATES) Demonstration Task and a parallel Technical Support Task. The purpose of the ATES Demonstration Task is to demonstrate the commercialization potential of aquifer thermal energy storage technology using an integrated system approach to multiple demonstration projects. The parallel Technical Support Task is designed to provide support to the overall STES Program. The initial activities of this task are primarily directed toward support of the ATES Demonstration Task. The long-range task goals include investigation and evaluation of other seasonal thermal energy storage concepts which may be considered for future emphasis. It is the intent of the Technical Support Task to reduce technological and institutional barriers to the development of energy storage systems prior to significant investment in demonstration or commercial facilities.

Management of the STES Program was assigned to PNL in FY-1979 (April 1979). A considerable effort was involved during this initial reporting period in establishing a STES program office and staffing to develop the technical and administrative activities required to meet program objectives and provide for management of these activities. Program plans were completed, and the Work

Breakdown Structure, budget, schedules, and reporting/review procedures were developed. Responsibility was assumed for existing, ongoing STES contracts and projects.

Under the ATES Demonstration Task, a Program Opportunity Notice (PON) was prepared to solicit interest for participation in ATES Demonstration Projects. At the direction of the Division of Energy Storage Systems (STOR), the PON was revised into a Request for Proposal (RFP) for development of ATES Demonstration Projects. The RFP was issued on September 7, 1979. Closing date for receipt of proposals was December 17, 1979. The Source Evaluation Official was appointed, the Source Evaluation Panel was constituted and the Technical Advisory and Business Evaluation Committees were appointed.

Under the Technical Support Task, existing contracts were reviewed, and follow-on proposals were requested from several contractors. Work was initiated on STES social, economic, and environmental assessments, and on the following technical areas: Thermal Energy Sources/Uses, Technology Compendia, and Advanced Analysis Methodologies. Work started on geohydrologic characterization at two possible field research pilot plant sites (Leading Edge Test Facilities - LETFs).

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1.0 INTRODUCTION

Storage of thermal energy is expected, in the near term, to provide a significant contribution toward achieving the goals of the National Energy Plan. This contribution will encourage a shift from use of insufficient or costly fuels such as oil and natural gas to more abundant or available energy sources such as coal, solar, and nuclear power. Thermal energy storage, when incorporated in energy supply and conservation systems, permits efficient and economical use of intermittent energy sources such as solar or off-peak electrical power. Thermal storage also may allow use of waste heat from industrial and utility sources.

The Seasonal Thermal Energy Storage (STES) Program, managed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy, Division of Energy Storage (STOR), is one element of the Thermal Energy Storage Program.

1.1 OBJECTIVES

The objective of the STES Program is to demonstrate the economic storage and retrieval of energy on a seasonal basis, using heat or cold available from waste sources or other sources during a surplus period to reduce peak period demand, reduce electric utilities peaking problems, and contribute to the establishment of favorable economics for district heating and cooling systems for commercialization of the technology. Aquifers, ponds, earth, and lakes have potential for seasonal storage. The initial thrust of the STES Program is toward utilization of ground-water systems (aquifers) for thermal energy storage.

The program has the further objective of evaluating other methods of seasonal storage, both from existing literature and by following current work in other countries. New program thrusts may be recommended as a result of these studies.

1.2 JUSTIFICATION

During the last decade, the storage of thermal energy in aquifers has received considerable attention. The motivations for storing large quantities

of thermal energy on a long-term basis have been numerous, including: a) the need to store solar heat that is collected in the summer for use in the winter months; b) the cost effectiveness of utilizing heat now wasted in electrical generation plants; c) the need to profitably use industrial waste heat; and d) the need to more economically provide summer cooling for buildings. Seasonal aquifer storage should contribute significantly to satisfy the above needs. 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 there are potentially suitable aquifers distributed throughout the United States. Recent studies and small-scale field experiments have reported energy recovery rates above 70 percent for seasonal storage. The U.S. Department of Energy predicts that, by the year 2000, seasonal aquifer storage could replace or conserve up to 350 million barrels of oil per year. However, successful demonstration of large-scale aquifer thermal energy storage has not yet been attempted and the concept's economic feasibility and institutional acceptability have yet to be established.

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. For heating, energy sources ranging from 50°C to over 250°C are available. Potential energy uses include space heating on an individual or district scale, heating for industrial or institutional plants and heat for processing/manufacturing.

1.3 ORGANIZATION AND PROGRAM MANAGEMENT

a) Organization

The management of the Seasonal Thermal Energy Storage (STES) Program includes the technical and administrative activities required to meet the program objectives and to provide for the management of these activities so that program objectives are met on schedule and within budget. The program is

managed by the STES Program Office reporting to the Director of Projects at the Battelle, Pacific Northwest Laboratory (PNL). Activities performed within the Program Office include:

- Developing STES Program Plans
- Establishing Work Breakdown Structures
- Providing administrative and technical management for all aspects of the program including the technical tasks performed within PNL
- Developing costs and schedules
- Allocating and controlling program funds
- Establishing and implementing reporting and review procedures and schedules
- Interfacing with STOR Division, DOE-HQ, and DOE-RL
- Maintaining contact and liaison with seasonal energy storage activities of the International Energy Agency covered by implementing agreements with the United States.

The Organization Structure is displayed in Figure 1. The Work Breakdown Structure is displayed in Figure 2. The Summary Network is displayed in Figure 3.

FIGURE 1. Organization Chart: Seasonal Thermal Energy Storage (STES) Program

FIGURE 2. Work Breakdown Structure: Seasonal Thermal Energy Storage (STES) Program

FIGURE 3. Summary Network Seasonal Thermal Energy Storage (STES) Program

2.0 CURRENT PROGRAM PLANS TO MEET OBJECTIVES

The STES Program is divided into an Aquifer Thermal Energy Storage (ATES) Demonstration Task and a parallel Technical Support Task. Seasonal storage in aquifers will be evaluated in the ATES Demonstration Task, beginning with the conceptual design of site-specific systems and operation of a smaller number of demonstration projects. The basic function of such an energy storage system is to accept, store, and discharge energy in accordance with availability and demand. Thus, the aquifer storage system provides a buffer between the time-dependent energy inputs and thermal loads or outputs. An aquifer thermal energy storage system is an integrated system consisting of an energy source, thermal transport, a storage aquifer, and a user application. Energy may be supplied for storage from a solar collector, heat pump, industrial heat source, a cogeneration power plant, or other sources. Conversely, chilled water may be supplied and stored for future use in air conditioning.

In response to a Request for Proposal (RFP), prospective contractors submitted proposals for ATES Demonstration Project site specific conceptual designs and aquifer characterization (Phase I). These proposals will be evaluated and contracts will be negotiated for implementation of the selected projects. The contractors will develop conceptual designs for integrated systems containing energy source, thermal transport, aquifer storage, and user subsystems. Aquifers will be characterized by geologic exploration and analysis of existing data. Functional design criteria will be developed for each subsystem and for the integrated systems. From the functional design criteria and the aquifer characterization reports, proposals will be evaluated for continued work on a smaller number of projects in Phase II. Phase II is the detailed design, construction, startup, and operation of ATES Demonstration Projects.

The parallel Technical Support Task is designed to provide support to the overall STES Program. The initial activities of this task are primarily directed toward support of the ATES Demonstration Task. These activities will include social, economic, environmental assessment, and technical research and development studies to provide a sound technical base for the demonstration projects. The long-range task goals include investigation and evaluation of

other seasonal thermal energy storage concepts which may be considered for future emphasis. It is the intent of the Technical Support Task to reduce technological barriers to the development of energy storage systems prior to the significant investment in demonstration or commercial facilities. Through research and testing on novel storage concepts, aquifer characteristics, system designs, and system operating criteria, this task can assist developers in obtaining a successful energy storage facility. This task is designed to not only provide technological information on energy storage systems, but also to assist in identifying systems which are economically sound, environmentally acceptable, and within existing legal and institutional constraints.

A major function under the Technical Support Task is development of one or more Leading Edge Test Facilities (LETFs). The LETF is a site or sites established to test heating and/or chilling technologies for energy storage in aquifers. This facility is the forerunner of demonstration projects for aquifer thermal energy storage. As a forerunner, the facility will assist in the development of energy storage technology through research and development activities. This facility will have the capability of performing full-scale tests on both heating and chill energy storage technologies. More than one LETF may be required. The aquifer requirements (confined versus unconfined), heat sources, and end uses of low-temperature versus high-temperature storage concepts may necessitate the use of more than one leading edge unit.

The Seasonal Thermal Energy Storage (STES) Program will involve industry, other Department of Energy (DOE) laboratories, and universities.

3.0 SUMMARY OF ACCOMPLISHMENTS

Management of the STES Program was assigned to PNL in FY-1979 (April 1979). A Program Office was established and staffed to develop the technical and administrative activities required to meet program objectives and provide for management of these activities.

3.1 TASK I - STES PROGRAM MANAGEMENT

STES Program plans were completed, and the Work Breakdown Structure, budget, schedules, and reporting/review procedures were developed. Responsibility was assumed for existing, ongoing STES contracts and projects.

3.2 TASK II - AQUIFER THERMAL ENERGY STORAGE (ATES) DEMONSTRATION PROGRAM

A Program Opportunity Notice (PON) was prepared to solicit interest for participation in ATES Demonstration Projects. At the direction of the Division of Energy Storage Systems (STOR), the PON was revised into a Request for Proposal (RFP) for development of ATES Demonstration Projects. The RFP was issued on September 7, 1979. Closing date for receipt of proposals was December 17, 1979. The Source Evaluation Official was appointed, the Source Evaluation Panel was constituted and the Technical Advisory and Business Evaluation Committees were appointed. Table I shows the Task II Milestones for FY-1979, and the first quarter of FY-1980. All milestones were met as scheduled except for the Proposer's Conference which was delayed one month due to the change from a PON to a RFP.

3.3 TASK III - TECHNICAL SUPPORT PROGRAM

Existing contracts were reviewed, and follow-on proposals were requested from several contractors. Work was initiated on STES social, economic, and environmental assessments, and on the following technical areas: Thermal Energy Sources/Uses, Technology Compendia, and Advanced Analysis Methodologies. Work started on geohydrologic characterization at two possible field research pilot plant sites (Leading Edge Test Facilities - LETFs). Table II shows the Task III Milestones for FY-1979 and the first quarter of FY-1980. All milestones were met as scheduled.

TABLE I. ATEs Program Milestones for FY-1979 and
First Quarter FY-1980

<u>Milestone</u>	<u>Scheduled Due Date</u>	<u>Projected Completion Date</u>	<u>Actual Completion Date</u>
Issue Program Opportunity Notice (PON) Draft	5-79		5-79
Issue Draft Announcement of PON Release to Commerce Business Daily (CBD)	6-79		6-79
Issue Announcement of RFP Release to CBD	8-79		8-79
Issue Requests for Proposal (RFP)	9-79		9-79
Conduct Proposer's Conference	9-79	10-79	10-79
Receive Conceptual Design Proposals	12-79		12-79

TABLE II. Technical Support Program Milestones for FY-1979
and First Quarter FY-1980

<u>Milestone</u>	<u>Scheduled Due Date</u>	<u>Projected Completion Date</u>	<u>Actual Completion Date</u>
Complete Contract Negotiations with Fugro, Inc. (Bellingham geohydrology investigation)	7-79		7-79
Complete FY-1980 Program Work Plan	8-79		8-79
Complete Review of ORNL On-going Contracts	9-79		9-79
Complete Preliminary Field Testing (Bellingham and Richland)	9-79		9-79
Complete Preliminary Recommendation on Proposed Bellingham LETF Sites	9-79		9-79
Complete Review of Alternative LETF Sites	9-79		9-79
Select Site for Leading Edge Test Facility	12-79		12-79
Define Program Plan for Assessment of ATES Economics	12-79		12-79

4.0 PROGRESS ON SEASONAL THERMAL ENERGY STORAGE PROGRAM PROJECTS

Detailed discussions are given in this section on the individual tasks and subtasks which comprised the STES Program during this reporting period. Topics discussed are: 1) Project Objectives, 2) Project Tasks, 3) Technical Progress, and Technical Problems. The topics are organized according to the Program Breakdown Structure.

4.1 AQUIFER THERMAL ENERGY STORAGE DEMONSTRATION PROGRAM (ATES)

Objective

The objective of the ATES Demonstration Program is to demonstrate the commercialization potential of aquifer thermal energy storage technology using an integrated system approach to multiple demonstration projects. This program is intended to stimulate the interest of industry by demonstrating the feasibility of utilizing an aquifer for thermal energy storage, thereby reducing crude oil consumption, minimizing thermal pollution, and significantly reducing utility capital investments required to account for peak power requirements.

Tasks

Phase I - Conceptual Design: The purpose of this work is to develop conceptual designs for integrated aquifer thermal energy storage demonstration systems.

Phase II - Final Design, Construction and Operation: The purpose of this work is to implement ATES demonstration projects selected from the Phase I conceptual designs.

Technical Progress

Phase I - Contractors will develop conceptual designs for integrated systems containing energy source, thermal transport, aquifer storage and user subsystem which will demonstrate the feasibility of using such a system on a seasonal basis in a heating and/or cooling application. This conceptual design constitutes Phase I of a two-phase program. In a Request for Proposal (RFP) published in September 1979, proposals were solicited for the Phase I work. A Proposer's Conference was held in October 1979, and subsequently,

proposals were received for Phase I projects on or before December 17, 1979. PNL is performing technical evaluation, business evaluation, and assessment of other factors as applicable to each proposal. The Source Selection Official will arrange the proposals in priority order for contract negotiation. Following a presentation of this priority to DOE-HQ in February 1980, PNL will initiate negotiation of contracts within this priority. Contracts will be awarded by the end of June 1980 and conceptual design will commence during or before July 1980. It is estimated that with the FY-1981 budget allocation, up to four contracts can be awarded. Aquifers will be characterized by geologic exploration and analysis of data. Functional design criteria will be developed for each subsystem and for the integrated systems. Phase I work will be completed by the end of FY-1982. From the functional design criteria and the aquifer characterization reports, conceptual designs will be developed and proposals submitted for continued work in Phase II. Phase II is the detailed design, construction, startup, and operation of Aquifer Thermal Energy Storage System Demonstrations.

Phase II - No work was done on Phase II during the reporting period, since Phase II will not begin until early FY-1983. From the conceptual designs and proposals for Phase II received from Subtask 2, contractors will be chosen for implementation of demonstration projects. Detailed design, construction, startup, and operation will be performed on a cost-sharing basis between the government and the contractors. Phase II work will be completed by the end of FY-1985.

Technical Problems

No significant problems were encountered in the ATES Demonstration Program during the reporting period.

4.2 TECHNICAL SUPPORT PROGRAM

The Technical Support Program is designed to provide technical support to the Seasonal Thermal Energy Storage Program which has the overall objective of commercially demonstrating the applicability of seasonal thermal energy storage. Task goals are designed to provide a sound technical base for development of the technologies being evaluated. This includes conducting technology

review to identify data and methodology needs and designing appropriate technology development programs to fill these gaps. Also, the experience gained by the program participants will be utilized to transfer the technology in order to accelerate the development of STES concepts and promote commercialization. Demonstration programs which are a key to the development and commercialization of STES concepts will require technical support in monitoring and directing contractor activities to assure that the maximum benefit is gained from the projects. The ATES Demonstration Program is being initiated in FY-1980 and will be the primary focus of technical support activities in the near term. Evaluations of other STES concepts will be continuing for future emphasis. To accomplish these goals, the following program breakdown has been developed:

- Task 1 - Social Assessment
- Task 2 - Economic Assessment
- Task 3 - Environmental Assessment
- Task 4 - Technical
- Task 5 - Non-Aquifer Seasonal Thermal Energy Storage

4.2.1 Social Assessment

Pacific Northwest Laboratory

Objectives

The principal objective of this task is to examine the legal and institutional issues which are likely to affect ATES development. The legal/institutional environment and any laws/regulations that may constrain ATES development are to be identified and analyzed. A secondary objective is to monitor the compliance of all demonstration contractors with legal and permit requirements.

Tasks

Task 1 - Examine the legal and regulatory requirements which will affect ATES.

Task 2 - Monitor the compliance of LETF contractors with applicable state and Federal permit requirements.

Technical Progress

Regulatory requirements applicable to ATES were identified. The principal Federal legislation applicable to the concept is the Safe Drinking Water Act of 1974. Regulations under this Safe Drinking Water Act applicable to ATES have not yet been promulgated. Legal/institutional issues applicable to storing and protecting the energy resource in an aquifer were identified and analysis was begun. Compliance of contractors doing preliminary work on the proposed Leading Edge Test Facility (LETf) with applicable permit requirements was monitored.

Technical Problems

No problems were evident in the social assessment work during the reporting period.

4.2.2 Economic Assessment

General Electric-TEMPO and Pacific Northwest Laboratory

Objectives

The role of the economic assessment subtask is to determine the economics of various seasonal thermal energy storage concepts and applications under a range of economic and technical conditions as directed by program staff, to assist in the evaluation of proposals and in the subsequent monitoring of external contracts, and to provide additional support as requested.

Tasks

Task 1 - Develop a methodology for evaluation of Seasonal thermal energy storage concepts.

Task 2 - Coordinate development of the Mission Statement for the Aquifer Thermal Energy Storage (ATES) Program.

Task 3 - Provide analytical support to the ATES Demonstration Program.

Task 4 - Initiate economic evaluation of chilled energy storage in aquifers.

Task 5 - Review outside analyses of STES concepts with regard to the economic assumptions and methodologies employed, and the conclusions reached.

Task 6 - Negotiate with an outside contractor for a technical/economic study of an ATES/STES concept.

Technical Progress

Task 1 - Development of a Methodology for Evaluation of STES Concepts.

Because of the emphasis placed on aquifer storage under the STES Program, a major effort was mounted to develop a computer code for analysis of the economics of ATES systems. An existing model (GEOCITY) was modified to meet the needs of the ATES Program. GEOCITY is a district heating model which uses geothermal energy as the heat source. It simulates (designs) transmission and district heating systems, and calculates costs based upon a suite of economic, technical, and environmental input data. It was modified to develop a new model (AQUASTOR) which 1) can be used for analysis of ATES cooling as well as heating systems, and 2) employs aquifer storage as the energy supply submodel. AQUASTOR was only operational for limited testing by the end of the year, and simulation cases were being run to verify the modifications.

Task 2 - Development of the Mission Statement for the ATES Program. DOE has requested that PNL develop a "mission statement" for the ATES Program which provides an in-depth rationale for the extensive ATES development program. Coordination of the document was assigned to the economics support task. An outline was generated and sent to DOE for review in October; it was subsequently approved with two minor comments. By December 1979, a first draft had been written, and was undergoing in-house review. The report is to be finalized for presentation to DOE in early March 1980.

Task 3 - Provide Analytical Support to the ATES Demonstration Program. A set of economic criteria for use in evaluation of demonstration project proposals was submitted to the Program Office in June for inclusion in the ATES Demonstration Program PON.

Task 4 - Economic Analysis of Chill Storage in Aquifers. An evaluation of the economics of chilled water storage in aquifers in the initial STES application will be analyzed using AQUASTOR. During development of the computer code, background work was done on the analysis, which mainly consisted of data gathering activities (cooling loads and meteorologic data) and literature review. Some of the initial AQUASTOR test runs were made in the cooling

test mode, and resulted in identification of additional required modifications to the code. It is anticipated that an in-depth evaluation of chill storage will be performed in FY-1980. An abstract was submitted in response to a call for papers from the 15th Intersociety Energy Conversion Engineering Conference, to be held in Seattle, Washington in August of 1980. The title of the paper is "The Economics of Aquifer Storage of Chilled Water for Air Conditioning".

Task 5 - Review of STES Analyses. Two outside economic analyses of Aquifer Thermal Energy Storage projects were identified by the program office staff for review. The first, "A Preliminary Economic Analysis of Aquifer Winter-Chill Storage at the John F. Kennedy Airport" showed that the proposed system was infeasible. The results cannot be applied to the chilled water storage concept in general, however, for a number of reasons, including the requirement that all construction would have to be done at a busy airport in the nation's highest cost labor market. The second study, a Carrier Corporation investigation of aquifer cooling of Phoenix also proved infeasible. Again, however, the results should not be applied to the general concept, since the investigation was carried out for a region of marginal winter chill.

Task 6 - Contract for a Technical/Economic Study of ATES/STES. The one type of information that seemed to be missing after an extensive STES literature review was a detailed manual on the design and evaluation of an aquifer thermal energy storage system. After several meetings with technical personnel within the program office, it was felt that such a document could be of great value to a number of ATES participants, including participants in the demonstration program. A review of potential contributors to such a manual indicated that there was only one entity with the breadth of experience to perform such a task: GE-TEMPO. A sole source RFP was subsequently issued to TEMPO for "A Methodology for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage Systems". Negotiations were proceeding at the end of December and it is anticipated that the contract will be finalized in the second quarter of FY-1980.

Technical Problems

During FY-1980, funding was not available to complete development of the AQUASTOR computer code, resulting in two problem areas: 1) The code is now

subject to a number of limitations, including a limited treatment of escalation and inflation, a crude and time-invariant simulation of aquifer efficiency, and an inefficient method of matching supply and demand. 2) The code is presently in-place on the Cyber computer, which is scheduled for replacement at the end of the fiscal year. Without additional funding to convert the program to the new Univac system, AQUASTOR will be nonfunctional after September 1980.

4.2.3 Environmental Assessment

Oak Ridge National Laboratory and Pacific Northwest Laboratory

Objective

To provide assistance in identifying, acquiring, and assessing environmentally-related information and preparing environmental documentation as required to support the Seasonal Thermal Energy Storage (STES) Program.

Tasks

The Environmental Assessment work has three tasks: 1) Environmental Documentation, 2) Environmental Research Assistance, and 3) Environmental Advisory Assistance.

Task 1 - Environmental Documentation. This is the primary support area of this work. Its purpose is to develop the environmental documentation requirements (Federal and state) in compliance with the National Environmental Policy Act (NEPA). Initial emphasis of this subtask is on aquifer thermal energy storage.

Task 2 - Environmental Research Assistance. This task helps identify and prioritize environmentally-related problem areas and information voids and assists in acquiring (during the research, testing, and demonstration phases) environmental data required to support STES environmental documentation and eventual commercialization.

Task 3 - Environmental Advisory Assistance. This task provides assistance to the STES Program on all environmental matters associated with demonstrating the feasibility of STES concepts. This includes such activities as responding to environmental inquiries, assisting the STES Program Office in evaluating the environmental components of demonstration proposals and assisting in the preparation of program-level reports and publications.

Technical Progress

Task 1 - This task has received major emphasis during the past year with activities being divided between programmatic (generic) documentation and site-specific environmental documentation.

Major programmatic environmental documentation activities to date have been directed toward coordinating and clarifying the environmental documentation needs relative to Aquifer Thermal Energy Storage (ATES) that must be fulfilled by the Division of Energy Storage Systems (STOR) to be in compliance with recently enacted NEPA Council on Environmental Quality (CEQ) regulations. This activity resulted in the decision to prepare a comprehensive programmatic Environmental Assessment (EA) for ATES formatted to be utilized, if necessary, as an Environmental Impact Statement (EIS) to ensure that uncertainties in environmental documentation requirements do not delay planned PNL ATES experimental and demonstration activities.

In response to a STOR request, this task prepared the environmental documentation plan for ATES and drafted appropriate correspondence requesting concurrence of the plan from the Office of Environmental Compliance and Overview, NEPA Affairs Division, and the Office of General Counsel (OGC).

This task was also responsible for reviewing the preliminary draft of the ATES EA prepared by the Oak Ridge National Laboratory (ORNL) during FY-1979. A written assessment was prepared in October 1979 containing the recommendation to redraft and reformat the EA. Task effort since that time has been directed toward obtaining appropriate support services from ORNL personnel to redraft the ATES EA during FY-1980 and to get agreement upon the appropriate contents and environmental priorities.

Site-specific environmental documentation activities during the past year included:

- Preparation of an internal report summarizing the state and local environmental restrictions and regulatory requirements and documentation needs associated with establishing ATES exploration well(s) near Bellingham, Washington (May 1979).

- Preparation of a report entitled "ATES Environmental Laws and Regulations" to support considerations involving the development of one or more low-temperature ATES test facilities. Federal laws and regulations applicable to ATES are described in the first section; applicable state laws and regulation for potential sites in each of six states are presented in the second section (June 1979).
- Preparation of a brief report describing environmental regulations and permits for operating a cooling tower in conjunction with a low-temperature test facility at Hanford (July 1979).
- Preparation of a preliminary environmental monitoring plan for the Leading Edge Test Facility (LETf) (November 1979).

Task 2 - Environmental Investigation Assistance. To date, effort in this task area has been minimal due to the emphasis being given to fulfilling the environmental documentation requirements of Task 1.

Task 3 - Environmental Advisory Assistance. Activities in this task area are unscheduled for the most part and are determined by the needs of the STES Program Office. Major inputs in this task area during the last year included:

- Preparation of an abstract for a paper to be presented at the Intersociety Energy Conversion Engineering Conference entitled "Environmental Considerations Associated with the Development of Underground Energy Storage Systems (December 1979).
- Review of the Draft Mini-Environmental Development Plan for ATES prepared by Hittman Associates, Inc. as requested by STOR. The response stresses the need for a significant revision of the report and requested a PNL review prior to finalization and distribution (December 1979).
- Preparation of environmental inputs to program plan and mission statements.

Technical Problems

Several potential problem areas have been identified that may hinder meeting task objectives within time and budget allocations.

- The fairly recent emergence of new and more rigorous NEPA/CEQ regulations (July 1979) makes it difficult to prepare an environmental document acceptable to everyone at this time. Accordingly, this task is stressing open communication and interaction among all interested technical and environmental offices in scoping and preparing required STES/ATES environmental documents in order to minimize anticipated finalization delays.
- Several DOE environmental documents are inaccurately describing the environmental concerns of planned ATES activities. It is imperative that all future reports be consistent or ATES commercialization may be delayed, even if effective technology is demonstrated.

4.2.4 Technical

The technical studies are designed to provide a sound base for development and evaluation of seasonal thermal energy storage concepts.

The following activities have been identified as key elements for support of the STES Program:

- A. Thermal Energy Sources/Uses
- B. Compendia of Existing Technology
- C. Leading Edge Test Facilities
- D. Advanced Analysis Methodologies
 - (1) Mathematical Modeling
 - (2) Laboratory Analysis
 - (3) Field Analysis

A. Thermal Energy Sources/Uses

Pacific Northwest Laboratory

Objectives

The objective of this work is to determine the primary sources of heat (or chill) that would be suitable for STES systems and determine typical temperature and thermal storage capacity requirements for use of such systems.

Tasks

Task 1 - Compile information needed to determine what STES applications have the greatest potential for energy savings to ensure that the program emphasizes technology support for those applications.

Task 2 - Evaluate the information to establish relative priority (based on potential energy savings) of STES Program with respect to other DOE research programs.

Task 3 - Characterize potential heat sources and energy users for STES.

Task 4 - Determine applications with highest potential energy savings and best supply/demand match.

Technical Progress

Work was initiated on Task 1 with a summary literature review of STES uses and sources, and a report was drafted on this subject. Work will continue on Tasks 1, 2, 3 and 4 during FY-1980.

Technical Problems

No problems were encountered in this work area during this reporting period.

B. Compendia of Existing Technology

Lawrence Berkeley Laboratory, Oregon State University, and Pacific Northwest Laboratory

Objective

The objective of the Compendia task is to assemble and transmit STES-related information to other program components. This goal is being met by establishing a library of STES-related information, by producing selected

literature reviews and summary papers, and by publication and distribution of the quarterly ATES Newsletter. Compendia efforts should assist the future development of STES technology and should provide guidelines for STES demonstration facilities.

Tasks

Task 1 - Library Establishment, Maintenance, and Development. This task involves all efforts necessary to provide a useful library of STES-related literature. These efforts include identifying and procuring new literature, indexing library articles, distributing updated bibliographies and subject listings, maintaining library operation, and computerizing the library.

Task 2 - Literature Reviews and Summary Papers. This task will result in the production of various papers covering important topics pertinent to STES. These papers are intended to support other STES Program efforts by providing information on topics that are of major concern to the program.

Task 3 - ATES Newsletter Publication. This task involves compiling, editing, publishing and distributing a quarterly ATES Newsletter.

Technical Progress

Task 1 - Compendia staff members have assembled a useful STES library. The library now contains approximately 1200 articles. Although the library contains articles pertaining to many types of seasonal thermal energy storage, the main emphasis is on the storage of thermal energy in aquifers. The library contains a wide range of key references on topics related to thermal energy storage.

During the past year, efforts were made to identify and procure STES-related articles. Customized searches were run on computerized data bases, including DIALOG and RECON. Reference lists were obtained from the Compressed Air Energy Storage and the Geothermal Program libraries at PNL. Several national laboratories, including LBL and ORNL, also provided reference lists. These reference lists and data base searches were used to initiate the procurement of STES-related articles. PNL staff members working on the STES Program also helped identify articles for the library.

Library articles have been indexed according to author, title, and subject. A card file was established for each index and the card files are kept in the library. Periodically, the author index and subject index have been typed and printed for distribution. These listings have helped spread knowledge about the library and its contents.

New articles are still being procured for the library, although the rate of procurement has tapered off recently. The library now contains a good sampling of the literature, so procurement is more selective.

Possibilities for library computerization are currently being researched. Library computerization will result in the establishment of an STES data base. This data base will ultimately contain an abstract, key words, and bibliographic information for each library article. Customized literature searches will be possible. The STES data base will probably be entered into the Integrated Information System. This system was established by Lawrence Livermore Laboratory (LLL) for the Division of Energy Storage systems of the U.S. Department of Energy.

Task 2 - Subjects have been identified for three papers. These three papers will be published as PNL reports in FY-1980. One of the papers will describe the geohydrologic considerations necessary for proper ATES development. It will provide guidelines for detailed site characterization but will not set specific operating criteria for an integrated aquifer thermal energy storage facility (source/user/aquifer). The second paper will contain information on aquifer plugging and/or consolidation, and the third paper will summarize work done on regional aquifer assessments during FY-1980. Work has begun on these three papers.

Task 3 - During this report period, Lawrence Berkeley Laboratory (LBL) continued publication of the ATES Newsletter. This newsletter is published quarterly. It contains brief reports of the goals, present status, and major results of ATES projects around the world. This newsletter has generated considerable response from its readers and has become an important means of information transmittal.

Subcontract Activities

A contract was placed with Oregon State University (OSU). Under the contract, OSU will survey large scale operations of ground-water-source heat pumps in the Portland area. The survey of large scale heat pump operations is now in progress. OSU has almost finished selecting the sites that will be studied, and soon they will begin the documentation of the sites. Data analysis will be done following documentation.

A request for proposal (RFP) will be issued in January. The subject to be studied under the contract is recharge experience in air conditioning applications. The objective of this work will be to assess ground-water reinjection experience in air conditioning applications. The approach will be to survey the operational experience of a representative cross section of such facilities in specified regions of the United States. Documentation of each site will consist of three parts: 1) well system design, 2) operational performance histories, and 3) a preliminary analysis of the causes of any reinjection problems. An overall assessment of regional reinjection experience in air conditioning applications will be required.

Another request for proposal will be issued in February. The work will involve regional aquifer assessments. The goal of this study is to qualitatively describe the ATES potential of major aquifers throughout the United States. This objective will be met by a two-step process: 1) assembling available information on the hydrogeology of major aquifers or aquifer systems throughout the U.S., and 2) evaluating each aquifer individually for ATES potential.

The Statement of Work for another RFP is currently being written. The subcontracted work will involve future library maintenance and development. Future library operation will be subcontracted to make the most effective use of Compendia task funds and staff.

Technical Problems

Task 1 - Library operation has been more time consuming than anticipated. This problem can be solved by placing a subcontract for library operation. Compendia staff will then be able to devote more time to fulfilling other task goals.

Tasks 2 and 3 - No major problems have been encountered.

C. Leading Edge Test Facilities

Sites are being selected and developed to obtain needed engineering design data and to conduct supporting research for the STES Program. Research will include implementation of test facilities to lead the demonstration programs (Leading Edge Test Facilities) in development of both unconfined aquifer storage systems and confined aquifer storage systems. Data collected at these test sites will provide required calibration and verification of advanced analysis methodologies being developed for site characterization and assessment. The LETF is designed to provide definition of the variables anticipated in aquifer thermal energy projects. The field operations will develop and test the procedures necessary to successfully demonstrate ATES. Information developed will be made available immediately to the ATES demonstration contractors. LETF activities will continue through FY-1985 and will work in conjunction with the Demonstration Program.

LETF and related activities have been carried out during the reporting period by: 1) Auburn University, 2) Texas A&M University, 3) Tennessee Valley Authority (TVA), 4) Fugro, Inc., and 5) Pacific Northwest Laboratory (PNL).

1. Leading Edge Test Facility - Auburn University

Objective

To test and evaluate the storage of thermally-enhanced ground water at a site near Mobile, Alabama.

Tasks

Task 1 - Develop a well field to inject and monitor the storage of thermally-enhanced ground water.

Task 2 - Inject ground water at a temperature of 55⁰C, store, and recover the energy.

Task 3 - Monitor the movement of the thermal plume and supply data for advanced computer analysis.

Technical Progress

Task 1, 2, and 3 have been completed under agreement with ORNL. With transfer of the STES Program to PNL, the working contract with Auburn University has been shifted. Two cycles of heat storage have been completed, resulting in recovery efficiencies approximately 70%. These two cycles did not, however, utilize a true doublet system. A contract is currently being negotiated between Auburn University and PNL to demonstrate and test a true doublet system. The problems experienced during the first two cycles are expected to be minimized using two wells completed in the same aquifer. Experimental plans call for injection of 55°C, 90°C, and 125°C water. These tests will serve to verify computer projections as to energy recovery efficiencies at elevated temperatures.

2. Leading Edge Test Facility - Texas A&M University

Objective

The objective of this project was to evaluate cold water aquifer storage on the Texas A&M test site.

Tasks

Task 1 - Develop and experimentally verify design criteria for operating a cooling pond in the 22 to 4°C temperature range.

Task 2 - Collect field data from a cold water aquifer injection experiment for use in verifying numerical models of aquifer thermal energy storage systems.

Task 3 - Evaluate any well plugging problems caused by injecting a highly aerated water into an aquifer.

Technical Progress

A cold water aquifer storage experiment was conducted at Texas A&M University during January, February and March of 1979. Parameters for designing cooling ponds to chill water from 22 to 4°C were developed. In addition, data on the movement of chilled water through a highly permeable, shallow,

unconfined aquifer were obtained. This study provided a least-cost method for obtaining data on chilled water movement in aquifers to verify numerical models and to evaluate problems with chilled water storage. Regional flow in the aquifer and natural recharge to the aquifer during the second wettest year in history reduced the thermal energy recovery from an expected 40% to 20%. No aquifer plugging problems were experienced during injection and recovery operations. The cooling pond operation was an exceptional success.

Technical Problems

As a demonstration of ATEs technology, the first cooling cycle at Texas A&M might be considered marginal because no useful cold water was recovered. However, as an experiment the project was very encouraging. Every aspect of the system operation equaled or exceeded expectations. There were no signs of well plugging during the injection cycle. The cooling pond proved to be an exceptionally efficient and low-cost method of producing cold water; and with the knowledge gained, a further increase in the cooling pond capacity is anticipated.

The simple sand filter worked perfectly, and in conjunction with the oxidation in the spray pond, completely removed the iron from the water. No plugging of the well was indicated during this initial injection cycle. The observation wells gave a complete hydraulic and thermal history of the aquifer during the experiment.

The poor thermal recovery was due to regional flow. This had been expected to a degree, but it was made worse by the second wettest winter and spring on record which raised the water table 1.7 m. During the next few months, this injection cycle will be simulated using computer models of the aquifer system.

3. Tennessee Valley Authority

Objective

The objective of this work was to make a technical feasibility study of low temperature thermal energy storage (LTES).

Tasks

Task 1 - Identify and evaluate significant technical parameters.

Task 2 - Identify and evaluate system components.

Task 3 - Identify parameter or components requiring further development work.

Technical Progress

An extensive review of the published literature in geology and geohydrology of the TVA service area was made which indicated that only the aquifers within the coastal plain area (western Tennessee and northern Mississippi) were consistently suitable for use for LTTEs thermal storage.

On the basis of their geologic and geohydrologic characteristics, the following four confined aquifers in unconsolidated sediments were considered potentially suitable to store the heated and/or chilled water:

- Memphis Aquifer (500-foot sand)
- Wilcox Group (lower Wilcox aquifer)
- Ripley Formation (McNairy sand)
- Coffee Sand.

Although these aquifers seem to possess necessary characteristics for an efficient and effective storage, several questions associated with water chemistry, increase in temperature and pressure, and ground-water flow need to be answered.

The TVA service area, in particular the coastal plain region, was surveyed to determine the presence of potential producers and users of low temperature thermal energy. To this end, the source of heat for input to LTTEs is defined as the waste heat from industrial facilities and the collection of thermal energy from solar arrays. Solar arrays can provide a viable heat input in locations where waste heat is not available.

The work performed during this survey indicated that there exists within the desired geographical area a large quantity of waste heat of suitable quality. These waste heat sources are located in clusters, near metropolitan areas, in relatively close proximity to potential users.

Aquifer LTTEs systems can also be used for the storage of chilled water for space cooling and/or light process cooling. The ultimate source for the cooling of this chilled water has been determined to be the atmosphere during the winter months through the use of cooling towers. Prior to cooling in the tower, precooling of the aquifer water, using cold surface waters as the source, is technically feasible.

The uses of low temperature thermal energy are concluded to exist primarily in the space heating/cooling of high population density residential areas and industrial, institutional, and commercial facilities. The work performed during the survey identified various users of low temperature thermal energy and specified their geographical location. User energy consumption for space heating/cooling was also estimated.

Because the survey of producers and users resulted in the determination that they are located in clusters, in relatively close proximity to one another, there exists an excellent opportunity to continue with the LTTEs development program.

Potential generic systems for the utilization of low temperature thermal energy were identified. Because of the wide range of design possibilities that depend largely on site-specific considerations, the work emphasized major design guidelines for the development of utilization schemes. For simplicity and convenience, the treatment of utilization systems was divided into four subsystems that maintain relatively independent functions, namely recovery, storage, transmission, and distribution.

The principal methods of reclaiming thermal energy from industrial and power plant waste heat, solar energy, and environmental energy sources make use of heat exchangers. Heat exchangers are available in a variety of design configurations to meet a wide range of system applications. For anticipated operating conditions of low temperature thermal energy utilization systems, off-the-shelf exchangers capable of meeting design requirements should be readily available. In situations where the quality of available thermal energy is insufficient for user needs, heat pumps can be used onsite to provide the needed temperature increase up to 121°C (250°F). The use of heat pumps extends considerably the potential for waste heat utilization.

The transmission distance between the points of supply and use is one of the most important parameters in the thermal energy utilization system. Transmission distance governs the acceptable supply temperature and the economics of waste heat utilization. The limits of heat transmission line design are set by constraints of economic feasibility, rather than by available technology. Practical transmission distance now ranges between 8 and 41 km (5 to 25 miles) for low temperature systems.

Several storage well configurations are possible, but the doublet storage well concept provides the most system flexibility for aquifer thermal energy storage. This doublet concept offers easy changeover between the charging and discharging modes. The use of indigenous ground water as the fluid medium also minimizes geotechnical problems.

The following conclusions were made by TVA which are preliminary as the feasibility study is not complete at this time.

- (1) The technology required to implement all phases of the energy utilization system is fully developed and commercially available and no foreseeable technical barriers to implementation are apparent. The major constraint on system feasibility is attributed to economic practicality and not to technical limitations.
- (2) The preferred transport medium for low temperature thermal energy is water, especially for long distance transmission.
- (3) The storage well doublet is the most flexible and practical storage system concept among several alternatives.

The necessary work for the determination of the technical feasibility of LTTES has been performed. Surface LTTES components require no development for implementation into LTTES; state-of-the-art equipment technology is adequate. Present knowledge of well drilling and the present technology of well pumps are sufficient for the requirements of LTTES.

The major development work required is the determination of the long-term effects on the aquifer and adjacent ground waters from the implementation of an LTTES plant.

4. Leading Edge Test Facility - Fugro, Inc. and Washington State University

Objective

To explore and evaluate a deep, saline, confined aquifer in the Bellingham, Washington area for use as a high temperature LETF site.

Tasks

Task 1 - Assemble Available Data. Obtain available data from all sources on the presence of confined, saline aquifers in the lower Nooksack River Basin. Optimize site selection within guidelines (proximity to identified heat source, minimization of environmental problems such as river crossings).

Task 2 - Aquifer Exploration. Conduct a test drilling program to ascertain the presence of the target aquifer. Meet all state and Federal guidelines for these activities.

Task 3 - Aquifer Evaluation. Upon defining the aquifer in Task 2, conduct appropriate hydrologic tests to evaluate the aquifer for LETF use.

Technical Progress

Based on available data from the USGS and the Washington State Departments of Ecology and Natural Resources, the optimum sites were selected within the imposed guidelines. Necessary permits and accesses were obtained and a drilling contract let. The first drill site on the property of the Thermal Reduction Company was drilled to a total depth of 505 feet without encountering a suitable water bearing horizon, and the hole was grouted back to the surface and abandoned. A second hole was initiated at Hovander County Park. Several shallow aquifer zones were penetrated, and the hole was drilled to a total depth of 650 feet. Bedrock was not encountered and the target aquifer (Esperance sand) was not sound.

Technical Problems

Several problems occurred during performance of this task. The prime difficulty was in the drilling technology. Use of state-of-the-art water well drilling techniques appears to be adequate for deep drilling for LETF or ATES purposes. However, care must be taken in the use and selection of drilling muds and other technology. The loss of a bit in the Hovander County Park well forced abandonment of the hole.

This effort will be terminated upon proper abandonment of the Hovander County Park well, as no satisfactory aquifer was found at the Bellingham site.

5. Leading Edge Test Facility - Pacific Northwest Laboratory

Objective

The objective of this program is to develop ATES technology in unconfined aquifers; by drilling, testing, and characterizing a shallow aquifer system typical of those prevalent throughout the United States.

Tasks

Task 1 - Assemble Available Data. Obtain available data on the unconfined aquifers in Central Washington. Optimize site selection process to assure selection of best available site.

Task 2 - Characterize Unconfined Aquifer. Select an appropriate site overlying an unconfined aquifer, design drilling program, and contract with driller. Conduct appropriate tests to characterize the aquifer at the selected site.

Task 3 - Design Surface Facility. Utilizing data from Task 2, design an appropriate test facility for the projected flow rates. Develop the design to the point that construction would be possible within a minimal timeframe.

Technical Progress

A potential LETF site was selected at Richland, Washington. The target aquifer was the Pasco gravel which occurs throughout the area. Drilling commenced in September, 1979 at two locations. The preferred site was chosen and a pumping test initiated. The aquifer shows a diversity of characteristics within short distances, making the site suitable for testing methods for flow modification. The site also has the potential for qualifying unconfined aquifers for ATES. The ability to use unconfined aquifers for thermal energy storage would greatly extend utility of the technology, since a large number of ground-water systems are under unconfined (non-artesian) conditions. A conceptual design for both high and low temperature LETFs has been completed, and a Test Requirements and Plan developed for LETF activities.

Technical Problems

No major technical problems have been encountered as yet in this task. Minor problems related to drilling of the test wells slowed progress in that area. Limitations on the capacity of available test pumps combined with the productivity of the aquifer minimized the usefulness of the pump test that was conducted. Funding has not been identified for continuation of these studies.

D. Advanced Analysis Methodologies

Work on advanced analysis methodologies was conducted in three areas:

- 1) Numerical Simulation and Predictive Modeling, 2) Laboratory Analysis, and
- 3) Field Analysis.

1. Numerical Simulation and Predictive Modeling

Lawrence Berkeley Laboratories, Washington State University, and Pacific Northwest Laboratory

Objectives

The objectives of this work are to develop and utilize a technology capable of predicting the transport and retrieval of a thermal energy resource within the ground-water environment; to conduct exact or asymptotic analyses to demonstrate the sound mathematical/numerical character of the technology; and to demonstrate the model's simulative ability through the simulation of experiments where data have been collected in situ.

Tasks

Task 1 - Development of Technology. Review those methodologies which are available for the solution of thermal transport and potentially more complex problems including chemistry in the ground-water environment. The coupled nature of such a fluid, energy, solute transport model requires a careful examination of the numerical methodology's conservation properties.

Task 2 - Exact or Asymptotic Analyses. Identify those analyses which may be used in an effort to verify one or two-dimensional versions of the proposed methodologies. Characterize the performance of the numerical model via relationships between problem parameters such as length and time scales, the dispersivity coefficients, and hydraulic conductivity.

Task 3 - Simulative Ability. Demonstrate both the ability of the numerical simulation to match in situ measurements and the methodology employed in making it work (i.e., problem setup). Data sufficient for both calibration and verification will be necessary for this task.

Technical Progress

The problem of predicting fluid flow in a thermally-influenced ground-water environment is best described as a three-dimensional, dynamic situation. However, in the simplified setting of homogeneous media and negligible ambient ground-water gradient, a two-dimensional axisymmetric domain will provide a more economical analysis. The modeling methodology selected for development should be capable of these problem specific requirements.

A review of current modeling capabilities reveals that both finite difference and finite element methodologies are applicable to the STES problem. However, considerable emphasis lies in the finite difference camp. Notable among the models available are the Intercomp model and Lawrence Berkeley Laboratory's CCC (compaction, conduction, convection) model. The former employs standard finite difference algorithms while the latter uses integrated finite difference techniques. It is generally acknowledged that finite element techniques exhibit a superiority to finite difference algorithms when considering the fit of arbitrary domain geometries. The trade-off may lie in the local characterization of the finite difference error as opposed to the finite element method's global (whole domain) representation. Of importance in reaching a decision on modeling methodology has been the experience of Battelle's PNL staff in the development and application of both modeling methods. Greatly influencing our decision was our perception of a need for a user-oriented, easily visualized technology, which could be readily extended to three-dimensional analyses. Also of consideration was the desire to provide an alternative to finite difference technology because of the flexibility for fitting elements to boundary and internal conditions. The decision has been to employ a finite element methodology through modification of an existing finite element code.

A previously developed model of ground-water flow for multi-dimensional systems has been employed as the core to the much broader model required for the technical support of STES. Energy and solute transport mechanisms have been added to the fluid (mass) transport model. The three partial differential equations are then solved in a cyclical uncoupled solution scheme which employs the most current estimates of the dependent variable values in the evaluation of nonlinear contributions and forcing functions. Both density and viscosity are functions of the local pressure, temperature, and/or solute concentration. For efficient simulation of field problems with complex geometry, the model has been structured to execute in stages. The staged structure affords one the opportunity to thoroughly check the geometric structure of the domain, the physical parameters of the problem, and aspects of the solution sequence prior to making the commitment of a complete run.

Exact or asymptotic analyses which will lend credence to the algorithm selected and developed have been identified from the literature. Specifically, the Intercomp and CCC literature includes those analyses desired. Aside from standard solutions to line source/sink problems, these reports also identify approximate or asymptotic solutions.

The initial development of an interactive automatic mesh generation capability has been completed. As a first step toward a general two and three-dimensional methodology, a two-dimensional areal field has been discretized. The mesh generator presently assumes a doublet axis collinear with the ambient ground-water movement. This assumption allows the discretization of a symmetric half plane. Extension of this mesh generation capability to include an arbitrary ambient flow will involve including the mirror image of the present half plane result. Further development to include the vertical dimension will employ a well log technique. Single well applications or those having non-interfering doublets may make use of an axisymmetric analysis giving rise to a vertical plane. Automatic discretization of this domain is currently under development. Code modification is being made to handle free-boundary conditions (unconfined aquifers).

Data sufficient for the calibration and verification of the model has been located. It is presently being acquired from the Lawrence Berkeley Laboratory.

Calibration and verification through the use of this Auburn University (Mobile, Alabama, test site) data will provide not only a check with in situ measurements but will also provide an excellent comparison with predictions made by competitive models which are currently available.

Technical Problems

A problem area in the development of any finite element model is the quantification of local (point) conservation properties of the algorithm. While guaranteeing a global flow/energy conservation, the methodology does not assure such conservation as with the model point or nodal output. The current effort toward supplying technical support for STES requires a good, if not excellent, methodology to achieve local conservation. Recent communication with others in finite element modeling has introduced a new interpretation of the local conservation property. As a result, current efforts are focused upon the development of conservation monitoring schemes and an investigation of this new interpretation of mass conservation.

2. Laboratory Analysis - Terra Tek, Inc. and Pacific Northwest Laboratory Objectives

The objectives of this task are: 1) conduct fundamental laboratory investigations concerning the physical and chemical stability of porous materials subjected to Seasonal Thermal Energy Storage (STES) conditions, 2) develop a suite of tests designed to provide direct support to site specific field projects, and 3) provide laboratory facilities required to generate data for design, operation, and maintenance criteria development and environmental report preparation.

Tasks

Task 1 - Physical and Chemical Stability of Aquifer Materials. This task is focused on identifying the potential for, and the magnitude and cause(s) of temperature-induced changes in porosity, permeability, compressibility, thermal diffusivity, and water quality. Supporting experiments are conducted under laboratory simulated field conditions, e.g. temperature, pore pressure, confining pressure, and flow rate.

Task 2 - Site Specific Field Support. The purpose of this task is to identify sediment and ground-water sample acquisition and preservation procedures. The second goal is to develop a suite of laboratory tests necessary to generate data in support of site specific design and operation criteria development and environmental report preparation.

Task 3 - Laboratory Support Capabilities Development. The main thrust of this task is the development of a laboratory support facility totally dedicated to underground energy storage requirements and specifically designed to permit careful simulation of aquifer temperature and stress conditions. Emphasis is on development of an elevated temperature and pressure flow system capable of simultaneous stress-strain, porosity, permeability, viscosity, and water quality measurements.

Technical Progress

Task 1 - Physical and Chemical Stability of Aquifer Materials. Efforts to date have centered on the available literature, new theoretical developments, experimental strategy, and identification and fabrication of test facilities. A topical report has been drafted covering the apparent degradation of permeability with moderate increases in fluid temperature. A variety of researchers have observed a 50 to 100% decrease in silica sand and sandstone permeability to liquid water when the temperature is increased from 20⁰C to less than 200⁰C (Figure 4). Similar changes are not observed when dry nitrogen, mineral oil, or dry alcohol is used as the working fluid. Unfortunately, sample deformation and fluid viscosity changes at temperature have not been monitored in previous studies. Equipment is currently being constructed to permit simultaneous measurement of fluid temperatures, pressures, viscosities, and chemistry as well as the stress and deformation of the porous material.

Three potential causes for the observed permeability changes are being systematically explored: 1) thermo-mechanical alteration (thermal expansion, thermal fragmentation), 2) physiochemical weakening of the silica dominated sediments (hydrolytic weakening, pressure solution), and 3) anomalous fluid viscosities due to temperature induced silica leaching. To test for thermo-mechanical alterations, experiments are to be conducted with either chemically

**UNCONSOLIDATED OTTAWA SILICA SAND
DISTILLED H₂O**

FIGURE 4. Example Permeability Versus Temperature Curve (Muhammadu 1975)

inert fluids (dry argon, nitrogen) or inert solids (methylated sand). To test for physicochemical weakening, silica sand and quartzose sandstones in combination with distilled deaerated water or 10^{-6} N ferric chloride solutions are to be used. Curves for viscosity as a function of temperature and silica concentration are being generated to replace the distilled water viscosity curves currently utilized. A schematic of the equipment and a summary of the basic experimental matrix are shown in Figures 5 and 6. A plot of a hypothetical viscosity curve required to explain the observed permeability reductions for Massillon sandstones is shown in Figure 7. Resolving the relative contributions of viscosity and chemical weakening at various temperatures should have a significant impact on predictions of long term stability (permeability, subsidence) associated with STES reservoirs. Such information should also be applicable to the Compressed Air Energy Storage (CAES) technology where hot, humid air may be the working fluid.

Progress is also being made on acquiring information on chemical reaction rates at temperature for some primary constituents in ground water. For example, Figures 8 and 9 contain data for silica at various temperatures. Data are also being collected on thermal conductivity, thermal expansion, and specific heat capacities. The fact that thermal expansion values in sandstones tend to be a factor of two to three greater in a direction perpendicular to the bedding compared to that parallel to the bedding may significantly affect incremental stresses induced by radial temperature gradients near the wells. Thermal conductivity for most porous materials appears to decrease slightly with increasing temperature.

Task 2 - Site Specific Field Support. Progress to date has been limited to preliminary development of field acquisition and handling procedures for sediment cores and ground-water specimens, and to identification of a suite of laboratory tests recommended for any given field site. The tests include, but are not limited to, the following:

- mineralogy and ground-water chemistry
- particle and pore size distributions

PERMEABILITY AND STRESS-STRAIN APPARATUS

FIGURE 5. Simplified Schematic of the Experimental Stress-Strain and Fluid Flow Measurement Equipment

SIMULTANEOUS FLUID-FLOW/STRESS-STRAIN EXPERIMENTS

POTENTIAL MECHANISMS	DEPENDENT MEASURABLES	PERMEABILITY	POROSITY	VISCOSITY	DISSOLVED SILICA	SUSPENDED SOLIDS (SIEVE ANALYSIS)	MICROCRACKING	CEMENTATION	REVERSIBILITY	WORKING FLUIDS
THERMAL-MECHANICAL CHANGES ALTERATIONS <ul style="list-style-type: none">• THERMAL EXPANSION• THERMAL FRAGMENTATION		*	*	*			*	*	*	DRY GAS
PHYSICO-CHEMICAL ALTERATIONS OF THE SOLID MATRIX <ul style="list-style-type: none">• STRESS CORROSION CRACKING• HYDROLYTIC WEAKENING OF ASPERITIES• PRESSURE SOLUTION		*	*	*		*	*	*	*	WATER
FLUID PROPERTY CHANGES <ul style="list-style-type: none">• BULK VISCOSITY• COLLOIDAL FIXATION		*	*	*	*	*			*	WATER

FIGURE 6. Basic Test Matrix (* indicates an anticipated observation if the associated mechanism is active)

MASSILLON SANDSTONE NO. 4 VISCOSITY VS TEMPERATURE

FIGURE 7. Viscosity Versus Temperature for Distilled Water and a Hypothetical Curve for Silica-Laden Water Necessary to Eliminate the Observed Permeability Degradation in Massillon Sandstone

- clay swelling and particle dispersion potential
- particulate plugging potential
- simultaneous stress-strain, elevated temperature, fluid flow, and water quality alteration tests
- casing corrosion tests.

Preliminary procedures for each test have been developed and will be part of a topical report scheduled for June 1980.

Task 3 - Laboratory Support Capabilities Development. The primary component of the support facility is a brine flow loop capable of elevated and cyclical temperatures and pressures and simultaneous monitoring of stress-strain behavior, fluid flow behavior, and water quality changes. Design specifications have been issued for competitive bidding. A vendor should be

FIGURE 8. Time Required to Achieve 90% Silica Saturation in a Quartz-Water System (Rimstidt 1979)

FIGURE 9. Silica Concentration Versus Time for Quartz Sand and Water at 110 C

selected by March 15, with fabrication to begin shortly thereafter. In the interim, experiments will be conducted at Terra Tek when suitable equipment is available.

Additional facilities are available to measure thermophysical properties, particulate plugging potential, clay swelling and dispersion potential, casing corrosion, particle and pore size distribution, mineralogy, and ground-water chemistry.

Technical Problems

The only technical problems encountered to date are: 1) no data are available on the effect of silica on ground-water viscosities and therefore such curves must be developed, and 2) efforts to make a sand or sandstone core chemically inert to water via mineral sputtering have not been totally successful. If the methylation treatment (chlorotrimethylsilane) proves unstable at elevated temperature, it may be necessary to rely on alumina beads. The alpha alumina is essentially inert and the surface area and grain size can be made

to match the silica sand, but the thermal, elastic, and strength properties are different.

3. Field Analysis - Pacific Northwest Laboratory

During this report period no work was funded under the Field Analysis task.

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