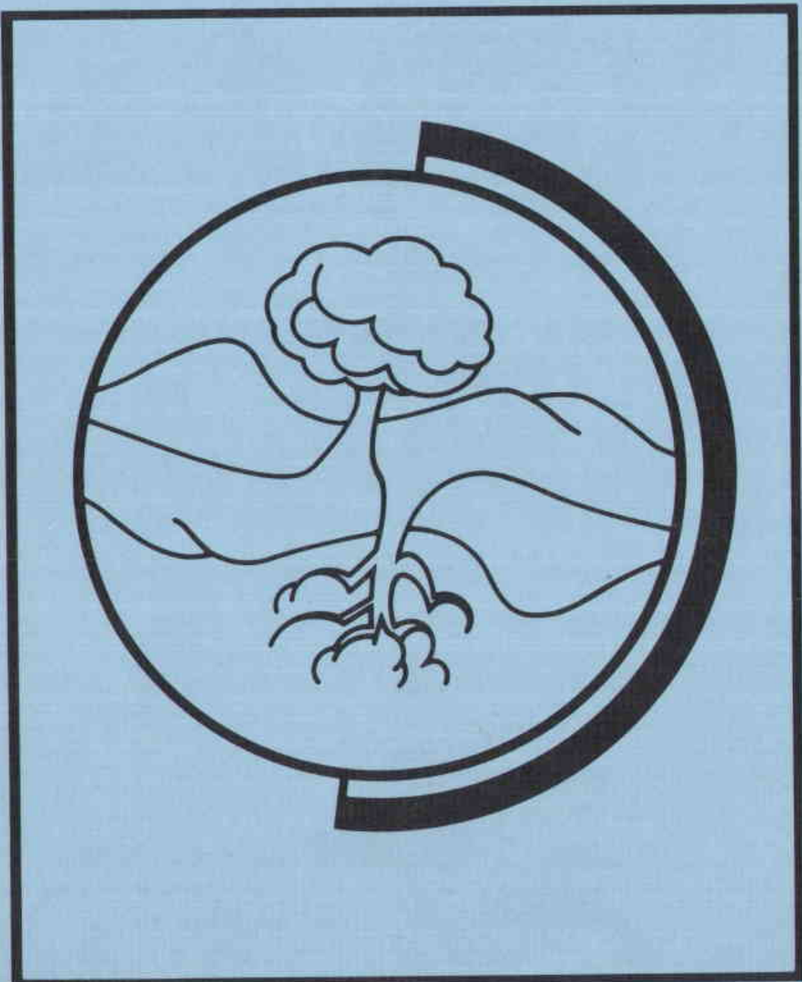
PNL-3746

UC-94e

Seasonal Thermal Energy Storage Program

Progress Report
January 1980—December 1980



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

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

Battelle

PNL-3746

PNL-3746
UC-94e

SEASONAL THERMAL ENERGY STORAGE PROGRAM PROGRESS REPORT JANUARY 1980 - DECEMBER 1980

J. E. Minor

May 1981

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

Pacific Northwest Laboratory
Richland, Washington 99352

ACKNOWLEDGMENTS

The author wishes to acknowledge the essential contributions made to the Seasonal Thermal Energy Storage Program by the following individuals:

PACIFIC NORTHWEST LABORATORY

D. E. Blahnik
R. N. Coy
J. R. Eliason
J. D. Etchemendy
K. Fox
D. L. Gale
P. L. Hendrickson
R. K. Johnson
C. T. Kincaid
K. M. Krupka
D. A. Myers
J. R. Raymond
R. W. Reilly
L. S. Prater
J. A. Stottlemyre
G. E. Wukelic

WASHINGTON STATE UNIVERSITY

V. Ichimura

AUBURN UNVIERSITY

F. J. Molz
A. D. Parr

LAWRENCE BERKELEY LABORATORY

C. F. Tsang

OAK RIDGE NATIONAL LABORATORY

D. W. Lee

OREGON STATE UNIVERSITY

G. M. Reisted
S. W. Childs

MIDWEST RESEARCH INSTITUTE

C. H. Lee
G. Casper

TERRA TEK

C. H. Cooley

LAWRENCE LIVERMORE LABORATORY

V. E. Hampel

CENTURY WEST ENGINEERING

D. B. Stoffel
S. K. Gupta

U.S. GEOLOGICAL SURVEY (MINNESOTA DIST.)

J. Guswa

MINNESOTA GEOLOGICAL SURVEY

M. Walton

UNIVERSITY OF MINNESOTA

W. Soderberg
J. O'Gara

DAMES & MOORE

L. Stern
W. Skinner

TRW, INC.

J. Cherne
W. Murphy

NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AGENCY

G. Walmet

CONTENTS

ACKNOWLEDGMENTS iii
EXECUTIVE SUMMARY xiii
1.0 INTRODUCTION 1.1
1.1 OBJECTIVES 1.1
1.2 JUSTIFICATION 1.2
1.3 ORGANIZATION AND PROGRAM MANAGEMENT 1.2
2.0 CURRENT PROGRAM PLANS TO MEET OBJECTIVES 2.1
3.0 SUMMARY OF ACCOMPLISHMENTS 3.1
3.1 TASK I - STES PROGRAM MANAGEMENT 3.1
3.2 TASK II - AQUIFER THERMAL ENERGY STORAGE (ATES) DEMONSTRATION PROGRAM 3.1
3.3 TASK III - SEASONAL STORAGE TECHNOLOGY (SST) PROGRAM . . . 3.6
4.0 PROGRESS ON THE SEASONAL THERMAL ENERGY STORAGE PROGRAM PROJECTS 4.1
4.1 AQUIFER THERMAL ENERGY STORAGE (ATES) DEMONSTRATION PROGRAM 4.1
4.1.1 Phase I Conceptual Design 4.1
4.2 SEASONAL STORAGE TECHNOLOGY PROGRAM 4.63
4.2.1 Legal/Institutional Assessment 4.64
4.2.2 Economic Assessment 4.67
4.2.3 Environmental Assessment 4.91
4.2.4 Field Test Facilities 4.96
4.2.5 Compendia of Existing Technology 4.101
4.2.6 Physiocochemical Analysis 4.107
4.2.7 Numerical Simulation 4.123
5.0 REFERENCES 5.1

FIGURES

1.1	Organization Chart: Seasonal Thermal Energy Storage (STES) Program	1.4
1.2	Work Breakdown Structure: Seasonal Thermal Energy Storage (STES) Program	1.5
1.3	Summary Network	1.7
4.1	Water Supply System - Flow Schematic	4.6
4.2	Interface with BUC	4.7
4.3	Aerial View of BUC with Roads and Pads as Constructed for Well Drilling	4.11
4.4	Recoverable Heat from BUC Diesel Generators Design Day Ambient Temperature: 90°C	4.13
4.5	Power Generation Logs - BUC 1979	4.14
4.6	Production Options	4.20
4.7	Cooling Tower Performance	4.21
4.8	Sample Strip Chart Flow Readings	4.28
4.9	Stony Brook ATES: Well Location Map	4.29
4.10	Static Water Level Contours, November 1980	4.35
4.11	Initial Aquifer Temperatures at Depth of 330 Feet in November Before Start of Pump Testing	4.37
4.12	Well Site Locations - A, B, C, "ATES" Project, University of Minnesota	4.44
4.13	Location Diagram of Test Wells and Monitor Wells	4.45
4.14	ATES Test Facility in Relation to Geology, University of Minnesota, St. Paul	4.46
4.15	Position of Tested Intervals During Hydraulic Testing of Core Hole AC1	4.48
4.16	Position of Tested Intervals During Hydraulic Testing of Core Hole BC1	4.49
4.17	Hydrologic Zonation of St. Lawrence Through Eau Claire Formations Based on Interpretation of Core Holes AC1 and BC1	4.50
4.18	Position of 100 Degree Temperature Front After 1, 2, 4, 8, 16, and 24 Days During 8-Day Inject, 8-Day Store, and 8-Day Withdraw Cycles and Position of 100 and 200 Degree Temperature Fronts After 1, 8, and 24 Days During 8-Day Inject 8-Day Store, and 8-Day Withdraw Cycles	4.55

4.19 Hydraulic Zonation of St. Lawrence Through Eau Claire Formations Based on Interpretation of Core Hole AC1 and Position of 100 and 200 Degree Temperature Fronts After 8 Days of Injecting 300°F Water at 1200 Gallons Per Minute 4.56

4.20 Logic Diagram for AQUASTOR Code 4.71

4.21 The Effect of System Size on the Cost of ATES Cooling . . 4.79

4.22 The Effect of Load Factor on the Cost of ATES Cooling . . 4.80

4.23 The Effect of Transmission Distance on the Cost of ATES Cooling 4.81

4.24 The Effect of System Reject Temperature on the Cost of ATES Cooling 4.82

4.25 The Effect of Source Availability on the Cost of ATES Cooling 4.83

4.26 The Effect of Source Temperature on the Cost of ATES Cooling 4.84

4.27 The Effect of Heat Exchanger Approach Temperature on the Cost of ATES Cooling 4.85

4.28 The Effect of Aquifer Thermal Efficiency on the Cost of ATES Cooling 4.86

4.29 The Effect of Well Cost on the Cost of ATES Cooling . . 4.86

4.30 The Effect of Electricity Cost on the Cost of ATES Cooling . 4.87

4.31 The Effect of the Cost of Capital on the Cost of ATES Cooling 4.88

4.32 Scheduling for Environmental Assessment 4.94

4.33 Flow Schematic 4.108

4.34 Ratio of the Final Permeability to the Initial Permeability at Each Temperature for Virgin Ottawa Sand 4.109

4.35 Ratio of the Final Permeability Value to the Initial Value at Each Temperature for Massillon Sandstone 4.109

4.36 Volume Strain Versus Temperature For Massillon Sandstone and Ottawa Sand Under a 90 Bar Effective Load 4.110

4.37 Viscosity Values for Deionized Water, Silica-Laden Water, and NaCl Brine Normalized to the Viscosity Value of Distilled Water at 50°C 4.111

4.38 Effluent Particulate Load as a Function of Temperature for Massillon Sandstone and Virgin Ottawa Sand 4.112

4.39 Particles Trapped by a 7.0 μm Filter During a Virgin Ottawa Sand Test 4.114

4.40 Kaolinite Particles Flushed from Ottawa Sand 4.115

4.41 SEM Results from a 0.45 μm Upstream Filter Used in a 150° Permeability Test 4.116

4.42 SEM Results from a 0.45 µm Upstream Filter Used in a $150^{\circ}C$ Permeability Test 4.117

4.43 Permeability Ratio Versus Temperature for Massillon Sandstone and Ottawa Sand Tests with Upstream Filtration 4.118

4.44 Photograph of Similar Equipment Developed for Dow Chemical Company 4.119

4.45 Schematic of the Injectivity Test Stand 4.121

4.46 Geochemical Modeling Capabilities 4.123

4.47 Recovery Factor as a Function of a Generic Volume Measure, $R^2_{TH}H$ 4.127

4.48 Recovery Factor as a Function of Aspect Ratios of Aquifer and Aquitard Thermal Conductivities 4.128

4.49 Recovery Factor as a Function of Total Cycle Time and Cycle Breakdown 4.129

4.50 Production Temperature as a Function of time for $55^{\circ}C$ Injection Experiment 4.130

4.51 Production Temperature as a Function of Time for $90^{\circ}C$ Injection Experiment 4.131

4.52 Computation Mesh, Potential Distribution and Thermal Plume as a Function of Time for an Injection/Withdrawal Doublet in a Confined Aquifer 4.132

4.53 (a) Isothermal Potential/Streamline Flownet (b) Flownet Mesh 4.134

4.54 Input and Output of Mass/Energy Filter 4.135

4.55 Point Values and Contours of Temperature @ 1000 Hours for the "Horizontal" Plane @ 20% Depth of Aquifer 4.136

4.56 Visualization Options Describing the Vertical Distribution of Energy 4.137

TABLES

3.1 ATES Program Milestones for CY-1980 . . . . . . 3.5

3.2 Seasonal Storage Technology Program Milestones for CY-1980 . 3.12

4.1 User Needs 4.18

4.2 Chilled Water Piping 4.22

4.3 Estimated Steam Use for Chilled Water Production (1979) . 4.24

4.4 Estimated Steam Use for Chilled Water Production (1980) . 4.25

4.5 Building Load and Cooling Source 4.26

4.6 Calculated Drawdown at Selected Distances from a Single Well Pumping at a Rate of 300 Gallons Per Minute for Several Values of Aquifer Transmissivity Storage Coefficient, and Pumping Times 4.51

4.7 Calculated 8-Day Drawdown at Selected Distances from the Discharging Well of a Doublet Well System using Several Values of Aquifer Transmissivity and Pumping Rates 4.52

4.8 Summary of Hydraulic and Thermal Properties Used in Preliminary Simulations 4.54

4.9 Summary of Hydraulic and Thermal Properties Used in Simulations RAD 5A-1 to 10 . . . . 4.58

4.10 Summary of Hydraulic and Thermal Properties Used in Simulations RAD 6A-4 . . . . 4.59

4.11 Summary of Pressure and Temperature Changes for Simulations RAD 5A-1 to 10 and RAD 6A-4 . . . . 4.60

4.12 Cost of ATES Heat Storage 4.75

4.13 Comparison of Aquifer Characteristics, 1976 Nondoublet Test and 1980 Doublet Test 4.97

4.14 Aquifer Property Test Facility Capabilities 4.120

EXECUTIVE SUMMARY

The Seasonal Thermal Energy Storage (STES) Program, managed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy (DOE), Office of Advanced Conservation Technologies (ACT), is one element of DOE's 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 Seasonal Storage Technology (SST) 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 SST 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 SST 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). Work continued during CY-1980 on Program Management elements initiated during the last reporting period. Program plans were revised, and the budget and schedules were updated. The STES Program Multi-Year Plan was prepared,

and the Program FY-1981 Annual Operating Plan was issued. A workshop on seasonal thermal energy storage was conducted, and the STES Program Office planned, coordinated and hosted the annual Contractors' Review Meeting for the DOE Mechanical, Magnetic and Underground Energy Storage Programs. In addition, plans were initiated for a STES/Compressed Air Energy Storage (CAES) International Conference to be held in the fall of 1981. Contacts were continued with managers of European STES Programs, and liaison was maintained with the International Energy Agency.

Under the ATES Program, proposals submitted in response to the RFP for Phase I ATES Demonstration Projects were processed through the proposal selection procedure. Based on the various findings and recommendations derived from the selection process, negotiations with selected proposers resulted in contracts for three Phase I (inplementation of aquifer characterization and conceptual design) ATES Demonstration Projects:

Site	Prime Contractor	Energy Source	Storage Temperature	User Application
Bethel, Alaska	TRW Inc.	Diesel-Electric Utility	<105°C	District Heating
State Univ. of New York, Stony Brook Campus, New York	Dames & Moore	Winter Chill	4°C	District Cooling
University of Minnesota, St. Paul Campus, Minnesota	University of Minnesota	University Heating Plant	150°C	District Heating

Drafts of the planning documentation were completed for the three projects, and in addition, documentation of the Functional Design Criteria was completed. Also, the required permits were obtained for test drilling to characterize site geohydrology.

During this reporting period the following additional work was accomplished on Phase I of the ATES Demonstration Projects:

Bethel, Alaska

Three test wells were drilled and analyses made for subsurface characterization. The wells were completed as observation wells for monitoring future pumping tests and thermal/tracer injection tests. Doublet (one injection well and one supply well) wells were completed for the thermal/tracer injection test and preliminary tests were made which indicated the presence of an aquifer that may be suitable for the demonstration project.

The amount and availability of waste heat from the Bethel Utility generators were defined, and energy requirements of candidate users were determined. Designs of the surface and subsurface systems for the Phase I tests were completed.

Drilling costs were much higher than anticipated for the Bethel Project. The increased costs required that work be suspended while a comprehensive economic and technical assessment of the project is made. TRW was issued a Stop Work Order on December 10, 1980, and the assessment is in progress.

State University of New York (SUNY), Stony Brook Campus

Work during this reporting period was concentrated on field investigations, although considerable study was made of the above ground installation and options. The user needs of the major buildings on the Stony Brook Campus were defined both in terms of peak tonnage and peak chilled water flow, and computer models of the load system were developed for the load analysis.

Two winter chilled water production methods are being studied for use on the Stony Brook Campus. The first method relies on the use of the existing cooling towers. The second method will use existing 100% outside air building fan systems to chill well water.

Nine test wells were drilled, sampled and geophysically logged. Piezometer tubes and thermal access tubes were installed in each well for monitoring temperatures and pressures during pumping tests and chill injection tests. An existing well will be used for one of the injection/production doublet wells. The second doublet well was drilled, sampled and tested during this reporting period.

Laboratory tests for heat capacity, thermal conductivity, permeability and grain size (sieve analysis) were made on drill core samples. Preliminary characterization of the aquifer was made which shows that the proposed production/storage zone appears satisfactory for chill storage.

A preliminary numerical model of the geohydrologic system at the test site was developed, and the model was used as an aid in designing the well doublet field experiment.

University of Minnesota, St. Paul Campus

Work began on the ATES system energy and economic analysis and data were collected for use in the analysis. Preliminary modeling was initiated, based on a present value analysis. Plans and specifications were developed for core drilling at the test sites, and two test wells were drilled, cored, logged, and packer tested. Plans and specifications were completed, bids were issued and a contract awarded for drilling five monitoring wells. The preliminary design for the doublet heat injection/water supply wells was completed.

Data from the core wells were used for preliminary aquifer modeling and development of the initial hydrodynamic/heat transport numerical model. Model runs show that the target aquifer should perform satisfactorily for the Phase I heat injection tests. However, aquifer permeability is lower and thickness is less than expected. These findings, if confirmed by the Phase I tests, may require conceptual design of the ATES project on a more limited scale than was originally proposed.

Specifications and working drawings for Phase I mechanical and electrical systems were prepared for bid advertisement.

Under the Seasonal Storage Technology (SST) Program, work continued on the tasks initiated last year:

Legal/Institutional Assessment

Probable Federal and state regulatory requirements for ATES projects were outlined and potential operator liability was determined as were legal factors involving thermal energy storage and recovery. The factors affecting energy delivery were noted, and a technical document containing the results of investigations under this study area was published.

Economic Assessment

An overall analysis of ATES systems was made, and the results were published. The analysis shows that ATES is a cost-effective, fuel-conserving technique for providing thermal energy for residential, commercial, and industrial users. Development of the ATES Economic Evaluation Computer Code, AQUASTOR, was completed, and the model was used during this reporting period to make several assessments of the cost of aquifer heat and chill storage.

Guidelines were developed for conceptual design and evaluation of ATES systems and documentation was issued. The guidelines were prepared as a tool for those considering the use of ATES systems.

Environmental Assessment

During this reporting period, environmental documentation requirements were developed for ATES projects (Federal and state) for compliance with the National Environmental Policy Act (NEPA), and a draft Programmatic Environmental Assessment was prepared for the ATES Program. In addition, assistance was provided in evaluating data and reports submitted by the demonstration project contractors for environmental compliance.

Field Test Facilities

Activities on Field Test Facilities (FTF) and related work were carried out during the reporting period at Mobile, Alabama; Tennessee Valley Authority (TVA); Bellingham, Washington and Richland, Washington.

Field work is in progress by Auburn University at the Mobile, Alabama Test Site to implement a true doublet ATES test system. New injection and supply wells were drilled into the storage aquifer, and initial hydrologic tests were made.

Negotiations with TVA to develop a cooperative ATES FTF within the TVA service area were halted after a potential site was identified near Memphis, Tennessee. TVA was unable to identify internal funding to cooperatively develop the facility.

Work was carried out to characterize the geohydrology near Ferndale (Bellingham), Washington for potential siting of an FTF adjacent to a high-temperature waste heat source (garbage burner). Test well drilling indicated that the target Esperance Sand Formation is not present at the site, therefore, the project was terminated based on these findings.

Preliminary test drilling was conducted near Richland, Washington to locate and characterize a shallow unconfined aquifer suitable for storage of low-temperature energy. Wide variations were noted in aquifer characteristics, which led to the site being set aside as a potential site for future testing of gradient control.

Compendia of Existing Technology

Library maintenance and development is continuing, with a working library of over 1700 STES related documents presently available. Literature reviews were made, and draft summary reports were completed during the past year on ATES related technology. Publication of the quarterly STES Newsletter continued, with the scope of the newsletter being expanded (from ATES) to include coverage of all types of seasonal thermal energy storage.

The STES Technology Information System (STES-TIS) was implemented as a subset of the Technology Information System developed at the Lawrence Livermore Laboratory under sponsorship of the DOE Office of Advanced Conservation Technologies. The STES-TIS encompasses library/bibliographic functions, program information files, computational/model facilities and communication capabilities.

The ATES Reference Manual was issued. The manual contains a complete description of the work being performed under the STES Program.

Physicochemical Analysis

Laboratory permeability/creep compaction tests were completed on samples of Massillon sandstone and Ottawa sand. As has been noted historically during laboratory permeability tests under similar conditions (increased temperature and pressure), a large decrease in sample permeability was observed in the present tests. However, none of the natural damage mechanisms investigated were responsible for the observed permeability degradation with temperature. It appears that the permeability degradation is caused by apparatus contamination-metal colloids derived from the laboratory equipment itself. The tests show that Massillon sandstone and Ottawa sand permeabilities are not particularly temperature sensitive under conditions of low to moderate stress and temperatures less than 150^{o}C.

Specifications were developed for a laboratory facility for testing the properties of geologic media samples under elevated temperature and pressure. A request for bids for facility fabrication was issued, the fabricator selected and a contract issued. Also, a field injectivity test stand was designed to carry out on-site injection studies at ATES project locations.

Chemical modeling was initiated, and an existing code, the WATEQ4 model, was selected for modification to ATES requirements.

Numerical Simulation

Work continued during this reporting period on development of numerical simulation methodology for analysis of ATES geohydrologic/heat transport systems. Additional improvements and modifications were made for the finite element code CFEST (Coupled Fluid, Energy and Solute Transport) and CFEST was tested on simulations of heat transport in confined aquifers.

Work was initiated on modification and application of the Intercomp Deep Well Disposal Model (DWDM) to run the code on IBM (or other restricted work size) hardware.

The Lawrence Berkeley Laboratory (LBL) continued to work on numerical modeling aspects of ATES by application of the Conduction, Convection and Compaction (CCC) code. Three specific tasks were undertaken by LBL during the year. They were: 1) to perform generic simulations and study the relationships between parameter groups describing the ATES aquifer system; 2) to carry out site-specific simulations and provide input for design and operational scenario at field test facilities, and 3) to complete preliminary investigations leading to nonisothermal modeling of unconfined aquifers overlain by unsaturated porous media.

Site-specific studies were undertaken for the Auburn University field test facility located at Mobile, Alabama. Simulations were undertaken to determine the appropriate location of sampling wells, feasibility of fully versus partially penetrating recovery wells, and energy recovery prospects.

LBL has begun work toward the development of a numerical simulation code capable of predicting the transient movement of both fluid mass and energy within the coupled saturated and unsaturated environments of an unconfined aquifer.

<u>Nonaquifer Seasonal Thermal Energy Storage</u>

Nonaquifer thermal energy storage literature was obtained and reviewed to keep abreast of development in these technologies. An initial survey, evaluation, and selection of potential nonaquifer seasonal thermal energy storage concepts was completed, and the results were incorporated in a formal report. Based on this preliminary evaluation, the currently most promising nonaquifer STES concepts worthy of more detailed evaluation are:

- Large engineered insulated-pond thermal energy storage (TES) with <95°C water (sensible STES heating)
- Wet earth TES with <95°C water (sensible STES heating)
- Natural lakes and ponds, solar ponds, rocks, and water in mines, caverns, and large tanks (sensible STES heating)
- Ice and compacted snow TES (latent STES cooling)
- Sulphuric acid/water heat pumps at 66 to 200°C (thermochemical STES heating and cooling).

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, Office of Advanced Conservation Technologies (ACT), is one element of the Thermal Energy Storage Program.

1.1 OBJECTIVES

The objectives 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 (Multi-Year Plan for Thermal and Mechanical Energy Storage Program, DOE/ET-0109 Draft, June 1979). 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 ACT Office, 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 1.1. The Work Breakdown Structure is displayed in Figure 1.2. The Summary Network is displayed in Figure 1.3.

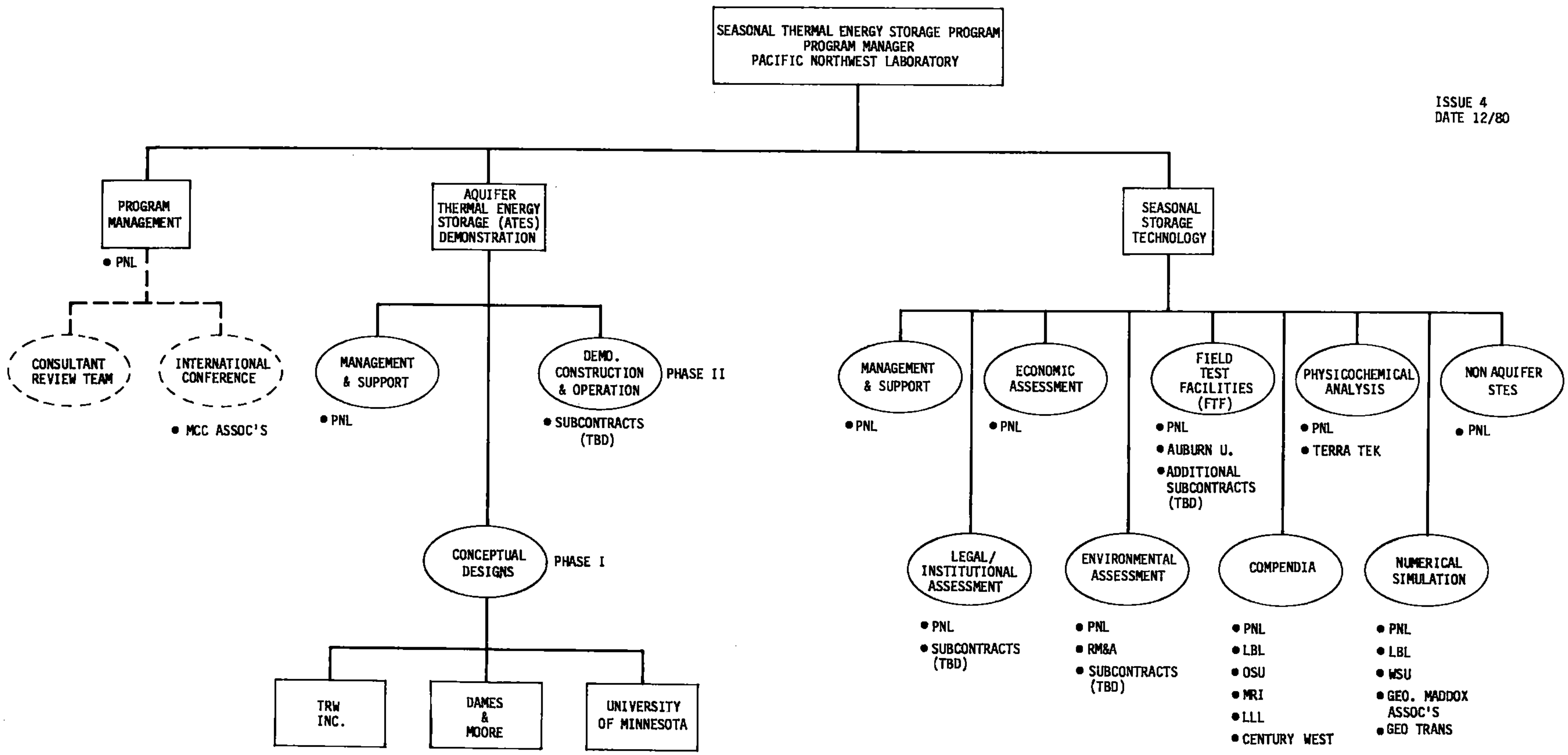


FIGURE 1.1. Organization Chart: Seasonal Thermal Energy Storage (STES) Program

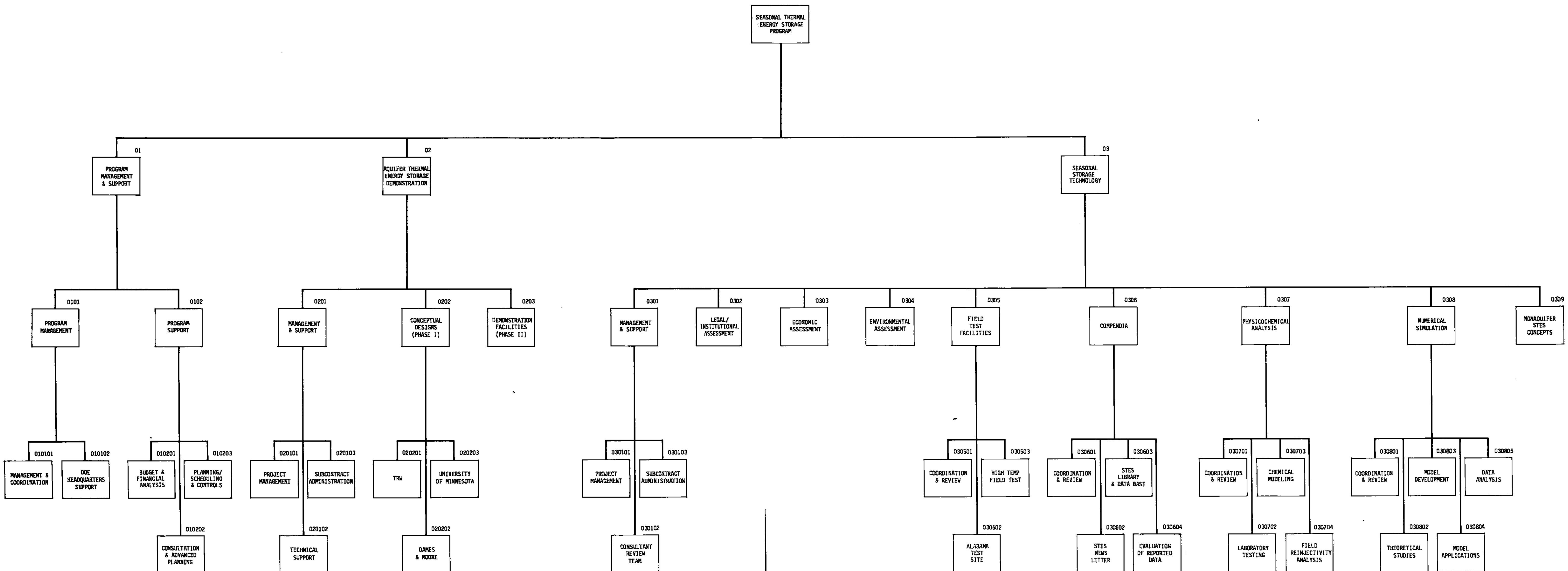


FIGURE 1.2. Work Breakdown Structure: Seasonal Thermal Energy Storage (STES) Program

SEASONAL THERMAL ENERGY STORAGE PROGRAM

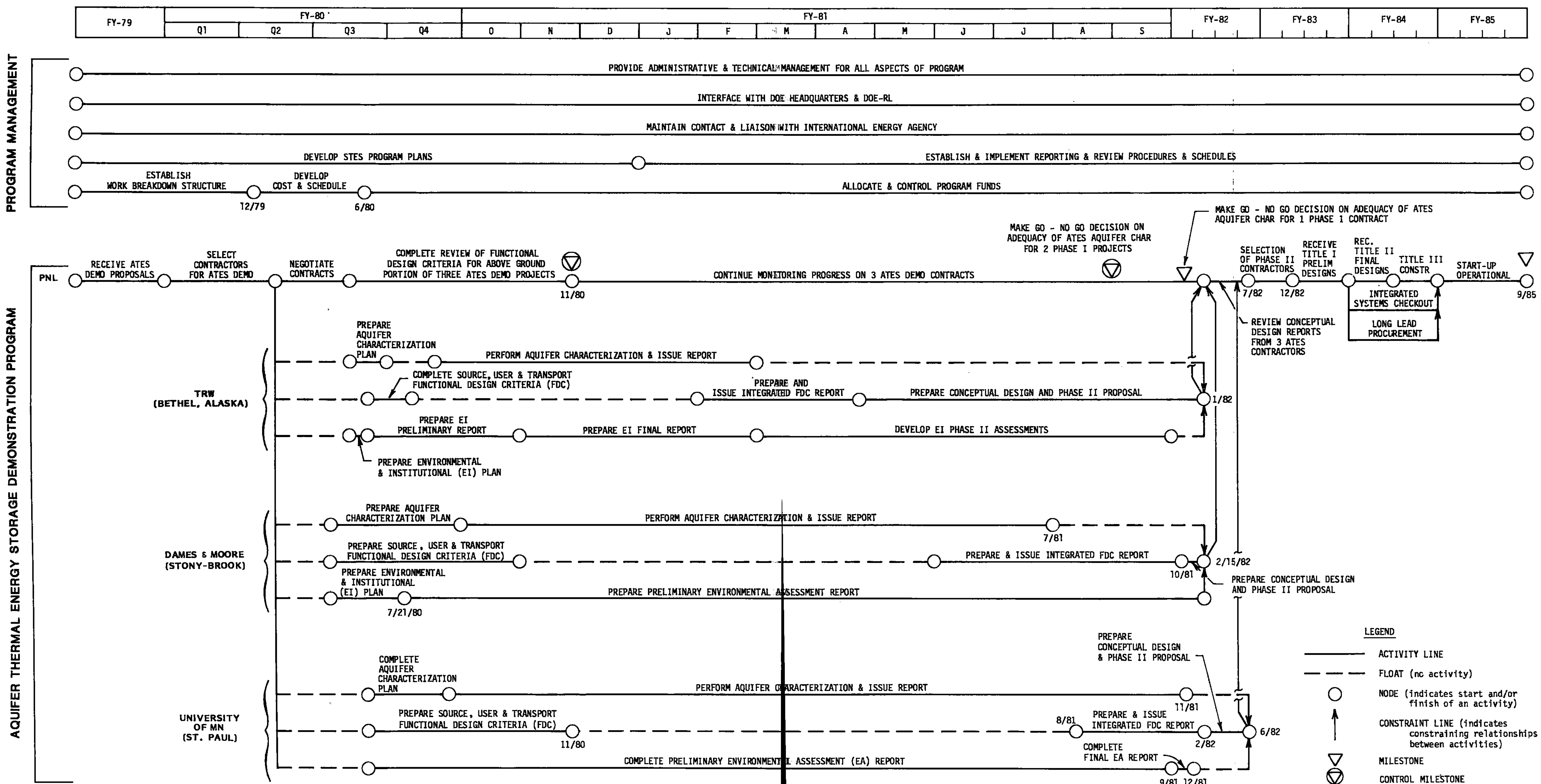
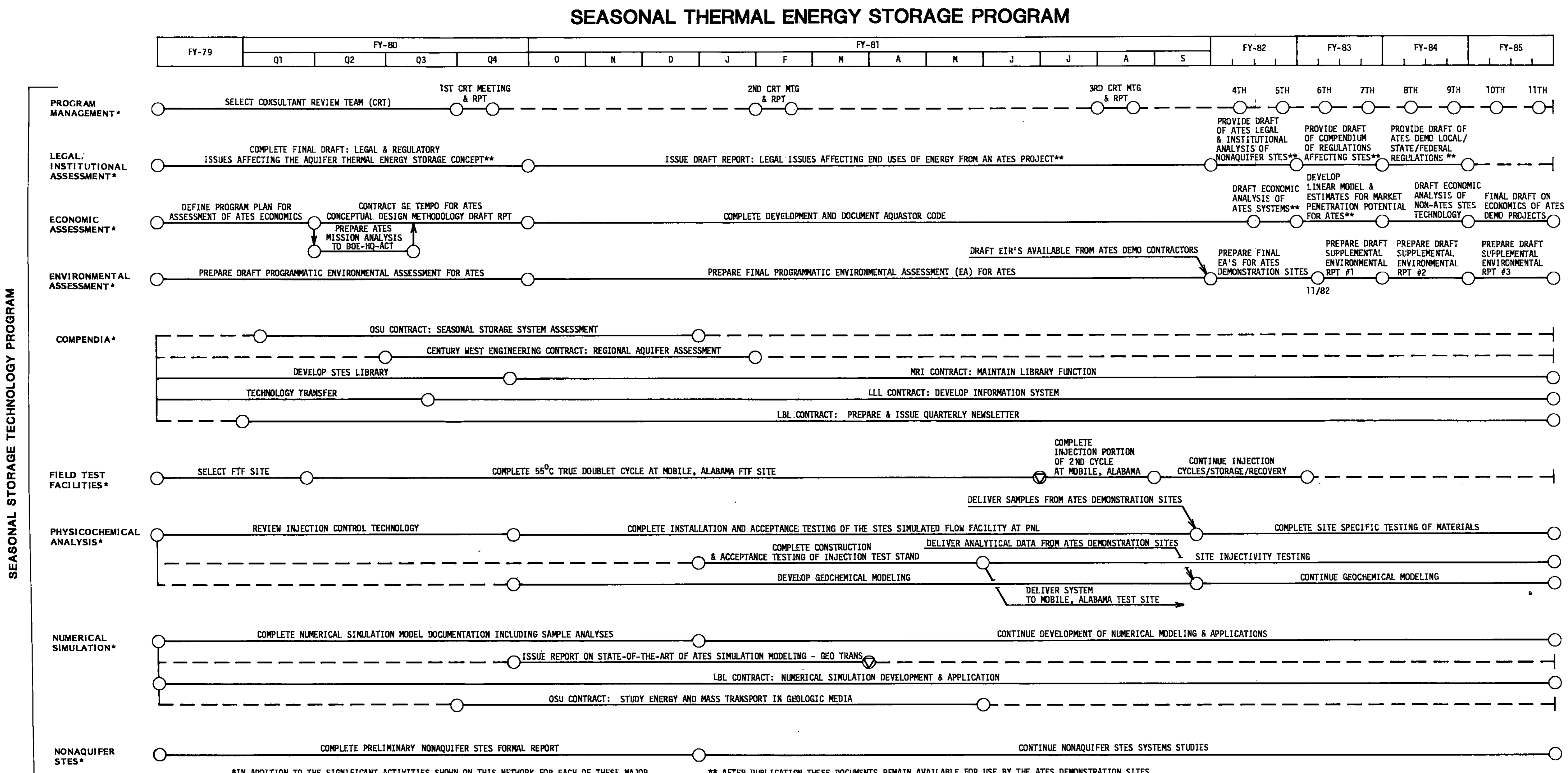


FIGURE 1.3. Summary Network



*IN ADDITION TO THE SIGNIFICANT ACTIVITIES SHOWN ON THIS NETWORK FOR EACH OF THESE MAJOR TASKS OF THE SEASONAL STORAGE TECHNOLOGY PROGRAM, THESE TASKS ALSO PROVIDE CONTINUOUS SUPPORT FOR THE ENTIRE DURATION OF THE STES PROGRAM.

** AFTER PUBLICATION THESE DOCUMENTS REMAIN AVAILABLE FOR USE BY THE ATES DEMONSTRATION SITES.

FIGURE 1.3. (continued)

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 Seasonal Storage Technology (SST) 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 were evaluated and contracts were negotiated for implementation of the selected projects. The contractors are developing conceptual designs for integrated systems containing energy source, thermal transport, aquifer storage, and user subsystems. Aquifers are being 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 SST 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 include legal/institutional, 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 SST 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 of 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 SST Task is development of one or more Field Test Facilities (FTF's). The FTF 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 heating and/or chill energy storage technologies. More than one FTF 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 involves industry, other Department of Energy (DOE) laboratories, and universities.

3.0 SUMMARY OF ACCOMPLISHMENTS

3.1 TASK I - STES PROGRAM MANAGEMENT

Work continued during CY-1980 on Program Management elements initiated during the last reporting period. Program plans were revised, and the budget and schedules were updated. The STES Program Multi-Year Plan was prepared, and the Program FY-1981 Annual Operating Plan was issued.

A workshop on seasonal thermal energy storage was conducted to provide a forum for discussion of STES technology by foreign and U.S. scientists and engineers. Also, the STES Consultant Review Team met to provide a peer overview of the Program.

The STES Program Office planned, coordinated and hosted the annual Contractors' Review Meeting for the DOE Mechanical, Magnetic and Underground Energy Storage Programs. In addition, plans were initiated for a STES/CAES International Conference to be held in the fall of 1981.

Contacts were continued with managers of European STES Programs, and liaison was maintained with the International Energy Agency.

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

Proposals submitted in response to the RFP for Phase I ATES Demonstration Projects were processed through the proposal selection procedure. Ratings of the proposals were made by the Source Evaluation Panel (SEP) and the competitive range was established for the proposals. Discussions were held with proposers that comprised the competitive range, and findings reported to the SEP and Source Selection Official (SSO). Based on the various findings and recommendations, the SSO proposed projects for Phase I (Aquifer Characterization and Conceptual Design) implementation, and these selections were presented to and discussed with DOE Richland Operations Office and DOE Washington, Division of Energy Storage Systems (now Office of Advanced Conservation Technologies). Subsequently, negotiations with the selected proposers resulted in contracts for three Phase I ATES Projects:

Site	Prime Contractor	Energy Source	Storage Temperature	User Application
Bethel, Alaska	TRW Inc.	Diesel-Electric Utility	<105°C	District Heating
State Univ. of New York, Stony Brook Campus, New York	Dames & Moore	Winter Chill	4°C	District Cooling
University of Minnesota, St. Paul Campus, Minnesota	University of Minnesota	University Heating Plant	150°C	District Heating

Drafts of the planning documentation were completed for the three projects. These documents are: 1) Management Plan, 2) Aquifer Characterization Plan, and 3) Environmental Assessment Plan. In addition, documentation of the Functional Design Criteria was completed for the three projects. Also, the required permits were obtained for test drilling to characterize site geohydrology.

During this reporting period the following work was accomplished on Phase I of the ATES Demonstration Projects:

Bethel, Alaska

Three test wells were drilled. These wells provided samples of the permafrost zone and underlying geologic formations for subsurface characterization. Laboratory analyses of the well samples were made. The wells were completed as observation wells for monitoring future pumping tests and thermal/tracer injection tests. Doublet (one injection well and one supply well) wells were completed for the thermal/tracer injection test and a preliminary pumping test was made for aquifer characterization. This test indicated the presence of an aquifer that may be suitable for the demonstration project.

The amount and availability of waste heat from the Bethel Utility generators were defined; energy requirements of candidate users were determined; and disucussions began on district heating distribution systems. Designs of the surface and subsurface systems for the Phase I tests were completed and pressure and temperature measuring instrumentation was installed in the observation wells. Strain gauges were installed on the doublet wells to determine casing elongation (and permafrost effects) during the heat injection test.

Drilling costs were much higher than anticipated for the Bethel Project. The uncertainties of weather and stratigraphy precluded a fixed price or unit price contract for drilling and the qualified drillers would only do the work on a per diem basis. The time required and complications encountered resulted in drilling costs of over $850,000, whereas less than $400,000 had been planned. Similar experience in under-estimating the cost of site preparation and mechanical work in the remote areas of Alaska caused further cost overruns. This situation required that work be suspended while a comprehensive economic and technical assessment of the project is made. TRW was issued a Stop Work Order on December 10, 1980, and the assessment is in progress.

State University of New York (SUNY), Stony Brook Campus

During this reporting period, work at Stony Brook concentrated on field investigations, although considerable study was made of the above ground installation and options. The user needs of the major buildings on the Stony Brook Campus were defined both in terms of peak tonnage and peak chilled water flow. The annual tonnage and flow are being determined by both historical means using chilled water logs and flow meter data, and by computerized load analysis. Computer models of the load system were developed for the load analysis.

Two winter chilled water production methods are being studied for use on the Stony Brook Campus. The first method relies on the use of the existing cooling towers. Discussions were held with manufacturers to determine the winter performance capabilities of the existing towers. In addition, the actual operating experience of similar cooling towers in the winter mode has been studied to identify potential problems. Based on preliminary data, the existing towers appear to have the necessary capacity. The second method will use existing 100% outside air building fan systems to chill well water. By using fan systems which must run continuously to supply building needs, the additional energy consumption of using cooling tower fans in winter may be avoided or reduced. The feasibility of using existing coils for this purpose is being discussed with manufacturers and the overall concept is under study.

The existing chilled water distribution and utility tunnel system was investigated for possible use as a well water transport system. The system is presently being under-utilized in terms of its water flow capacity.

The injection/production well doublet for the Phase I tests were designed and let for bid. A contractor was selected and construction was completed in November 1980. Nine test wells were drilled, sampled and geophysically logged. Piezometer tubes and thermal access tubes were installed in each well for monitoring temperatures and pressures during pumping tests and chill injection tests. An existing well will be used for one of the injection/production doublet wells. The second doublet well was drilled, sampled and tested during this reporting period.

Laboratory tests for heat capacity, thermal conductivity, permeability and grain size (sieve analysis) were made on drill core samples. Preliminary characterization of the aquifer was made. The initial well tests show that the proposed production/storage zone in the Upper Magothy Formation (about 300 to 350 feet below land surface) appears satisfactory for chill storage.

A preliminary numerical model of the geohydrologic system at the test site was developed using the GREASE-2 code. The model was used as an aid in designing the well doublet field experiment.

University of Minnesota, St. Paul Campus

Work began on the ATES system energy and economic analysis. Data were collected for use in the analysis, and preliminary modeling and computer programming was initiated based on a present value analysis. Work has begun on an energy/thermodynamic model for Phase II concept.

Plans and specifications were developed for core drilling at the test sites, and two test wells were drilled, cored, logged, and packer tested. These wells were completed as monitoring/observation wells. Plans and specifications were completed, bids issued and a contract awarded for drilling five monitoring wells. Construction of the wells will begin early in January 1981. The preliminary design for the doublet heat injection/water supply wells was completed and routed for review.

Data from the core wells were used for preliminary aquifer characterization and development of the initial hydrodynamic/heat transport numerical model. Model runs show that the target aquifer (Franconia-Ironton-Galesville) should perform satisfactorily for the Phase I heat injection tests. However, aquifer permeability is lower and thickness is less than expected. These findings, if confirmed by the Phase I tests, may require conceptual design of the ATES project on a more limited scale than was originally proposed.

Specifications and working drawings for Phase I mechanical and electrical systems were prepared for bid advertisement.

Table 3.1 shows the Task II Milestones for CY-1980. All milestones were completed on or ahead of schedule.

TABLE 3.1. ATES Program Milestones for CY-1980

Milestone	Scheduled Due Date	Projected Completion Date	Actual Completion Date
Contractor Selection for Aquifer Demonstration Program	2/80		2/80
Present ATES Demonstration Program Selection Decision to the Office of Advanced Conservation Technologies	2/80		2/80
Complete Conceptual Design Contract Negotiations (those for which funds are available)	6/80		5/80
Issue Notices to Proceed on ATES Phase I Contracts	7/80		5/80
Complete Review of Functional Design Criteria for Above Ground Portion of Three ATES Demonstration Projects	11/80		11/80

3.3 TASK III - SEASONAL STORAGE TECHNOLOGY (SST) PROGRAM

During this reporting period, work continued on the tasks initiated last year:

Legal/Institutional Assessment

Probable Federal and state regulatory requirements for ATES projects were outlined and potential operator liability was discussed as were legal factors involving thermal energy storage and recovery. The factors affecting energy delivery were noted.

A technical document containing the results of investigations under this study area was published in October (Hendrickson 1980).

Economic Assessment

An overall analysis of ATES systems was made. The results of this analysis shows that ATES is a cost-effective, fuel-conserving technique for providing thermal energy for residential, commercial, and industrial users. While there are some technical and institutional problems, the negative aspects are minor, and do not seem to pose a threat to widespread commercialization. The results of this analysis was published in June (Reilly 1980).

Development of the ATES Economic Evaluation Computer Code, AQUASTOR, was completed. AQUASTOR combines demand, aquifer, and supply characteristics with climate, cost functions, and economic parameters in one systematic model. It provides the flexibility to individually or collectively evaluate the impact of different economic and technical parameters, assumptions, and uncertainties on the cost of providing heat (chill) from an aquifer storage system. AQUASTOR was used during this reporting period to make several assessments of the cost of aquifer heat and chill storage.

Guidelines were developed for conceptual design and evaluation of ATES systems. The guidelines were prepared as a tool for those considering the use of ATES systems. The guidelines will assist in the preliminary design effort and in evaluation of the technical and economic feasibility of using the ATES technology. Documentation of the guidelines was issued in October (Meyer 1980).

Environmental Assessment

During this reporting period a major emphasis was placed on developing environmental documentation requirements for ATES projects (Federal and state) for compliance with the National Environmental Policy Act (NEPA). A draft Programmatic Environmental Assessment was prepared for the ATES Program. In addition, assistance was provided to the ATES Program Manager in evaluating data and reports submitted by the demonstration project contractors for environmental compliance.

Field Test Facilities

Activities on Field Test Facilities (FTF) and related work were carried out during the reporting period at Mobile, Alabama; Tennessee Valley Authority (TVA); Bellingham, Washington and Richland, Washington.

Field work is in progress by Auburn University at the Mobile, Alabama Test Site to implement a true doublet ATES test system. New injection and supply wells were drilled into the storage aquifer, and initial hydrologic tests were made. Comprehensive aquifer tests are in progress, and plans were completed for the hot injection/tracer tests scheduled to begin in February 1981.

Negotiations were made with TVA to develop a cooperative ATES FTF within the TVA service area. This effort was halted after a potential site was identified near Memphis, Tennessee. TVA was unable to identify internal funding to cooperatively develop the facility.

Work was carried out to characterize the geohydrology near Ferndale (Bellingham), Washington for potential siting of an FTF adjacent to a high-temperature waste heat source (garbage burner). Test drilling was conducted at two sites near the location of the garbage burner. The target was the Esperance Sand, a deep (∿600 feet below land surface) saline water-bearing formation known to exist several miles to the west of the proposed FTF site. The Esperance was not found at the two test well sites, and the project was terminated based on these findings. The tests, of course, do not preclude existence of aquifer satisfactory for aquifer thermal energy storage elsewhere in the Nooksack Basin.

Preliminary test drilling was conducted near Richland, Washington to locate and characterize a shallow unconfined aquifer suitable for storage of low-temperature energy. Wide variations were noted in aquifer characteristics, which led to the site being set aside as a potential site for future testing of gradient control.

Compendia of Existing Technology

A working library of over 1700 STES related documents were assembled. Library maintenance and development is continuing under subcontract with Midwest Research Institute.

Literature reviews were made, and draft summary reports were completed during the past year on: ATES site characterization methods, regional aquifer assessment, energy and mass transport in geologic media, and aquifer reinjection experience where ground water was used for building heating/cooling.

Publication of the quarterly STES Newsletter continued during this reporting period. The scope of the newsletter was expanded (from ATES) to include coverage of all types of seasonal thermal energy storage.

The STES Technology Information System (STES-TIS) was implemented during the past year. The STES-TIS is a subset of the Technology Information System developed at the Lawrence Livermore Laboratory under sponsorship of the DOE Office of Advanced Conservation Technologies. The STES-TIS encompasses library/bibliographic functions, program information files, computational/model facilities and communication capabilities.

The ATES Reference Manual was issued in August (Prater 1980). The manual contains a complete description of the work being performed under the STES Program.

Physicochemical Analysis

Laboratory permeability/creep compaction tests were completed on samples of Massillon sandstone and Ottawa sand. As has been noted historically during laboratory permeability tests under similar conditions (increased temperature and pressure), a large decrease in sample permeability was observed in the present tests.

None of the natural damage mechanisms investigated were responsible for the observed permeability degradation with temperature. It now appears that the permeability degradation is caused by apparatus contamination-metal colloids derived from the laboratory equipment itself. The particulates are predominantly zinc, iron, and aluminum oxides or hydroxides presumably derived from corrosion and/or degradation of equipment components upstream of the sand and sandstone samples. It is concluded that laboratory tests at temperature should be done in corrosion resistant vessels and include upstream filtration. With respect to field sites, operators of ATES wells must investigate the nature of the suspended particle loads being injected into the reservoir. "Injectivity testing" should be conducted at all field sites where elevated temperatures are planned. It would appear from this study, that for low to moderate effective stress and temperatures less than 150^{o}C, that Massillon sandstone and Ottawa sand permeabilities are not particularly temperature sensitive. Site-specific aquifer materials should be similarly tested. Furthermore, the potential problems with scaling (relatively small scale laboratory test results extrapolated to field conditions) effects of the small lab/field travel path ratio should be explored because of the apparent temperature-induced mobilization of natural fines internal to porous aquifer materials.

Specifications were developed for a laboratory facility for testing the properties of geologic media samples under elevated temperature and pressure. A request for bids for facility fabrication was issued, the fabricator selected and a contract issued. Engineering design and system construction drawings are nearly complete, and long lead hardware items were ordered. Also, a field injectivity test stand was designed to carry out on-site injection studies at ATES project locations. Negotiations for test stand fabrication are in progress.

Chemical modeling, a new task, was initiated in November 1980. An existing code, the WATEQ4 model, was selected for modification to ATES requirements. Mass transfer (precipitation/dissolution) capabilities were added to the code and progress is being made towards adding elevated temperature ($<150^{o}$C) capabilities in an equilibrium or kinetic mode. The data bank has been enhanced and a literature review on the kinetics of calcite, gypsum, silica, geothite, and ferrihydride is progressing.

Numerical Simulation

Work continued during this reporting period on development of numerical simulation methodology for analysis of ATES geohydrologic/heat transport systems. Additional improvements and modifications were made for the finite element code CFEST (coupled fluid, energy and solute transport). Flownet and rectangular grids have been included in the automatic grid generation package, and a data processing package has been developed to display and filter the raw field data from an aquifer thermal energy storage facility. CFEST was tested on simulations of heat transport in confined aquifers.

During CY-1980, contracts were placed with Washington State University (WSU), Oregon State University (OSU), and GeoTrans, Inc. This work involves modification and application of the Intercomp Deep Well Disposal Model (DWDM), a preliminary examination of mass and energy transport in unsaturated media, and the preliminary study leading to a state-of-the-art paper dealing with numerical simulation of the aquifer environment. At WSU, modifications have been made to the DWDM code necessary to run the code on IBM (or other restricted work size) hardware. OSU has completed a literature review, written a preliminary interpretive report, and annotated bibliography on energy transport in unsaturated media. Current publications and details of ongoing research have been sought for inclusion in the paper on state-of-the-art in modeling fluid flow and heat transport in aquifer geologic media being prepared by GeoTrans.

The Lawrence Berkeley Laboratory (LBL) continues to work on numerical modeling aspects of ATES. Three specific tasks were undertaken by LBL during the year. They were: 1) to perform generic simulations and study the relationships between parameter groups describing the ATES aquifer system; 2) to carry out site-specific simulations and provide input for design and operational scenario at field test facilities, and 3) to complete preliminary investigations leading to nonisothermal modeling of unconfined aquifers overlain by unsaturated porous media.

Site-specific studies were undertaken for the Auburn University field test facility located at Mobile, Alabama. Three heat injection cycles are presently contemplated for the Auburn field test facility. Each will have a progressively higher injection temperature (55, 90, 125^{o}C). Simulations were undertaken to determine the: appropriate location of sampling wells, feasibility of fully versus partially penetrating recovery wells, and energy recovery prospects.

LBL has begun work toward the development of a numerical simulation code capable of predicting the transient movement of both fluid mass and energy within the coupled saturated and unsaturated environments of an unconfined aquifer. An isothermal code for the analysis of transient flow in unsaturated and saturated porous media (TRUST) is being expanded to include nonisothermal effects. Code development of this magnitude is a multi-year effort and work is continuing through 1981.

Nonaquifer Seasonal Thermal Energy Storage

Nonaquifer thermal energy storage literature is being obtained and reviewed to keep abreast of development in these technologies. An initial survey, evaluation, and selection of potential nonaquifer seasonal thermal energy storage concepts was completed, and the results were incorporated in a formal report in December (Blahnik 1980). Based on this preliminary evaluation, the currently most promising nonaquifer STES concepts worthy of more detailed evaluation are:

- Large engineered insulated-pond thermal energy storage (TES) with <95^{o}C (sensible STES heating)
- Wet earth TES with <95^{o}C water (sensible STES heating)
- Natural lakes and ponds, solar ponds, rocks, and water in mines, caverns, and large tanks (sensible STES heating)
- Ice and compacted snow TES (latent STES cooling)
- Sulphuric acid/water heat pumps at 66 to 200^{o}C (thermochemical STES heating and cooling).

These recommended concepts should be considered for use in conjunction with heat pump systems, for use with each other, and perhaps, except for thermochemical STES, for coupling with aquifers.

Table 3.2 shows the Task III Milestones for CY-1980. All milestones were met on or ahead of schedule except for the draft Environmental Assessment (EA), documentation of the numerical simulation model (CFEST), and the Consultant Review Meeting.

The review process for approval of the EA document required more time than expected. Instability problems with CFEST required development and incorporation of "upstream" weighting to the code which delayed model completion and documentation by approximately 3 months. The Consultant Review Meeting was delayed due to the Mt. St. Helens volcanic event.

TABLE 3.2. Seasonal Storage Technology Program Milestones for CY-1980

Milestone	Scheduled Due Date	Projected Completion Date	Actual Completion Date
Present ATES Mission Analysis to the Office of Advanced Technologies	3/80		3/80
Conduct Consultant Review Meetings	4/80	7/80	7/80
Complete Generic Environmental Assessment and Issue Draft	9/80	10/80	10/80
Publish Prelininary ATES Reference Manual	8/80		8/80
Conduct STES Workship	9/80		8/80
Complete Preliminary Nonaquifer STES Formal Report	12/80		12/80
Complete Numerical Simulation Model Documentation Including Sample Analyses	12/80	3/81	

4.0 PROGRESS ON THE SEASONAL THERMAL ENERGY STORAGE PROGRAM PROJECTS

Detailed discussions are given in this section on the individual tasks 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 Work Breakdown Structure.

4.1 AQUIFER THERMAL ENERGY STORAGE (ATES) DEMONSTRATION PROGRAM

The goal 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. The ATES Demonstration Program is comprised of the following tasks:

Task 1 - Phase I Conceptual Design.

Task 2 - Phase II Final Design, Construction and Operation.

4.1.1 Phase I Conceptual Design

TRW, Dames & Moore and University of Minnesota.

Conceptual designs for integrated systems containing energy source, thermal transport, aquifer storage and user subsystems are under development by contractors. In response to the Request for Proposal (RFP) issued last year (September 1979), proposals were submitted on or before December 17, 1979 for Phase I work. During the first quarter of CY-1980, at the conclusion of the proposal selection procedure, the following three ATES Phase I Projects were awarded:

Site	Prime Contractor	Energy Source	Storage Temperature	User Application
Bethel, Alaska	TRW Inc.	Diesel-Electric Utility	<105°C	District Heating
Stony Brook, New York	Dames & Moore	Winter Chill	4°C	District Cooling
St. Paul, Minnesota	University of Minnesota	University Heating Plant	150°C	District Heating

Aquifers are being characterized by geologic exploration and analysis of data. Functional design criteria are being developed for each subsystem and for the integrated systems. The functional design criteria and the aquifer characterization reports will be the basis for the conceptual designs, which will be completed in FY-1982.

Objectives

The objectives of Phase I are to:

- Develop conceptual designs for fully integrated thermal energy storage systems which each include an energy source, thermal transport, a storage aquifer and a user application.
- Identify and characterize usable aquifers at each site.
- Establish the economic viability of the conceptual systems.
- Identify the institutional and environmental concerns associated with future development and commercialization of the systems.
- Development of plans for accomplishment of Phase II.

Technical Progress

4.1.1.1 Bethel, Alaska Project
TRW, Inc.

The Management Plan, Aquifer Characterization Plan and Environmental/ Institutional Plans were submitted and approved. These documents form the baseline for the project.

Most of the work accomplished during this reporting period was in Test Site Development. This task consisted of the following elements:

- Obtaining permits and licenses
- Procurement and transport of materials and equipment
- Design of the site
- Design of the hot water test system
- Selection of contractors for site preparation, test system construction and well drilling, and
- Drilling and completing the wells.

Obtaining Permits and Licenses

The task of obtaining permits and licenses to permit well drilling was made relatively simple by implementing the process developed by the State of Alaska to convene a permit conference incorporating all concerned State and Federal agencies.

The details of all the agencies' concerns and actions are presented in "Phase I Environmental Assessment/Monitoring and Environmental/Institutional Investigation Plan," TRW No. 80.1455.JMC.127, dated August 25, 1980.

Procurement and Transport of Materials and Equipment

The key facet in the procurement of materials and equipment was the short time between the project start and the planned start of drilling. Some of the constraints included the various transportation difficulties to Bethel. The last barge from Seattle leaves on September 6. Gravel for the roads and pads must come from 90 miles up river. The Kuskokwim River recedes around August 15 each year, making barge transport impossible. Orders for the gravel were placed to match with these transportation restrictions.

A number of items required a fairly long lead time. These included:

- down hole pump
- heat exchangers
- booster pumps, and
- aquifer instrumentation.

Early design decisions were made on the selection of these items so that the procurement lead time could match the most economical transportation mode.

The most critical transportation problem concerned the drill rig and well casing. The two methods of bringing this equipment to Bethel are by barge or by air, both from Anchorage. Selection of the drilling contractor was not made in time to use the barge. In any event, demobilization of the drill rig back to Anchorage was always an air operation due to the scheduled time (winter). Drill rig transport by air has become a common practice in Alaska due to the extensive drilling on the north slope.

Design of the Site

Since the site for the five test wells is undisturbed tundra, the test site had to be prepared to minimize the effect on the tundra. Drill rig weight had to be distributed to an acceptable stress on the soft tundra. Thermal effects on the tundra had to be minimized. The design of the roads and pads went through several iterations with the potential contractors.

Design of the Hot Water Test System

The aquifer characterization experiments require the injection of hot water into a well. The water will be extracted from a production well and heated by waste heat from the diesel generators of the Bethel Utility Corporation (BUC). Two systems, one for pumping, heating and distributing the water, the other for conditioning and distributing the electric power for the water pumps and the instruments, were designed. These systems are described below.

The Water Supply System

The function of this system is to pipe water from the extraction well to the injection well through heat exchangers during the hot water tests, and by-pass the heat exchangers during isothermal tests. The heat necessary to raise the water temperature by up to 100^{o}F is extracted from the coolant of the diesel generator units of the BUC. The water will be pumped from the extraction well at the rate of 200 gpm by a down hole pump and will flow through the tubes of two heat exchangers, connected in parallel, prior to reaching the injection well. The flow schematic, Figure 4.1, shows the main components of the system; Figure 4.2 shows how the new system will fit into the existing engine cooling system. Note that the coolant temperature entering each engine is always controlled by its own mixing valve which adjusts the proportion of engine coolant by-passing the radiator loop. The "new" portion of the cooling loop is under construction now, to prepare for the installation of additional generator units. In the meantime, the aquifer characterization loop will be connected in the place of one of the generators. A pump, P-01, is provided to compensate for the appreciable pressure drop (up to 23 psi) in the diesel coolant when flowing through the shell side of the heat exchangers. The maximum flow rate is 500 gpm from each diesel generator and the BUC usually has two units on line during the day and only one at night.

The flow rate of the aquifer water will be controlled to a constant value of 200 gpm by throttling (V-7); thus, the water temperature at the injection well will vary as a function of the power output of the utility.

Rhodamine dye stored in a 100 gallon tank (T-2) will be injected into the hot water through a calibrated capillary and the dye concentration at the injection well will be measured.

The Power Supply System

The BUC produces power at 2400 Volts alternating current (Vac) and distributes power at 208 Vac whereas the instrumentation system on the wells and the heating strips (required to prevent freezing of the wells) require 110 Vac while the 200 gpm, 25 horsepower down hole pump and the 1000 gpm, 25 horsepower pump are best driven by 460 Vac motors. Accordingly, the electrical system specification was issued and a walk-through was held at the BUC on August 19, 1980. As a result of discussions with prospective bidders and the utility personnel, the bid request was modified to include an overhead electrical distribution system, as well as a ground based network. The distribution system evolved into two distinct networks. These are a 460 V, 3 phase, 60 Hz, 3 wire, 40 kva and a 208 V/120 V, 3 phase/1 phase, 60 Hz, 4 wire, 32.5 kva.

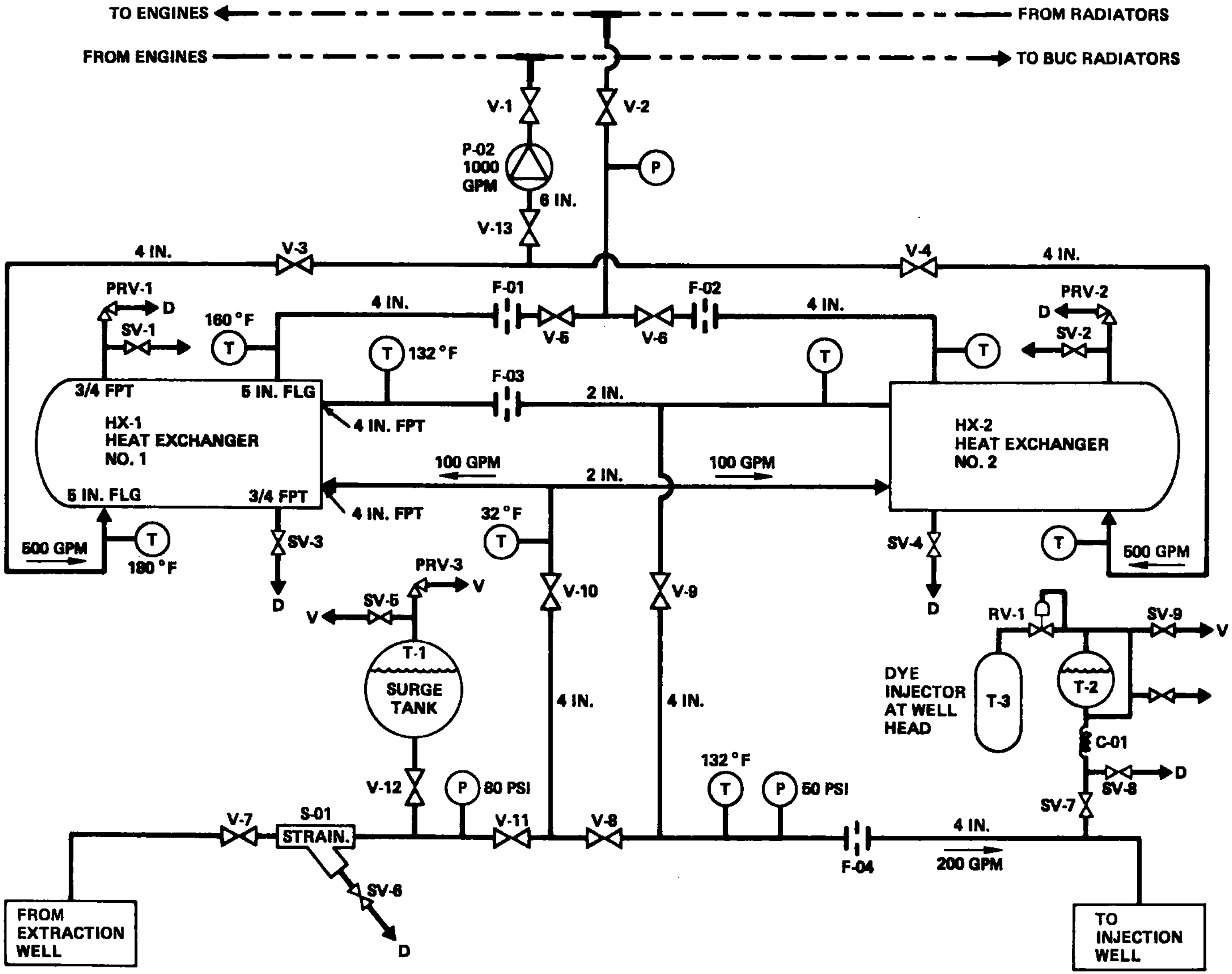


FIGURE 4.1. Water Supply System - Flow Schematic

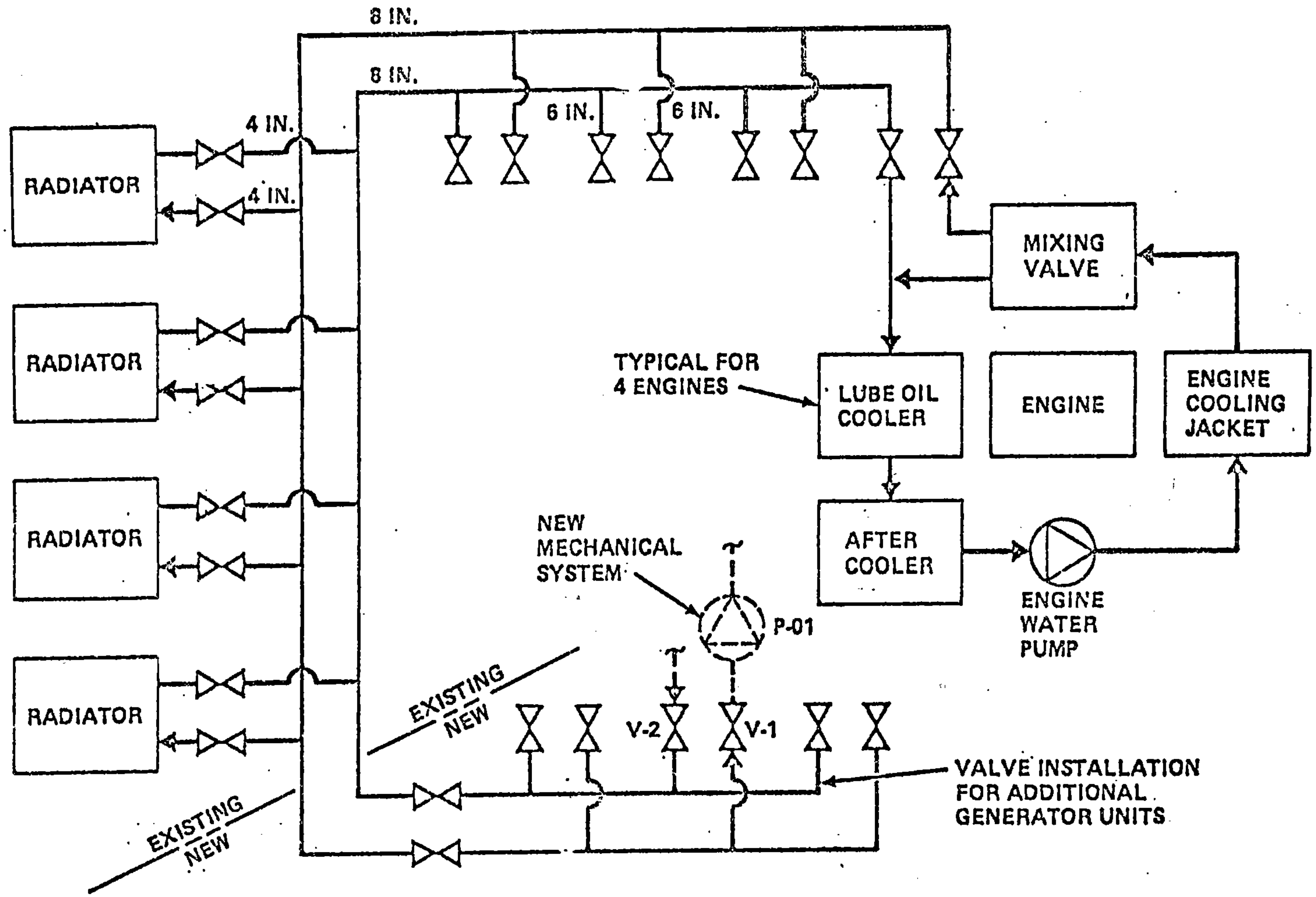


FIGURE 4.2. Interface with BUC

The 460 Vac system supplies the production well pump (W2) and the circulation pump for the heat exchanger. The 460 voltage level was chosen to adequately supply the motor inrush and operating currents without incurring undue losses, costs and wire size penalty.

The 120 Vac/208 Vac network is basically a Y connected system. Line to neutral voltage is used to power the instrumentation and heater systems. Both systems are metered for electrical energy output and are suitably protected by fused disconnects, breakers and grounding.

During operation, each pump is powered via an independent supply line and a pump control panel thus allowing full flexibility of operation, i.e., single pump, dual operation or programmed. Each well is supplied by an individual 45A, 120 Vac, single phase line. These lines originate at the central TRW control panel which is equipped with dedicated circuit breakers. A permanently connected 15A utility outlet and a 30A fused disconnect are provided at each wellhead. The fused disconnect will be used to de-energize the heaters during sensitive measurements and data collection periods.

Instrumentation

In Aquifer Characterization Planning, the instrumentation requirements were defined. In this task the details of the instrumentation system were selected, the elements of the system procured and shipped to the site.

The Aquifer Characterization instrumentation program comprises temperature, pressure, flow and strain measurements. Thermocouple connectors are provided at each well head for the type T thermocouples. The temperature will be measured using a Fluke 2190A digital thermometer, a Fluke Y2001 thermocouple selector and a Fluke Y2009 battery pack. The temperatures will be manually recorded at least once a day during the test program. The temperature from W-1, the injection well, will be continuously recorded on the Fluke Datalogger.

Hydrostatic pressure in the observation well will be sensed using Sensotec pressure transducers equipped with 0-5 V amplifers. A Fluke Datalogger will automatically record these pressures at a predetermined interval. The data will also be transcribed on a Techtran 817 data cassette. Production well pressure at the 200 ft level and atmospheric pressure will be sensed and recorded using Paroscientific DIGIQUARTZ pressure transducers, and pressure computers feeding a Hewlett Packard 150B printer.

Flow will be sensed with an Electronic Flo-Meters Inc. type F-3-500 flowmeter and Type DC-16 instrument. Data will be recorded on the Fluke 2240B Datalogger.

Sinco model 52621 vibrating wire strain gages on the casings of the water wells will have connectors terminating at the injection and production well heads. A Sinco portable readout will be used to display the change in strain directly and these readings will be manually recorded.

Stationary data acquisition equipment will be powered through an Elgar 6006B 110 Vac line conditioner. Portable equipment will be battery powered.

Selection of Contractors for Site Preparation, Test System Construction and Well Drilling

Request for bids for the two systems were published in the Bethel News-paper, Tundra Drums, on August 14, 1980, and bids received. Contract negotiations took place in September; the work schedule specified to the bidders required work completion by October 10, 1980. Note that work schedule is in part predicated on, and paced by, well completion schedules.

Drilling and Completing the Wells

Mobilization of the drilling equipment and materials was completed by September 20, 1980 and drilling started on Observation Well O-1.

Drilling of this first well was a learning experience for all concerned. The driller, who was the most highly recommended water well driller in Alaska, was used to punching a hole down to an aquifer without regard to performing the tests required by this program. Difficulties were experienced obtaining core samples with the wire line hammer available (9-in. throw). A heavier, longer throw (36-in.) hammer had to be flown in from Anchorage. Finally a drill rod subassembly was machined in order to get split spoon samples on the drill rod.

Drilling of the second observation well went much smoother and a usable gamma log was obtained, indicating two possible aquifer locations; one at

530-590 ft level and another between 700 and 800 ft. At this point a joint decision between TRW, Harding & Lawson and PNL was made to drill the withdrawal well, W-1 next, in order that a pumping test could be run to determine the most suitable aquifer. W-1 was drilled without significant incident and a 300 gpm pump installed. Initial tests showed excellent conditions with approximately 40 ft drawdown at maximum pump capacity. An additional pumping test was conducted with the lower aquifer zone plugged off. This test confirmed that most of the water was contributed from the zone at the 530-590 ft level. Subsequently, the remaining wells, 0-3 and W-2, were drilled to a depth of 620 ft rather than 800 ft in recognition of the upper zone as being the productive one. All observation wells were instrumented in accordance with the plan in order to collect data during the isothermal and energy injection tests which will follow.

The geotechnical investigation on the site performed by R&M Consultants in preparation for design of the roads and drill pads on the tundra is complete. Figure 4.3 is an aerial photograph of the site as constructed, and shows the final configuration of the roads and pads.

Equipment problems developed due to the remote location. These ranged from inadequate fork lifts to a failure of an electronic component in the electric logger equipment.

Additional work was done on System Design Criteria, Environmental and Institutional Issues and Quality Assurance and Safety.

System Design Criteria

The development of design criteria has been initiated by establishing contacts with the Bethel people responsible for producing the thermal energy that will be the source for the district heating project and those who will be managing and using the heat. The information obtained in these contacts fall into three categories:

- Availability of waste heat from the utility
- Physical requirements for the distribution system, and
- Energy requirements and existing heating plant of potential users.

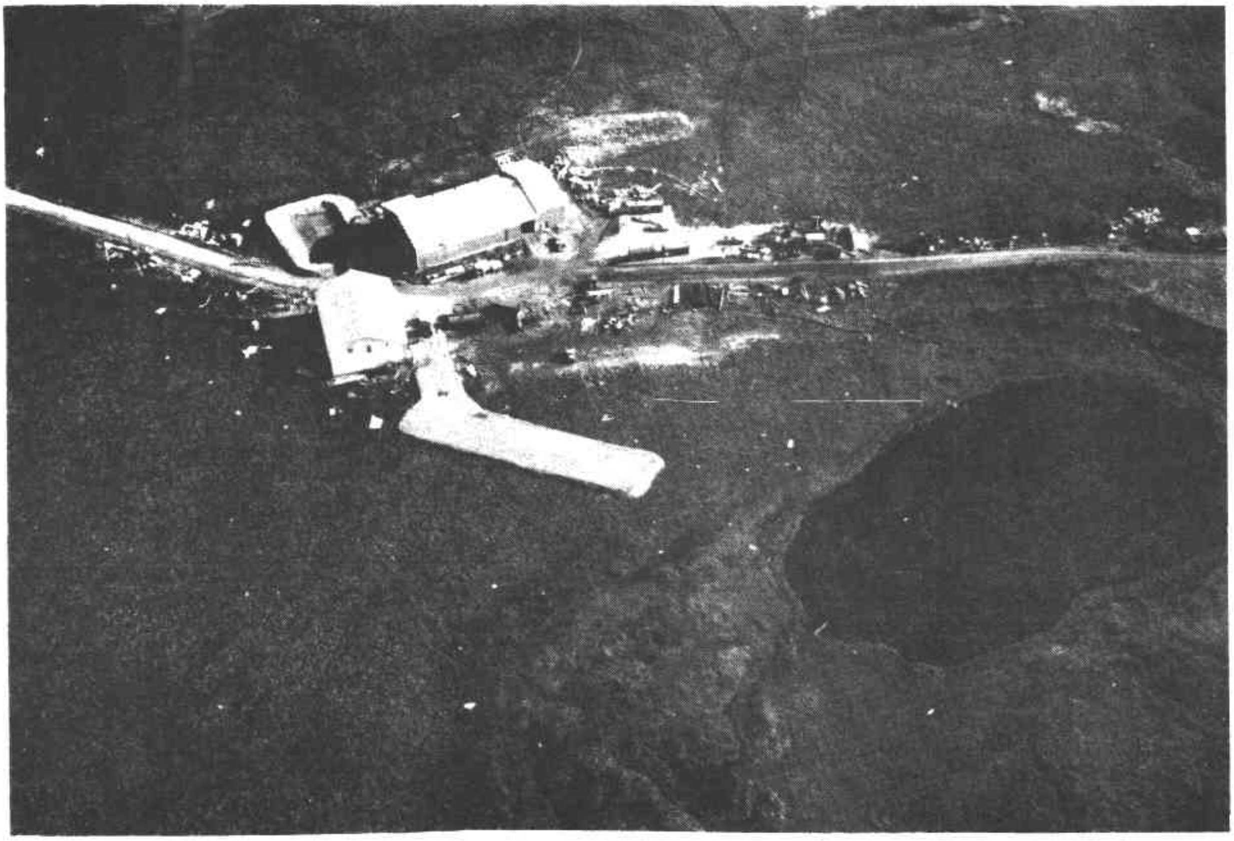


FIGURE 4.3. Aerial View of BUC with Roads and Pads as Constructed for Well Drilling

TRW is still in the process of obtaining and evaluating information so that the following discussion must perforce be considered as preliminary. More importantly TRW found, while assembling information needed to establish design criteria, that these were so intimately tied to the conceptual design that both are best developed simultaneously. TRW, therefore, plan to initiate the conceptual design effort and carry it forward in parallel with the continuing work on design criteria.

Waste Heat from the Diesel Generator Units

The Bethel Utility Corporation has four General Motors Diesel (GMD) S16-EMD-2100 generator units installed to date. Each is rated at 2100 kW or 3070 hp. Heat can be extracted from the engine cooling water and from exhaust gas streams.

The engine cooling water flow rate is 850 gpm; each of the radiators is rated at 500 gpm and can extract up to 6.45 x 10^6 BTU/hr. The coolant leaves the engine at 180 to 185^{o}F. The heat removed is proportional to the energy output, according to information obtained from GMD. Figure 4.4 shows the heat available from the coolant stream of each unit as a function of the load. Some of the design criteria, such as the acceptable flowrate variations in the distribution loop, the design value and the seasonal adjustment in the supply temperature, will depend on the design concept for control of waste heat utilization.

Figure 4.5 shows the power generated by BUC in October and November 1979.

The District Heating Distribution System

Practical experience with Utiliduct domestic water and sewer system serves to eliminate some previously considered options. The manager of the City of Bethel Facilities, Mr. Gary Volkman, has operated an underground water distribution system before that system was destroyed by freezing during a prolonged power outage due to fire at the BUC. Mr. Volkman insisted on having the replacement piping installed above ground in the Utiliduct, and finds that this system, which was much cheaper to install, is easier to maintain and operate. He recommends that TRW consider above ground insulated steel piping with Victaulic fittings supported on mud sills. Mud sills are more versatile and cheaper than pipes. The heat losses should not be excessive since the losses in the 1.5 mile long domestic water loop result in 0.5 to 1^{o}F temperature drop in the water flowing at 50^{o}F and a rate of 350 gpm. PVC is not usable; it is subject to creasing in cold weather, gets torn up by snowmobiles and shot full of holes. Steel piping with Victaulic fittings has stood up well.

Automatic equipment (i.e., controls, motorized valves) is not appropriate because of power fluctuations and outages, and because of a tendency of the operators to neglect inspections and maintenance when manual operation is not required.

Each pump must have a spare in place, plumbed in since maintenance in winter is too difficult.

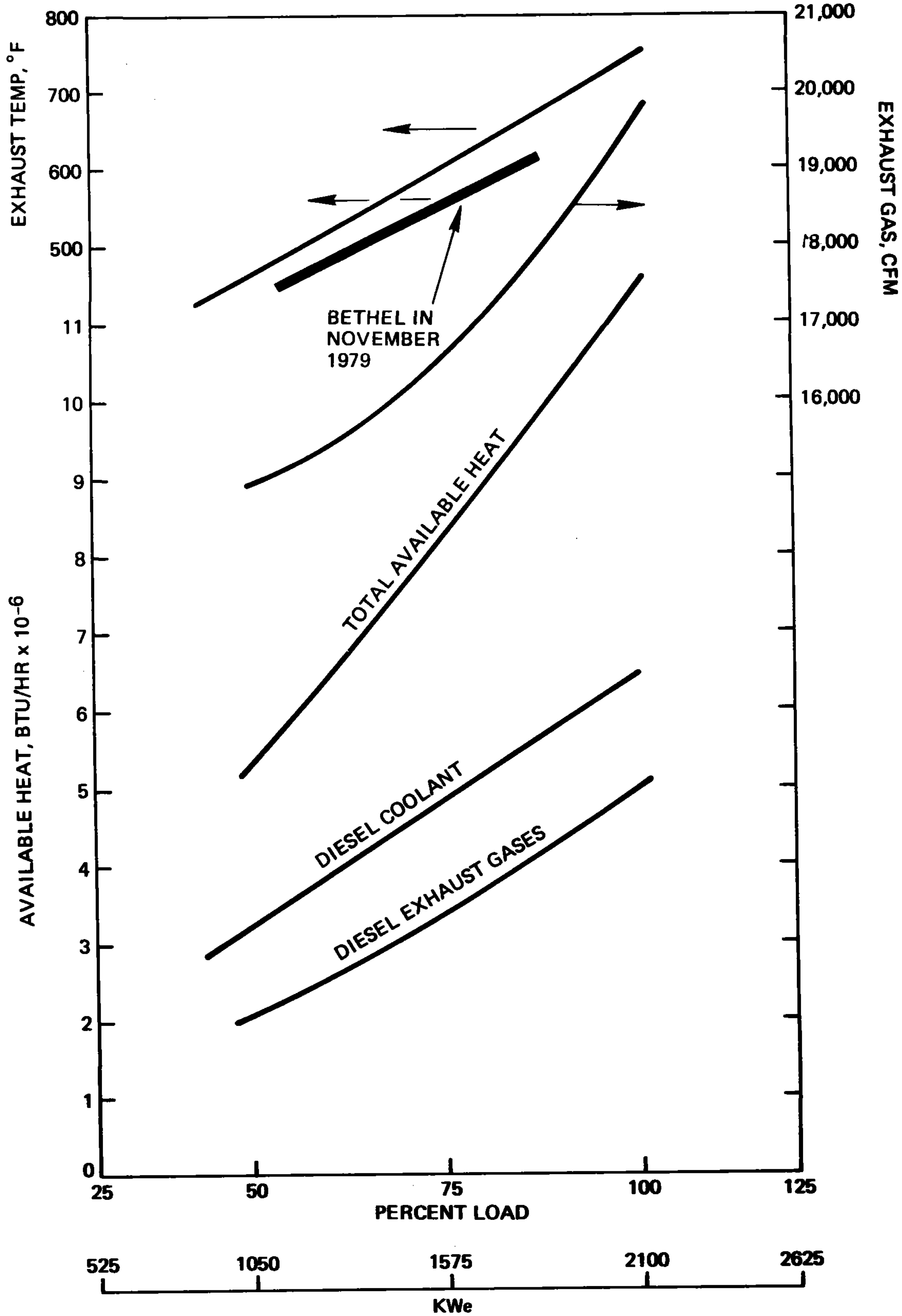


FIGURE 4.4. Recoverable Heat from BUC Diesel Generators
Design Day Ambient Temperature: 90°C

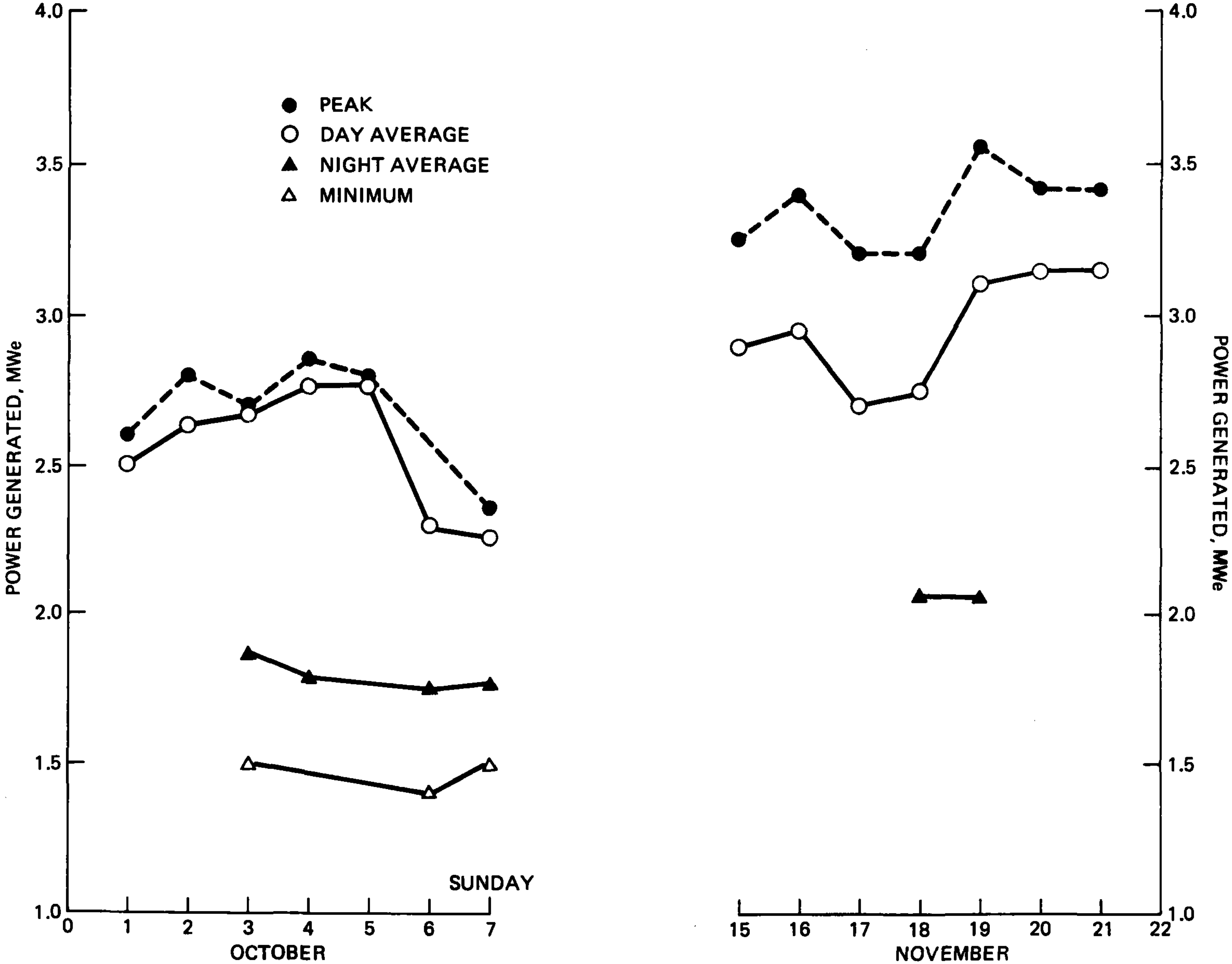


FIGURE 4.5. Power Generation Logs - BUC 1979

The above experience will be incorporated into the Design Criteria for the district heating system.

Energy Requirements and Existing Heating Plants of Candidate Users

Potential users for the District heating system are:

Bethel Hospital
Municipal Building Complex
Kuskokwim Community College
Kilbuck Elementary School
Domestic Water Heating System (the Utiliduct)
Bethel High School
Bethel Heights Housing Complex

The most remote user is the Bethel Heights Housing Complex. The 190 small houses each have a domestic water heater and a forced air heater. If the presently used water temperature in the forced air heater is higher than the distribution temperature, the heaters will have to be either modified to accept more coils, or be replaced.

The Bethel High School is served by three large (300 hp, or about 10^7 BTU/hr each) boilers delivering water at 22 psig and 210 to 220^{o}F. Two boilers are on line, the third one is coasting. The return temperature is above 170^{o}F. Space heating of the school is in part by baseboard convectors and in part by fan units. It is clear that connecting this system to a district heating distribution system will require some substantial equipment modification, either to adapt the space heaters to a lower temperature water supply or to modify the boiler to boost that temperature by burning oil, as needed. Note that the high school has spent $350,000.00 on heating oil, during the 1979 - 1980 heating season, paying $1.25/gallon. The price of oil is going up so that even a very substantial capital investment in a district heating system may pay back rapidly.

The domestic water heating system is a large heating oil consumer. The pump house for the domestic water supply includes two 10^6 BTU/hr boilers and two water tanks: 100,000 and 60,000 gallons. The 60,000 gallon tank is heated, so that the domestic water supply is maintained at 50^{o}F. The heat source is No. 2 oil in summer, No. 1 oil in winter.

The pump house is clearly a good candidate for the use of heat recovered from the aquifer even when the recovery temperature is too low to be utilized in the district heating loop.

TRW has not collected the desired information on the heating arrangements and heat loads in the Kilbuck Elementary School, Kuskokwim Community College and in the Municipal Complex. Too many people were on vacation in July, when they went there in connection with the construction of the electrical and hot water supply systems for the aquifer characterization test. They will obtain this information during the next quarter. It does not appear that the demonstration project will incorporate this facility because of financial limitations.

The new Bethel Hospital is the prime candidate for utilizing heat from the utility. It is located near the utility and its new heating plant uses 180°F water for space heating and 140 and 110°F for hot water. TRW obtained a set of drawings of the heating plant and is now in position to examine the several ways of integrating the hot water from BUC into this plant. Since the needs of a hospital to maintain space and water temperatures are critical to the well being of the patients, the oil fired water heaters will have to be able to operate with and without the district heating and will have to be maintained and periodically exercised. The actual fuel consumption of the hospital is not available as yet, since the hospital has barely opened its doors, but TRW will be able to monitor the operation of the plant through the 1980 - 1981 heating season.

The new hospital provides the ATES demonstration project with particularly favorable conditions: a large user, modern plant, proximity to the utility and to the aquifer, and high fuel costs. It appears that a suitable demonstration may be possible using the hospital only.

Environmental and Institutional Issues

During the report period an "Environmental/Institutional Investigation Plan" (TRW No. 80.1455.JMC.112, dated June 3, 1980), and an "Environmental Assessment and Monitoring Plan" (TRW No. 80.1455.JMC.114, dated July 15, 1980), were issued. After comments were received from PNL, these two plans were revised and incorporated in a "Phase I Environmental Assessment/Monitoring and Environmental/Institutional Investigation Plan (TRW No. 80.1455.JMC.127, dated August 25, 1980)."

Quality Assurance and Safety

Quality Assurance Plan

The Quality Assurance Plan was generated and submitted to Battelle on June 16, 1980, as part of the Management Plan.

A subcontract was negotiated with the Institute of Water Resources of the University of Alaska to review and evaluate the geohydrological aspects of the ATES system. The first independent review prepared by the University of Alaska was of the Aquifer Characterization Plan. A copy of this review is on file at PNL.

Project Status

Owing to substantial cost overruns in the field work in Bethel, the project was suspended on 10 December until additional funds could be identified to support continuation of the work, and an overall assessment made of the project.

4.1.1.2 State University of New York, Stony Brook Campus, New York Project

Dames & Moore, Inc.

The first 6 months of work in Stony Brook concentrated on the field work, although considerable study was made in the above ground installation and options. Work was accomplished on the following elements during this reporting period:

- Define User Needs
- Installation of Wells
- Site Stratigraphy
- Baseline Aquifer Characteristics
- Mathematical Modeling of the Hydrologic System

The user needs of the major buildings on the Stony Brook campus have been defined both in terms of peak tonnage and peak chilled water flow (see Table 4.1. The annual tonnage and flow are being determined by both historical means using chilled water logs and flow meter data, and by computerized load analysis. Computer models were developed and their results will be available in the near future.

TABLE 4.1. User Needs

Building	Peak Load (Tons)	Peak Chilled Water Flow (GPM)
#1 - Humanities	18	50
#2 - Chemistry	37	100
#2G - Graduate Chemistry	2,720	4,226
#3G - Math/Physics	3,190	-- *
#3V - Van De Graaff	120	170
#4 - Biology	70	150
#4G - Biological Sciences	3,150	4,920
#5 - Library	1,500	3,600
#11 - Engineering	118	310
#12 - Light Engineering	250	-- *
#13 - Heavy Engineering	310	500
#19 - Earth & Space Sciences	720	1,040
#20 - Administration	450	450
#21 & 22 - Fine Arts I & II	935	-- *
#24 - Social Sciences	190	-- *
#25 - Lecture Hall	280	475
#26 - Instructional Resource Center	310	525
#27 - Lab Office Building	160	1,000
#28 - Social & Behavioral Sciences	880	-- *
#37 - Campus Center	480	1,170

*Information to be obtained.

Two winter chilled water production methods are being studied for use on the Stony Brook campus (see Figure 4.6). The first method relies on the use of the existing cooling towers. Discussions have been held with manufacturers to determine the winter performance capabilities of the existing towers. In addition, the actual operating experience of similar cooling towers in the winter mode has been studied to identify potential problems. Based on preliminary data, Figure 4.7, the existing towers appear to have the necessary capacity. The second will use existing 100% outside air fan systems to chill well water. By using fan systems which must run continuously to supply building needs, the additional energy consumption of using cooling tower fans in winter may be avoided. The feasibility of using existing coils for this purpose is being discussed with their manufacturers and the overall concept feasibility should be known in early 1981.

The existing chilled water distribution and utility tunnel system has been investigated for possible use as a well water transport system. The system is presently being under-utilized in terms of its water flow capacity. For each leg in the distribution system (as shown on the site plan), the maximum flow capacity has been established and is presented in Table 4.2.

The mechanical system for the well doublet was designed and let for bid. A contractor was selected and construction was completed in November 1980.

The work accomplished will be described in detail under the applicable tasks which describe the work plan.

Define User Needs

This task has two basic purposes:

1. To define the amount of energy used by the user buildings for cooling purposes so that the potential energy cost saving of an aquifer system can be estimated.
2. To determine the amount of refrigeration effect which must be stored in the aquifer system to meet the annual requirement. This has a direct bearing on the size and number of wells and the overall system construction costs.

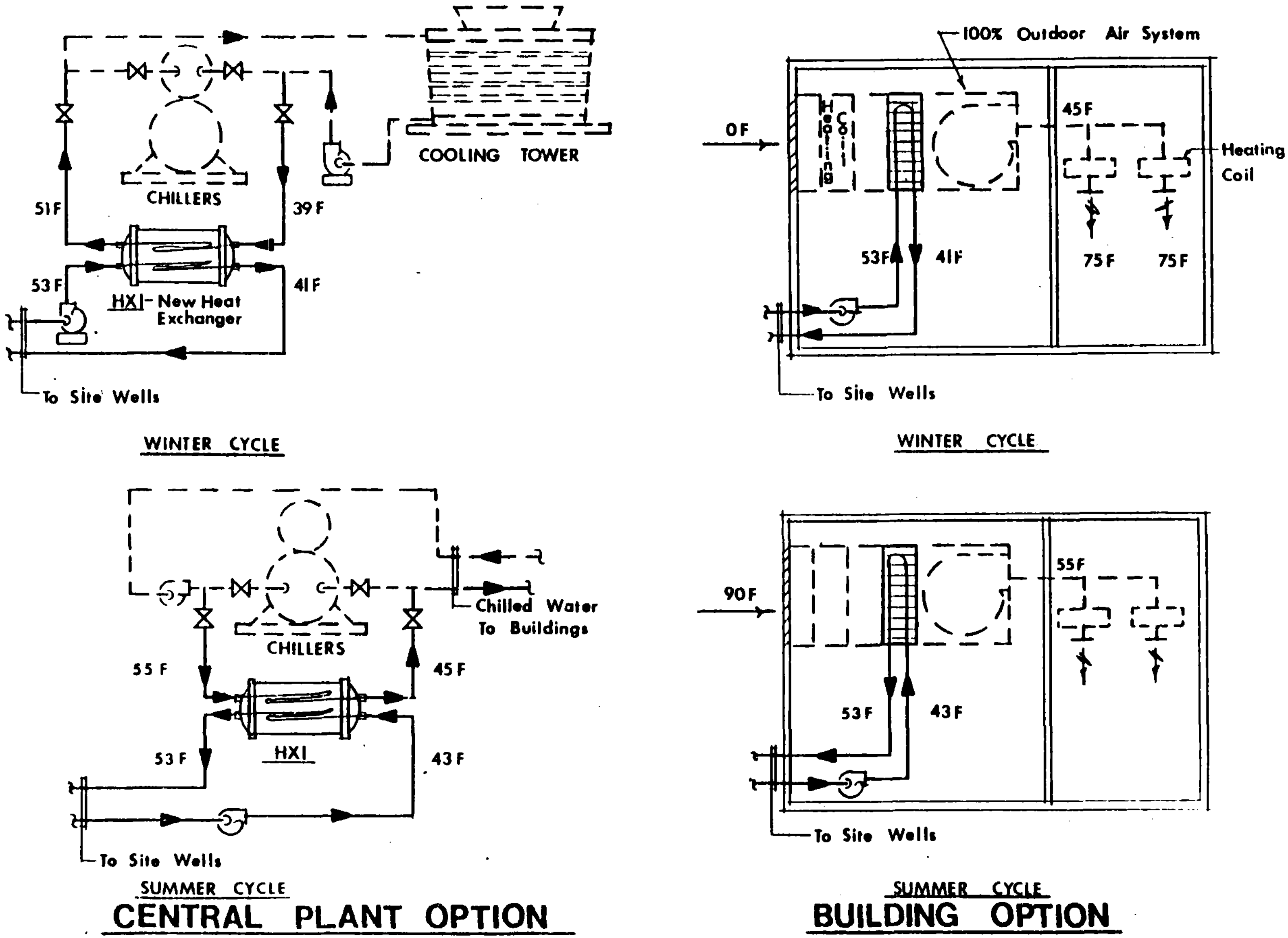


FIGURE 4.6. Production Options

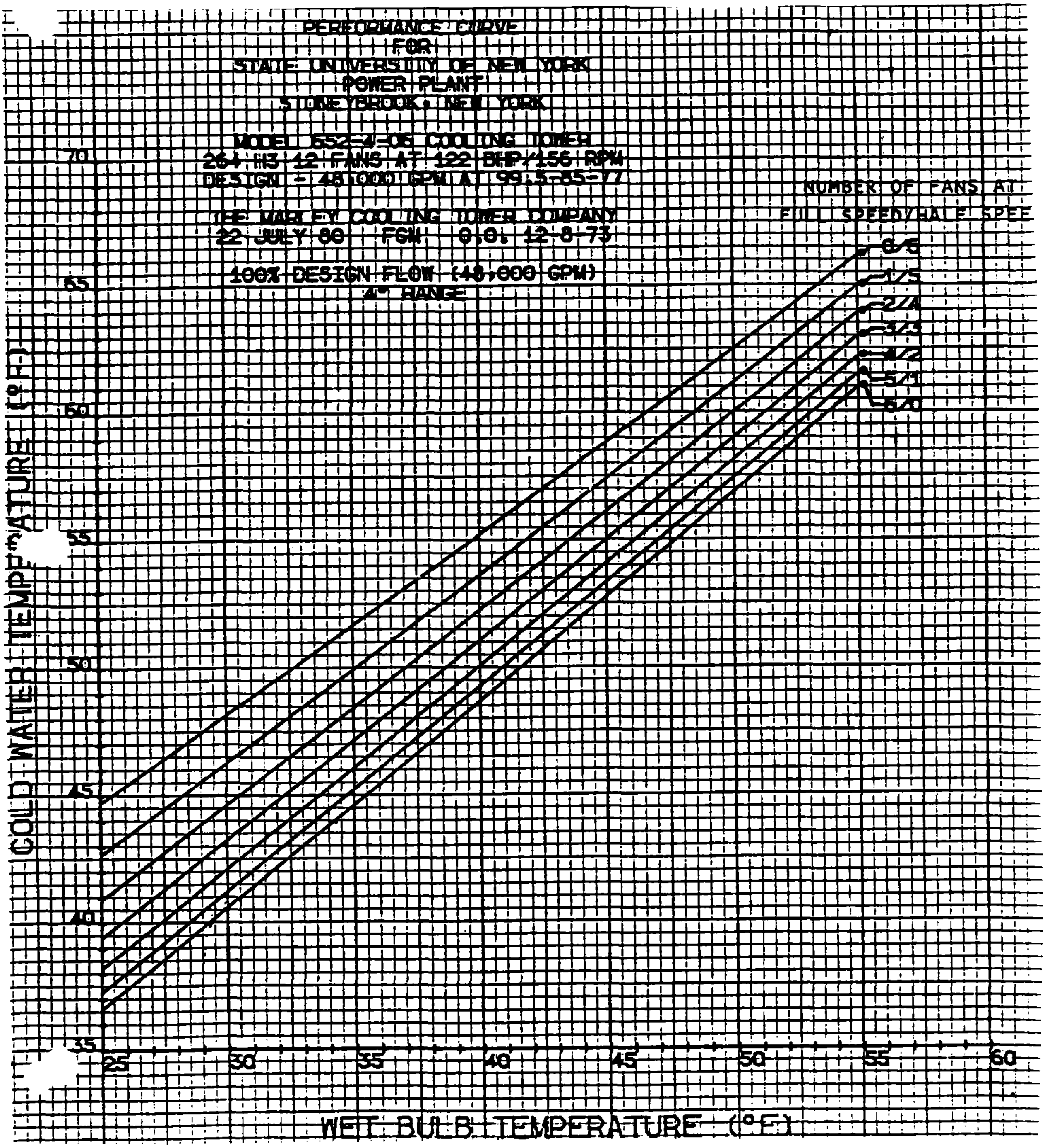


FIGURE 4.7. Cooling Tower Performance

TABLE 4.2. Chilled Water Piping

Distribution Segment No.*	Pipe Diameter (Inches)	Maximum Flow (GPM)	Pressure Drop (Ft. H_2O)
1	36	29,130	17.8
2	24	12,500	28.3
5	24	12,500	6.9
8	18	7,000	12.4
9	18	7,000	12.6
13	16	5,500	16.3
17	14	4,200	34.5
19	10	2,460	27.5
20	8	1,560	62.2
22	8	1,560	28.9
23	12	3,500	11.4
28	16	5,500	19.6
31	16	5,500	38.6
32	16	5,500	29.8
35	16	5,500	24.0
36	10	2,460	21.7
44	12	3,500	9.3
46	10	2,460	26.9

*see site plan

In order for a chilled water plant and distribution system to fulfill its purpose, it must deliver two related quantities to the user building: tonnage or cooling effect and required water flow. If the tonnage is available to the building but the flow is not consistent with the hydraulic requirements of the user building's mechanical system design, the user building's cooling load will not be satisfied. Therefore, in order to define the user building cooling needs both quantities must be established. Progress in both areas is discussed below.

The design connected loads for the individual buildings have been determined. A summary of these peak loads is presented in Table 4.1.

This information represents the instantaneous demand of the user buildings; it does not, however, relate directly to annual cooling consumption of each building. Two methods are being used to determine the annual consumption:

1. The first consists of a detailed examination of the chilled water plant logs and boiler plant fuel usage. This method examines user needs from the standpoint that the chiller plant must meet the load and therefore its output represents what is actually needed. Chiller logs were examined for 1979 and 1980. Pertinent data recorded include chilled water temperature in and out of the plant, outside air temperature (dry and wet bulb), number of circulating pumps operating and energy input to the steam turbine drives in terms of pounds of steam used. When related to the total plant, fuel consumption and estimates of the cooling effect can be made. A major drawback in relying on these data is the fact that they are incomplete. Steam flow data was not recorded for every month and therefore must be prorated based on percentage of total steam usage. The results of this analysis are presented in Table 4.3 and 4.4. However, due to a major chiller malfunction, only one chiller was available in July 1980; during this time the plant output was not enough to meet user needs. As a check of the empirical data, a theoretical basis is needed.

2. Analysis by Computer model. This basis is a computer model of the thermal loads of the user buildings. The model which is being used is DOE-II. Input data for all of the user buildings being developed and consist of the following information: building size, skin "U" values, internal equipment and lighting loads, occupancy schedules, HVAC system configuration and capacity, operating temperatures and humidity, and system control sequences. A sample of the input information is shown in Table 4.5.

   Once the input to the computer model are entered, the tonnage needed to satisfy the cooling loads to the user buildings will be defined. This output will be compared with the historical data. The impact of planned changes to the building operation and the impact of building energy conservation efforts will be simulated using the model, so that future tonnage requirements can also be established.

TABLE 4.3. Estimated Steam Use for Chilled Water Production,* (1979)

Month	Total Fuel Consumption (Gallons)	Total Steam Production (Lbs.)	Steam Used for Chilled Water (Lbs.)
Jan. 1979	949,200	N/A	0
Feb.	1,012,900	N/A	0
Mar.	754,100	N/A	0
Apr.	582,300	N/A	0
May	389,200	36,023,200	697,230
June	596,500	64,406,400	23,186,300
July	582,478	75,165,300	31,969,170
Aug.	587,570	71,260,000	39,159,330
Sept.	445,803	60,250,900	21,734,170
Oct.	441,580	67,337,100	2,070,330
Nov.	589,312	72,201,900	0
Dec.	765,005	N/A	0
Total	7,695,948	410,665,762	118,816,530

*Based on empirical data, and estimated prorations of total steam usage.

TABLE 4.4. Estimated Steam Use for Chilled Water Production,* (through September 1980)

Month	Total Fuel Consumption (Gallons)	Total Steam Production (Lbs.)	Steam Used for Chilled Water (Lbs.)
Jan. 1980	841,967	101,269,200	0
Feb.	857,764	97,590,600	0
Mar.	771,521	87,732,610	0
Apr.	482,570	56,184,800	0
May	241,770	29,930,900	450,570
June	438,439	52,107,000	18,758,520
July	492,809	56,297,900	33,684,920
Aug.	552,370	62,817,800	34,160,000
Sept.	---	---	21,195,000
Oct.	---	---	0
Nov.	---	---	0
Dec.	---	---	0
Total	4,679,210	543,930,810	108,249,010

*Based on empirical data, and estimated prorations of total steam usage.

TABLE 4.5. Building Load and Cooling Source

Building	Peak Load (Tons).	Original Design Cooling Source
#1 - Humanities	18	Well Water
#2 - Chemistry	37	Well Water
#2G - Graduate Chemistry	2,720	Central Plant
#3G - Math/Physics	3,190	Central Plant
#3V - Van De Graaff	120	Individual Plant
#4 - Biology	70	Well Water
#4G - Biological Sciences	3,150	Central Plant
#5 - Library	1,500	Central Plant
#11 - Engineering	118	Well Water
#12 - Light Engineering	250	Individual Plant
#13 - Heavy Engineering	310	Individual Plant
#19 - Earth & Space Sciences	720	Individual Plant
#20 - Administration	450	Central Plant
#21 & 22 - Fine Arts I & II	935	Central Plant
#24 - Social Sciences	190	Individual Plant
#25 - Lecture Hall	280	Individual Plant
#26 - Instructional Resource Center	310	Individual Plant
#27 - Lab Office Building	160	Central Plant
#28 - Social & Behavioral Sciences	880	Central Plant
#37 - Campus Center	480	Individual Plant

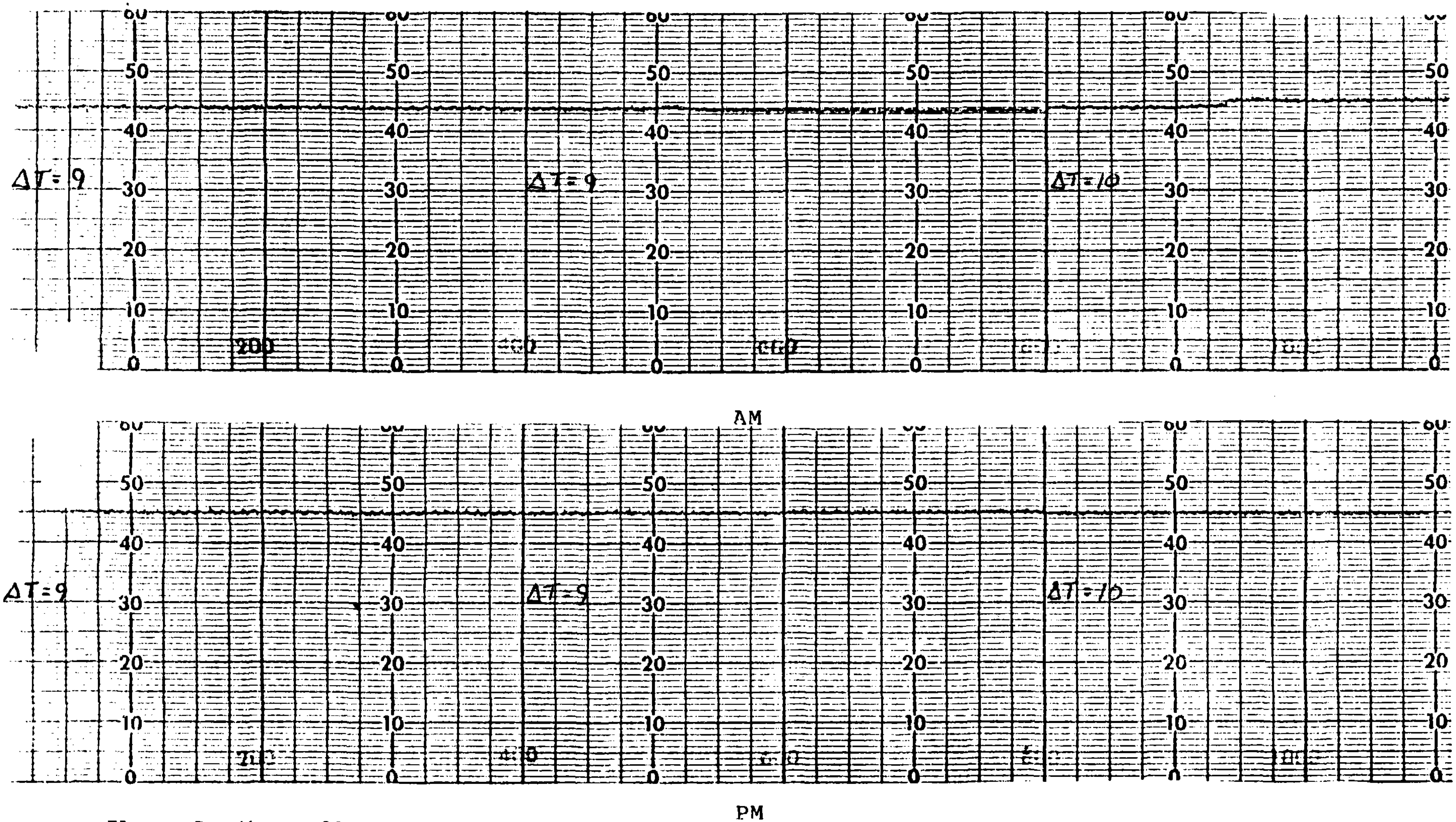
The flow requirement is a function of the design of the mechanical system in both the plant and the user buildings. It relates to the selection of cooling coils, sizing of pipe, use of bypass valves, etc. As is the case with tonnage, the peak flow rates for each building have to be established. However, it is much more difficult to determine how the flow rate varies with temperature and load throughout the year. To this purpose a chilled water and flow meter installed in the central chilled water plant which has been inoperative for the past several years was rehabilitated for the recalibrated as part of this task. This meter has been functioning properly since August 1980. A portion of strip charts recorded during this period is presented in Figure 4.8. It shows the flow at 8,500 gpm,; this flow has been shown to be quite constant during the period of observation. Because the chilled water plant has been shut down since September 1980, the next period of useful recording will begin in May 1981.

In addition to measurement of the central plant output, periodic measurements of the flow to the individual buildings were made using a portable measuring instrument and the existing Venturi flow meters installed in the major building. The combination of the central plant not being totally functional and mild weather resulted in unrepresentative data. A more complete spot meter program is planned for the next cooling season.

Installation of Wells

The drilling program was designed to complete the installation of necessary wells and pump to provide for the Stony Brook ATES feasibility study doublet test.

The site selected for the test was a wood lot and parking area south of the Engineering Heavy Laboratory. Figure 4.9 shows the test site and well locations. A well and pump formerly used for air conditioning the laboratory was incorporated in the doublet test. A driller's log of this well indicated approximately 160 feet of coarse glacial sediments of the Harbor Hills Formation overlay fine to medium grained silty/clayey sediments of the Magothy Formation. Discussions with local drillers indicated either the reverse rotary or straight rotary method could be used. The straight rotary method was selected because the 6 to 8 inch borehole required cannot be drilled with the reverse method, and drilling a larger hole would not be cost effective.



Flow = Reading x 200
Date: September 13, 1980

FIGURE 4.8. Sample Strip Chart Flow Readings

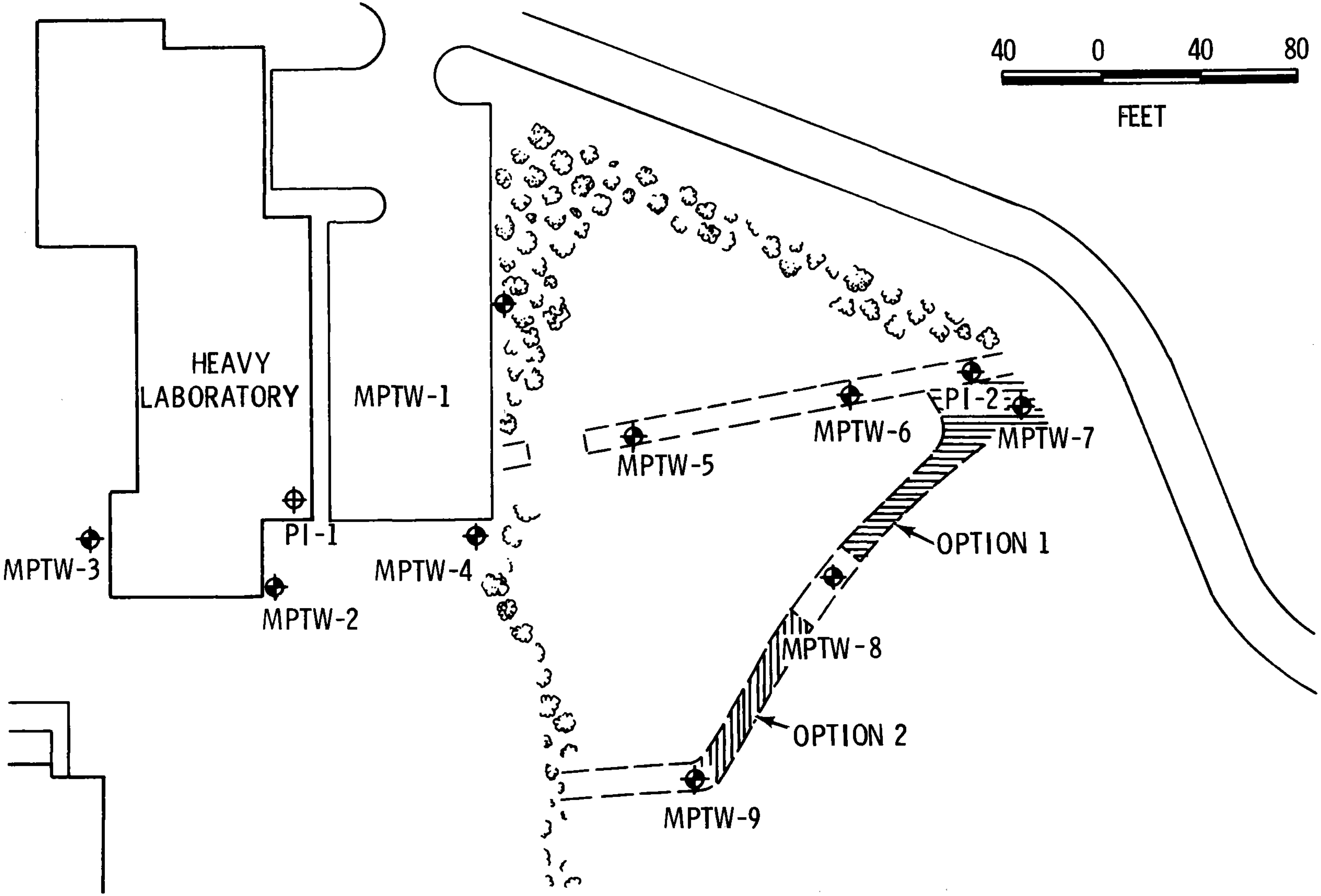


FIGURE 4.9. Stony Brook ATES: Well Location Map

Some clearing of the wood lot along the doublet line and between wells TPMW-8 and -9 was necessary to provide access to the well locations. Before clearing, trees for cutting were marked by the task leader in cooperation with personnel responsible for environmental studies.

The price for drilling the monitoring wells was based upon a per hole rate with addition for overdrill/feet, split barrel samples/each, Dames & Moore samples/hour, and logging standby time/hour. After specifications were let and bids received, Delta Well Company submitted the low bid for drilling services and was awarded the contract.

The equipment used by Delta Well Company was a Franks KF-50 combination air and mud rotary drill. Revert was selected as a drilling fluid because of the required viscosity and characteristic self-destruction after use. Extenders were used to delay breakdown when necessary. Earth mud pits were used to settle cuttings. After use, the remaining drilling fluid was removed and the mud pit backfilled.

A tricone bit was used to drill through the glacial sediments. This was then changed to an "open bottom" drag bit to permit extraction of split barrel samples through the drill rock from the underlying Magothy Formation. Dames & Moore samples require removal of the drill rods because of the tool diameter. This type of sample is obtained only when relatively undisturbed samples are needed.

Ten (10) split-barrel and three (3) Dames & Moore samples were obtained from PI-2. Heat capacity, thermal conductivity, and laboratory permeability were performed on the Dames & Moore samples. A sieve analysis was performed on selected split barrel samples for the purpose of selecting the proper screen slot size.

On the basis of the sieve analysis, fifty (50) feet of 0.035 inch six (6) inch Johnson "irrigator" galvanized steel screen was attached to the bottom of the six (6) inch welded joint steel casing and installed in the borehole and gravel packed with a #2 Morie well gravel. Following installations of materials, preliminary development of the well was performed with compressed air.

After completion of monitoring well boreholes and before material installation, the drilling equipment was moved to the next boring location to provide time for scheduling logging service. After logging, the 3/4 and 1-1/4 inch plastic tubing was manually installed in the 400 foot hole. The upper end of the pipe was difficult to manage without some means of support. This is provided by placing the backhoe near the borehole and resting the tubing against the raised bucket.

Gravel and bentonite pellets were poured in pre-measured quantities and each "lift" measured with a sounding line to assure proper placement of these materials. The upper end of the PVC tubing is protected with a steel casing cemented in upper two feet of borehole.

Wells TPMW-2 and TPMW-8 were exceptions to this installation procedure. In addition to 3/4-inch and 1-1/4-inch PVC pipes, two (2) 1-inch PVC piezometers were included to provide for an assessment of vertical transmissibility above and below the injection zone to test the uniformity of the hydrostatic levels in the wells as a function of depth.

Well TPMW-2 screened intervals are as follows:

1	1-1/4 inch	325 feet to 345 feet
1	1 inch	225 feet to 235 feet
1	1 inch	378 feet to 388 feet

Well TPMW-8 screened intervals are as follows:

1	1 inch	370 feet to 380 feet
1	1 inch	240 feet to 250 feet
1	1-1/4 inch	315 feet to 335 feet

The 3/4-inch PVC pipes in all monitoring wells were installed without a screen and then filled with water. All 3/4-inch PVC pipes were designed to be used as stilling wells for thermal measurements.

At the completion of each borehole, a geophysical log was obtained to confirm the stratigraphic log prepared during the drilling program on the basis of split barrel and ditch samples. The logging services were performed by

1) the United States Geological Survey; responsible for logging PI-2 and TPMW-3, 2) Leggett, Brashears, and Graham, a consulting firm from Wilton, Connecticut for TPMW-1, 2, 5, and 9 and 3) the remaining boreholes TPMW-4, 6, 7 and 8, were logged by Dames & Moore personnel.

Situations arose which made it necessary to further modify the well field design which had been set up. Specifically, four (4) well sites were relocated from the original scheme. TPMW-3 was relocated 37 feet to the southwest of the original surveyed point. This move was requested in order to have the drilling operation and observation well located at the side of the Engineering Heavy Laboratory Building, rather than directly in front.

Due to the presence of an extensive network of buried pipes, electrical and telephone lines, TPMW-1, 2 and 4 were relocated in areas beyond the existing underground obstacles but at as near the same radius from PI-1/2 as designed.

Well TPMW-1 was located at the edge of a leach basin for the storm sumps extending out from the Engineering Heavy Laboratory Building. Six-inch steel casing was installed to a depth of 60 feet below the ground surface. This casing was installed to retard the loss of drilling fluid into the leach basin.

During the preparation of the relocated site for TPMW-2, a 500 gallon tank was uncovered where the earth mud pit was being excavated. This mud pit was backfilled and re-excavated a greater distance from the tank.

<u>Site Stratigraphy</u>

The project site is underlain by the following sequence of sediments (in descending order):

1. Pleistocene deposits,
2. Magothy Formation (Cretaceous Age), and
3. Raritan Formation (Cretaceous Age - Raritan clay and Lloyd sand member).

The Raritan Formation was not penetrated during this study, therefore, it will not be discussed in detail in this section. The following general description is provided for the stratigraphic section studied for aquifer characterization. Two generalized geologic cross sections have been prepared for the doublet test area and illustrate the sequence of sediments to be discussed below. Soil description notations are defined as follows (with clay as an example):

1. Trace clay (10% clay),
2. Little clay (10-20% clay),
3. Some clay (20-35% clay), and
4. Clay (35-50% clay).

Glacial sediments of Upper Pleistocene Age range in thickness from 154 feet to 176 feet at the Stony Brook Campus and in the study area are composed of the following units:

1. Harbor Hill Unit (terminal moraine),
2. Lacustrine Unit, and
3. The Ronkonkoma Unit (ground moraine).

The Harbor Hill and Ronkonkoma ice advances both formed irregular ridges trending east-northeast across Long Island. The doublet test area is located on the Harbor Hill Terminal Moraine. This moraine is generally composed of crudely stratified sand and gravel layers and ranges in thickness from 42 feet to 60 feet. Sand strata are yellow brown to moderate yellow brown fine to coarse grained with little to some silt, with a trace to little amount of fine gravel. The gravel layers are generally composed of fine gravel and little to some fine to coarse sand and a trace to little silt. The layers range in thickness from a few inches to several feet.

Underlying the Harbor Hill Terminal Moraine is a light olive gray to brown silt and clay of lacustrine origin with some beds of fine to coarse sand and fine gravel ranging in thickness from 6 feet to 18 feet. The extent of these lake deposits is not fully known but may be relatively small in areal extent.

A ground moraine probably associated with the retreat of the Ronkonkoma ice advance underlies the lacustrine sediments and generally ranges in thickness from 87 feet to 108 feet with a greater thickness of 122 feet at TPMW-2.

The deposit consists of discontinuous layers of pale brown, to yellow brown sand with a trace to some amounts of silt, and layers of sandy fine gravel with various amounts of silt. This glacial unit appears thinnest in the area of Well TPMW-9 and thickest in the area of Well TPMW-2.

The glacial sediments unconformably overlie an erosion surface of the Upper Magothy. This formation consists of beds light to medium to light olive gray fine to coarse sands, containing traces to some amounts of small interclasts of silt and clay, interlayered with thin to thick beds of light yellow brown, pale yellow orange, dark yellow orange clayey and silty sand. The sand layers and the layers of silty and clayey sand range from 5 to 35 feet in thickness. The formation contains variable amounts of muscovite and lignite.

It appears that the upper 40 to 60 feet of the Magothy Formation has possibly been oxidized as an aeration zone during the period when the erosion surface developed. The transition zone of the oxidized yellow brown sediments to non-oxidized light gray sediments occur at a relatively uniform depth of 215 feet or of an elevation of 70 feet below sea level.

The Magothy Formation was not totally penetrated for this project, therefore, the exact total thickness of the formation in the doublet test area is not known. A log of deep well south of the doublet test area indicates the Magothy Formation is approximately 600 feet in thickness at the Stony Brook Campus.

Baseline Aquifer Characteristics

After completion of the observation well construction and development, static water levels and ambient aquifer temperatures were measured in all of the observation wells. Static water levels represent the piezometric surface at a depth of approximately 325 feet below the land surface. The screened intervals of the piezometers (10 feet) were centered at a depth of 325 feet.

A potentiometric contour map for the aquifer zone to be tested (300 to 350 feet depth) is shown in Figure 4.10. The contour interval is 0.10 feet. The distribution pattern of the potentiometric contours indicated that the aquifer is non-homogeneous in its water transmitting characteristics.

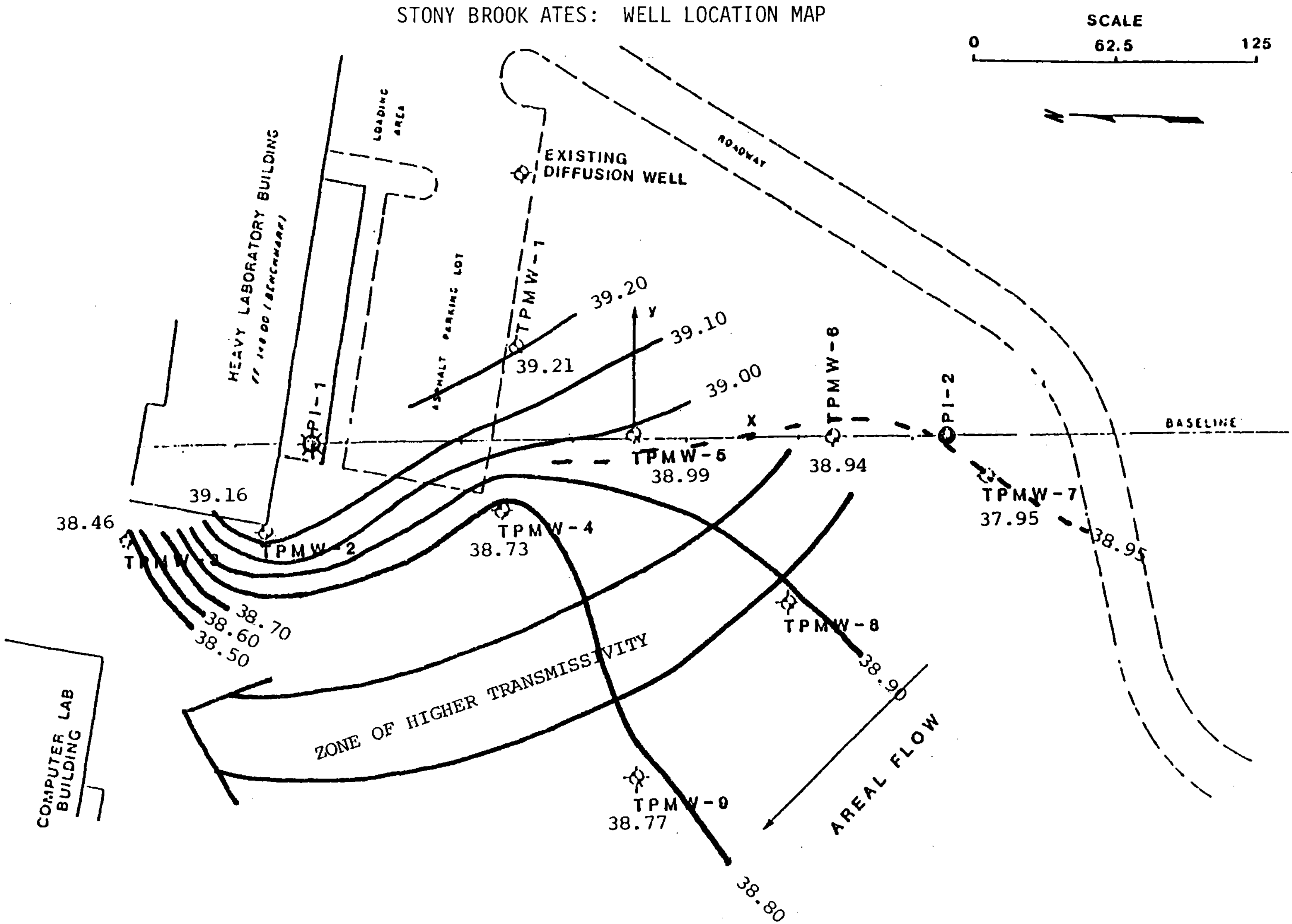


FIGURE 4.10. Static Water Level Contours, November 1980 (Feet Above Mean Sea Level)

Based on the premise that the ground water flows at right angles to the potentiometric contours toward zones of lower potential, it can be seen that the ground water is flowing generally from east to west and southeast to northwest.

Background temperature measurements were made in the observation wells during the month of November 1980. A map view of the background aquifer temperatures at a depth of 330 feet is shown in Figure 4.11. The contour interval is $0.1^{o}C$. For the area of observation, the minimum temperature is $10.2^{o}C$ (at TPMW-6) and the maximum is $11.3^{o}C$ (at TPMW-2). It has been shown by Supkow (1971) that ground-water flow and ground-water temperatures are generally related as follows:

1. Ground water generally increases in temperature in the direction of ground-water flow. (This results from the ground water adsorbing geothermal heat and/or atmospheric heat from the land surface as it flows through the ground.)
2. The rate of ground-water temperature increase is at a minimum along the axis of the zone of maximum ground-water flow rate.

By using these two basic principles as a guide, the axis of the zone of maximum ground-water flow rate can be determined from the temperature contour map of the aquifer along with the ground-water flow direction in the area under study. This axis is delineated by the large arrow in Figure 4.11. By comparing Figure 4.11 with Figure 4.10, it can be seen that the axis of the zone of maximum ground-water flow rate deduced from the temperature contour map corresponds to the axis of the zone of relatively high transmissivity deduced from the potentiometric contour map. This is exactly what one expects from theory; that is for a given aquifer regime, the ground water is expected to flow most rapidly along the zone of highest transmissivity. Agreement between the results of the thermal analysis and the results of the potentiometric analysis provides support to the confidence level of the aquifer characteristic analysis.

The foregoing analysis provided only relative aquifer characteristics; that is, only the locations of the zones of maximum and minimum transmissivity and ground-water flow rates were indicated. In order to determine the absolute value of the aquifer parameters, an aquifer performance test was conducted.

STONY BROOK ATES: WELL LOCATION MAP

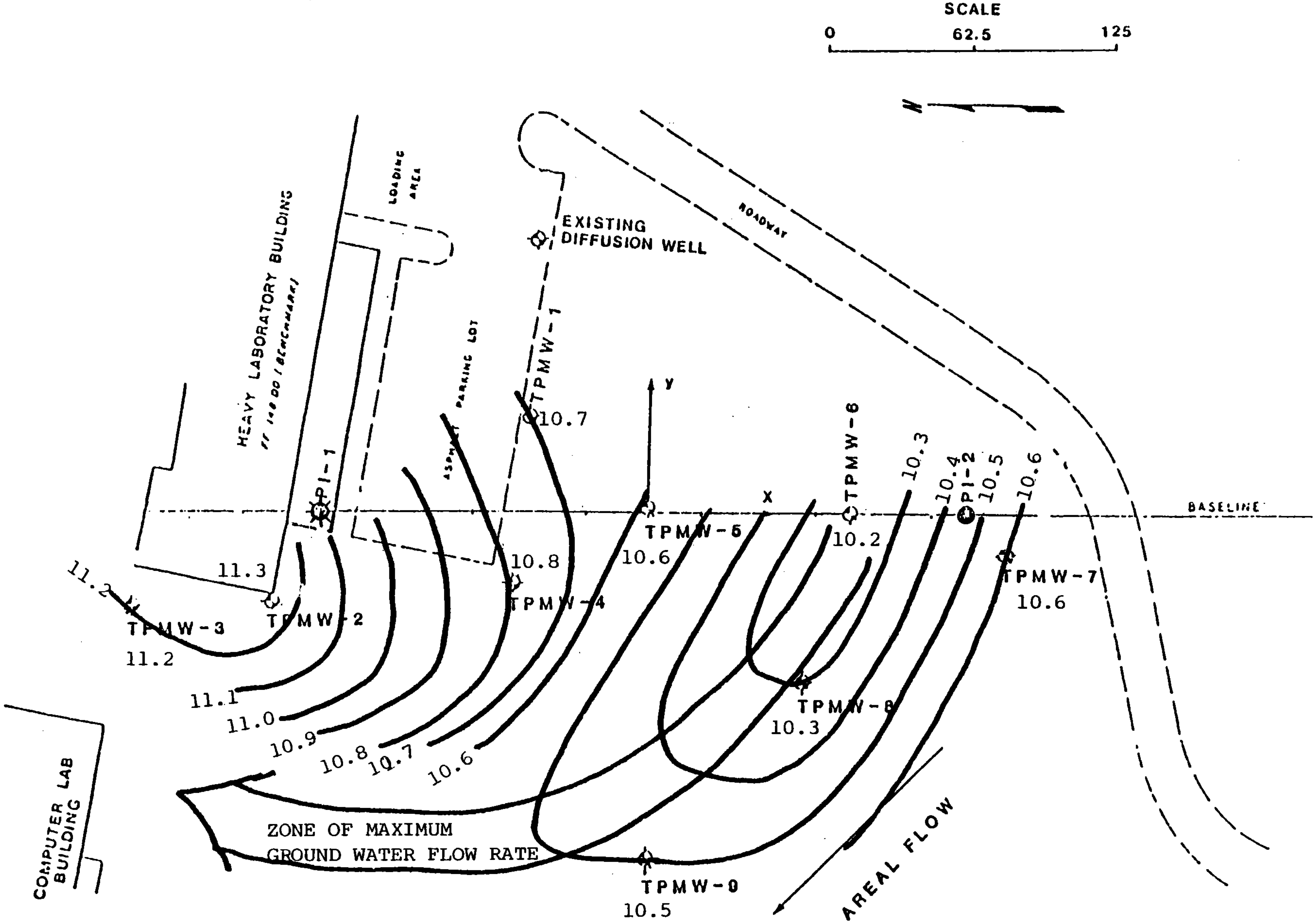


FIGURE 4.11. Initial Aquifer Temperatures at Depth of 330 Feet in November 1980 Before Start of Pump Testing (In ^{o}C)

Basically, Well PI-2 was pumped at a constant rate of 312 gpm for 48 hours. Drawdowns were measured in all of the observation wells. Analysis of the pump test data indicates the following:

1. The aquifer zone being tested (300 to 350 feet depth) is non-homogeneous and anisotropic in the horizontal plane.
2. The aquifer zone being tested appears to behave like a leaky artesian aquifer.

By using the Jacob straight line method, the initial drawdown data (before the effect of leaky conditions became significant) were analyzed by hand calculations to determine the aquifer transmissivity and storage coefficient. These data are summarized in the computer data section. In addition, the data were also analyzed by computer with equivalent results.

The effects of leaky artesian conditions became significant at different times for different observation wells. Departure times from the straight line portion of the time-drawdown plots for the observation wells vary from extremes of 30 minutes (TPMW-9) to 1500 minutes (TPMW-8). The remaining values are in the range of 70 to 160 minutes.

The drawdowns at the end of 100 minutes were plotted. The drawdown contours do not form uniform concentric circles around the pumping well. The distortions in the drawdown contours result from inhomogeneities in the aquifer transmissivity. In general, it can be expected that the cone of depression will spread most rapidly away from the pumping well along the zone of maximum transmissivity. This will result in a protuberance in the drawdown contours along the zone of higher transmissivity. These zones of drawdown contour distortion correspond with the zones of higher transmissivity deduced from the baseline potentiometric and temperature data.

The various values of transmissivity determined from the pumping test, in a relative sense, appear to be consistent. The zone of higher transmissivity appears to extend from the vicinity of the pumped Well PI-2 northwestward toward the vicinity of observation Well TPMW-3. The transmissivity in this zone appears to be in the range of 18,000 to 28,800 ft^2/day. This zone is flanked by transmissivities in the range of 10,200 to 11,900 ft^2/day.

Results of the pumping test analysis are consistent with the results of the baseline potentiometric and aquifer temperature data. This increases the confidence level of the overall aquifer characterization which will thereby allow the aquifer system to be modeled with a correspondingly high level of confidence.

Mathematical Modeling of the Hydrologic System

In this work, we are concerned with the use of the computer model (GREASE2) to develop an understanding of the flow and temperature behavior for various well systems during reinjection of cooled water into aquifers. The well patterns considered thus far include doublet, triplet and five-spot systems. Input data (hydraulic and thermal projections, doublet spacing and flow rates etc.) used in the preliminary simulations are based on currently available information. For the doublet system, a comparison between the numerical solution from GREASE2 and the analytical solution developed by Gringarten and Sauty (1975) is presented. The information gained from the numerical simulation has been used as an aid designing the well doublet field experiment currently in progress. Temperature data collected thus far and drawdown time data collected from a supplementary 48-hour pump test conducted to evaluate the aquifer properties are included in this report.

The following general comments pertain to these data:

- It appears that the temperature data collected thus far are accurate and within the limits predicted by preliminary computer simulations. It is also evident from the preliminary analyses that the anomalous temperature profiles (in the zone above - 300 feet elevation) caused by surface heating will not have significant effect on the temperature distribution in the main aquifer located between -300 and -350 foot elevations.
- The collected pump test data reveal that the average transmissivity of the aquifer is on the order of 10,000 ft^2/day and the average storage coefficient is on the order of 5×10^{-3}.

4.1.1.3 University of Minnesota Project

University of Minnesota (Physical Plant Operations)

Drafts of The Management Plan, Aquifer Characterization Plan, and Environmental/Institutional Plan were submitted. These documents form the baseline for the project.

Work was accomplished on the following elements during this reporting period:

- Hot Water Technology
- System Economic and Energy Assessment
- Well Drilling
- Aquifer Characterization and Modeling
- Surface System Design
- Legal and Institutional.

Hot Water Technology

Reviews were made of well construction design and expected expansion problems, and above ground hardware and flow diagrams. Development was initiated on modeling of advanced heat exchange technology.

Literature research was started on the following mechanisms:

a) Antifouling Heat Exchangers
b) Direct Contact Heat Exchangers
c) Shallow Solar Ponds
d) Direct Contact Power and Heat Pump Cycles
e) Geothermal Power Systems

Calculations have been completed on a constant property model heat pump. The report on the performance of the contact heat pump is being prepared. Summarily, this report indicates that the use of this system will reduce fouling from the hot water, provide a means of deriving more heat on an annual basis with lessened fuel input, and provide a means of extracting more heat from the stored water by reducing the return temperature.

Calculations on the preliminary design of a heat exchanger are in the form that permits comparative estimation of system performance against the direct contact heat exchanger viz-a-viz the number of transfer units in the exchanger.

System Economic and Energy Assessment

The main objectives of this work are to characterize the overall system performance of the proposed ATES system concepts and configurations, on the basis of energy management and conservation, and to compare the economic viability of the different proposed options. The energy and economic analyses will independently verify the results of the concepts and system engineering studies with inputs generated by the aquifer characterization and modeling studies.

Simple energy models are developed for the whole system which is made up of the several thermal energy sources on the Minneapolis and St. Paul campuses including the cogeneration S.E. plant, the heat transport subsystems, the various thermal and electrical loads, and the aquifer storage subsystem. These models are inherently simple because they are based on idealized thermodynamic relations expressing the mass and energy flows--the heat balances--within the whole system for various operating conditions. Since the thermodynamical models are essentially static, they are expressible in the form of algebraic equations which can be formulated conveniently on a small computer or even a programmable calculator. However, the models are general and flexible to allow for the simulation of monthly and daily operating conditions and to account for changes in system configurations or in operating strategies designed to improve the system performance in some sense. These models will be used to establish system efficiencies, in particular with regard to aquifer storage and its effect on plant operation following a series of change-discharge cycles.

In parallel with the above energy system studies, preliminary economic analyses are performed to evaluate the merits of various concepts and configurations proposed for the possible deployment of the ATES system. The methodology to be used is a standard present value economic analysis; the values of the systems are determined on the basis of life-cycle costs and savings. Various criteria will be adopted for assessing the economic benefits of the systems. The final assessment is guided by determining how much fuel and capacity displacement (capacity factor changes) will accompany the use of the aquifer storage. An attempt will be made to formulate simple economic mathematical models which can be optimized in the sense of minimizing annual expenditures and fuel costs for the projected thermal loads. Full benefits from electricity generation as by-product of the cogeneration are accounted for as credits in the cost estimates. The objectives of the value analyses, based on inevitable simplifying assumptions, will not be to provide complete financial status or precise detailed cost estimates; rather the formulation will lead to the determination of the influence of various parameters and variables, thereby serving as guidelines for the selection of a preferred candidate ATES system and for its design.

The tentative analysis indicates resolution of the economic and energy parameters and variables for the following system configurations:

ATES Options

Option		
0	Reference case:	Minneapolis ICES separate from St. Paul Campus
1	Base case	Minneapolis ICES added to corridor, St. Paul Campus with aquifer
2	Reduced case:	Minneapolis ICES separated from St. Paul Campus with aquifer
3	Extended case:	Base case with high-temperature water enhancement

Data were collected for use in the economic and energy assessment analysis. Preliminary modeling and computer programming was initiated based on a present value analysis. Work has begun on an energy/thermodynamic model for Phase II concept.

Well Drilling

Development of well specifications and locations, and drilling of the core holes and monitoring wells were major efforts during this reporting period. Figure 4.12 shows the well site locations on the University of Minnesota, St Paul Campus. Figure 4.13 shows the well location detail and defines the well codes and symbols.

Plans and specifications were completed for core drilling and bid invitations issued, with a return date of August 5, 1980. A contract was awarded on August 8, 1980 for $122,665 for the core drilling. Drilling started at core location AC-1 on September 1, 1980 and the core hole was completed on September 23, 1980. Drilling of BS-1 (changed from BC-1) began on September 24, 1980 and was completed on October 11, 1980. Core Hole BC-1 (changed from BS-1) was started on October 13, 1980 and was completed on October 27, 1980. Core Holes AC-1 and BC-1 were completed as monitoring wells.

Plans and specifications were completed, bids issued, and a contract awarded for the following monitoring wells:

Designation Number	Description
AS-1	Supplemental Monitoring Well
AM-1	Monitoring Well
AM-2	Monitoring Well
AM-3	Monitoring Well
CM-1	Monitoring Well

The contractor will begin drilling operations early in January 1981.

The preliminary design for the heat injection well and the water supply well was completed and routed for review.

Aquifer Characterization and Modeling

The major emphasis during this reporting period was an evaluation of data provided by the drilling activities and on implementing the hydrology and heat transport models. Figure 4.14 shows the general geologic stratigraphy underlying the test site. The Franconia-Ironton-Galesville formations are the target aquifers for thermal energy storage at this site.

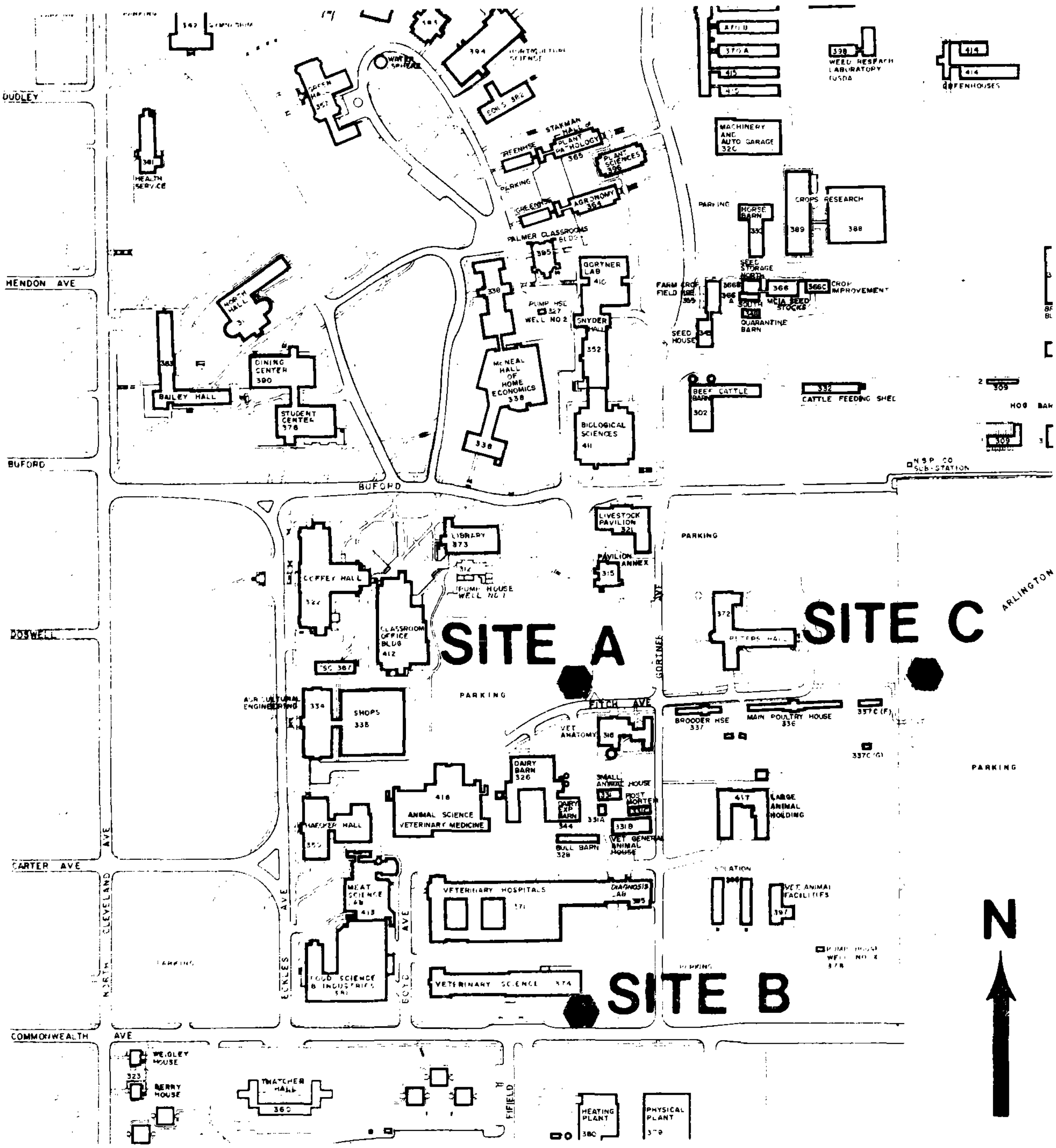
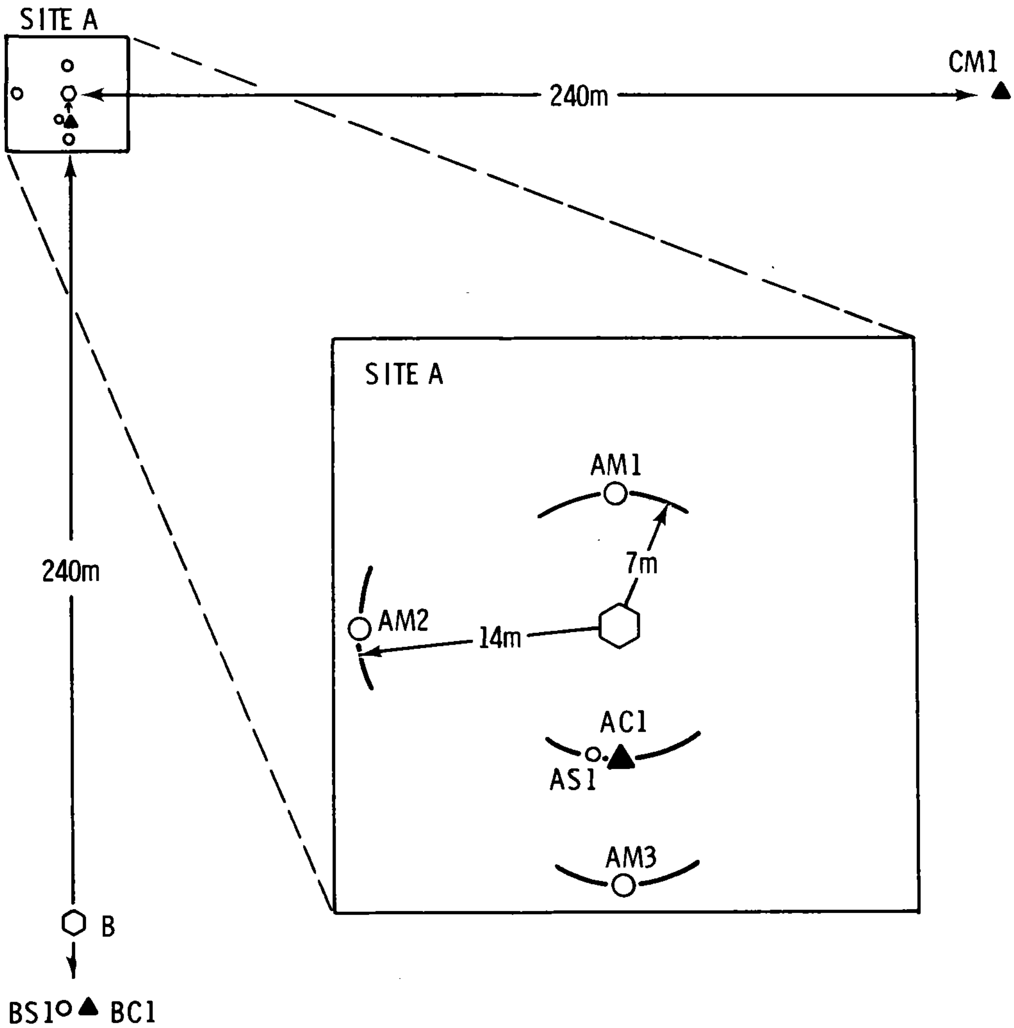


FIGURE 4.12. Well Site Locations - A, B, C, "ATES" Project, University of Minnesota



LOCATION DIAGRAM OF TEST WELLS AND MONITOR WELLS

A = HEAT INJECTION WELL
B = WATER SUPPLY WELL
AC1, BC1 = CORE BORINGS
AS1 AND BS1 = SUPPLEMENTAL MONITOR WELLS
FOR AC1 AND BC1
AM1, 2 AND 3, CM1 = MONITOR WELLS

5 MONITOR WELLS, 2 PRODUCTION WELLS
2 CORE BORING WELLS

FIGURE 4.13. Location Diagram of Test Wells and Monitor Wells

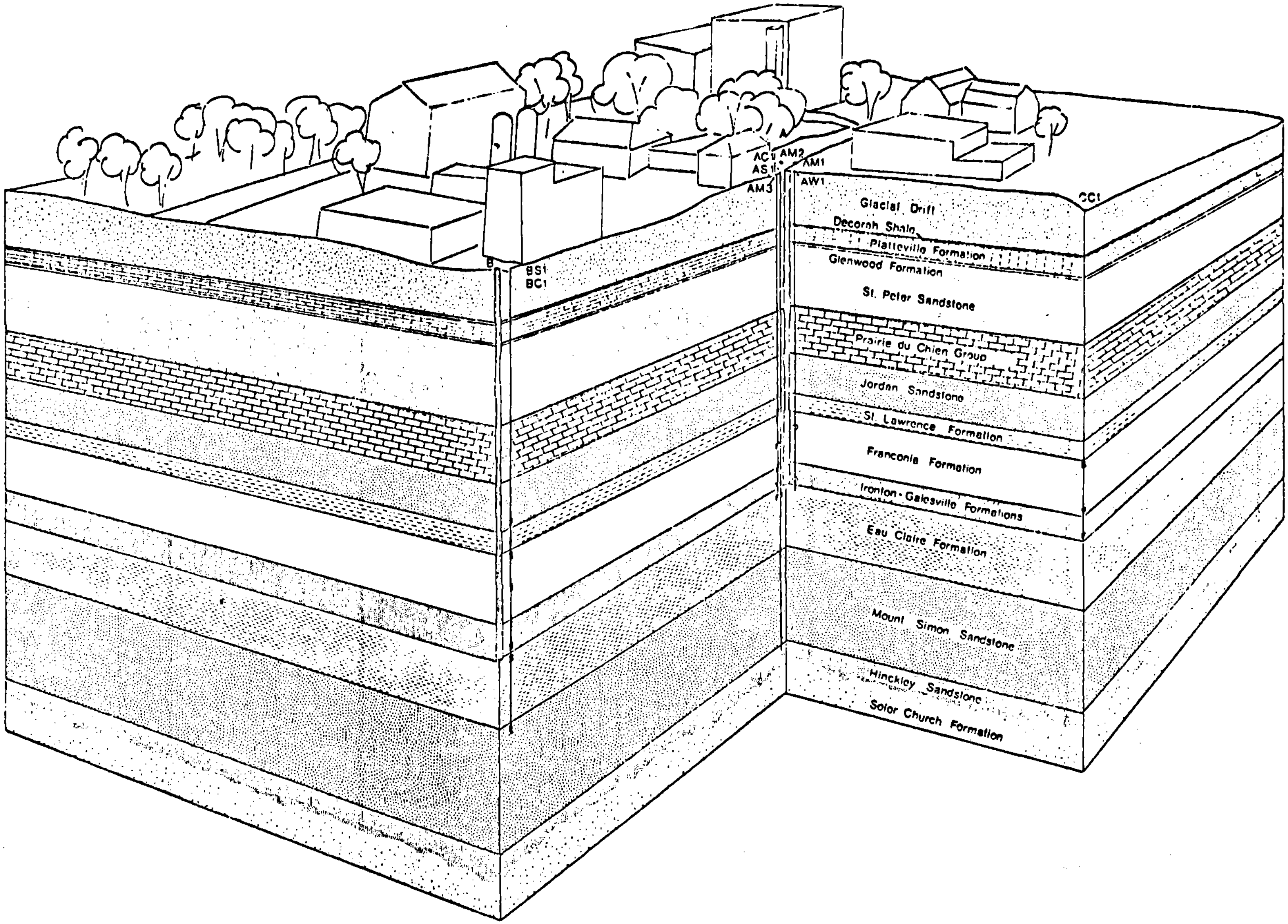


FIGURE 4.14. ATES Test Facility in Relation to Geology, University of Minnesota, St. Paul

All Paleozoic rock units were penetrated, and most were cored. Only the St. Peter and Jordan formations presented problems because the sandstone was poorly consolidated and did not core. Nearly complete core recovery was accomplished in the Franconia-Ironton-Galesville (FIG) formations (the aquifer) and the St. Lawrence and Eau Claire formations (the upper and lower confining beds, respectively).

Activities at the drilling sites were continuously monitored by the Site Control Officer. All cores were logged, photographed, sealed in polyester sleeves and boxed for storage. A television camera was lowered into Hole AC-1 to observe the results of casing perforation required by the Health Department. Well packer tests were conducted to determine hydraulic conductivity of the formations. Hole alignment tests on the holes were performed to insure that the test data during heat injection would be accurate and not misleading by not knowing inter-hole distance, etc., at the hole bottoms.

After core drilling at test Holes AC-1 and BC-1 was completed, geophysical logging and hydraulic testing by use of inflatable packers was performed. Geophysical logs run included natural gamma, single point resistivity, self-potential, caliper, temperature, specific conductance, and bore-hole flow meter. Eight packer tests were made on AC-1. Locations of the packed intervals are shown on Figure 4.15. Fourteen packer tests were made on Test Hole BC-1 with both packers inflated, and four tests were made with only one packer inflated. Figure 4.16 shows the location of the test intervals. The spacing between the packers is 21 feet. The relatively close packer spacing provided detailed information about the position and thickness of the less-permeable parts of the target-injection zone. Analysis of the results of hydraulic tests made in the fractured and more permeable strata, however, were complicated by vertical movement of water adjacent to or near the packers. Visual inspection of the cores and the results of the hydraulic testing and geophysical logging of test Hole BC-1 support the conceptual model of six hydrologic zones within the Franconia-Ironton-Galesville stratigraphic sequence.

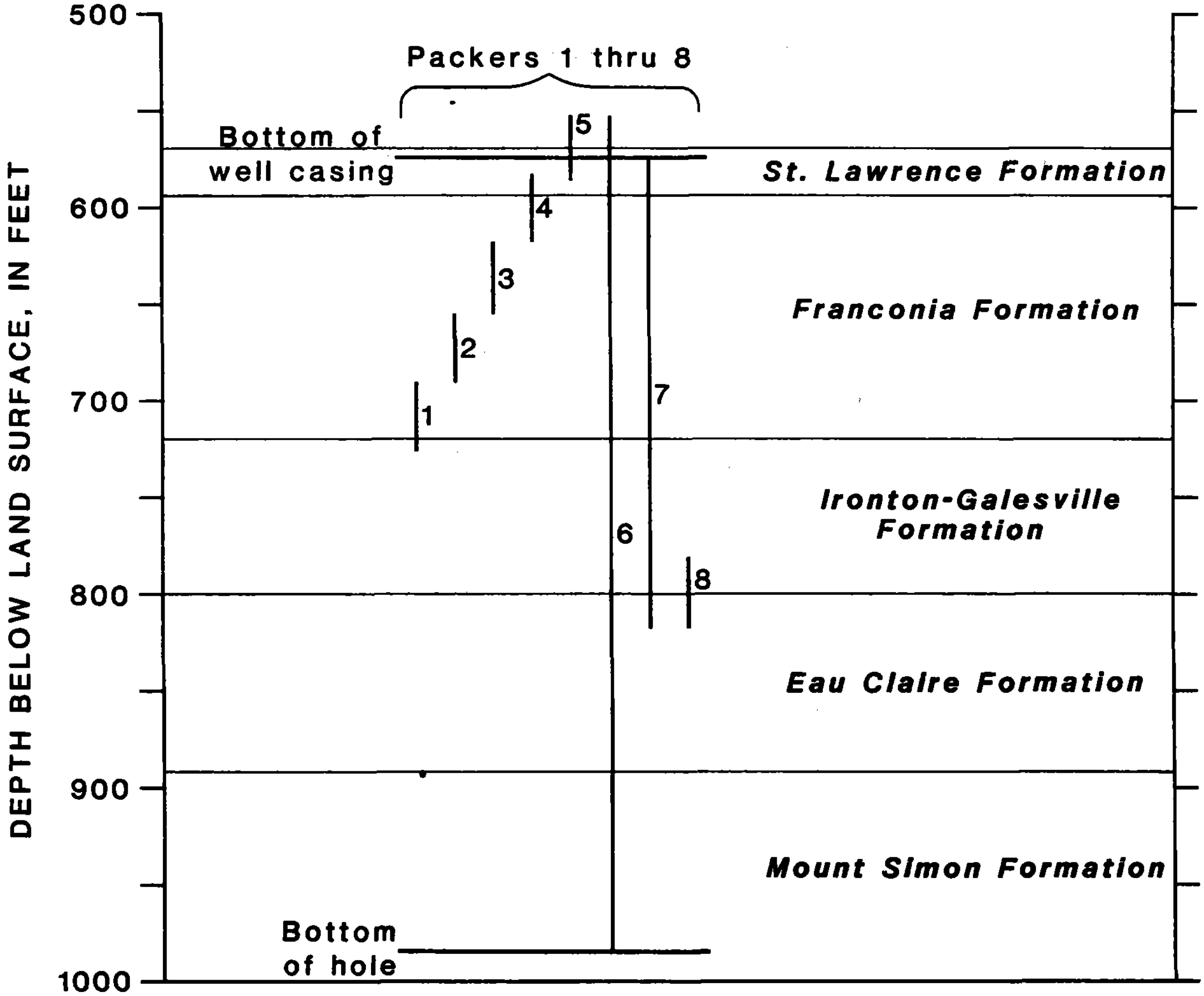


FIGURE 4.15. Position of Tested Intervals During Hydraulic Testing of Core Hole AC1

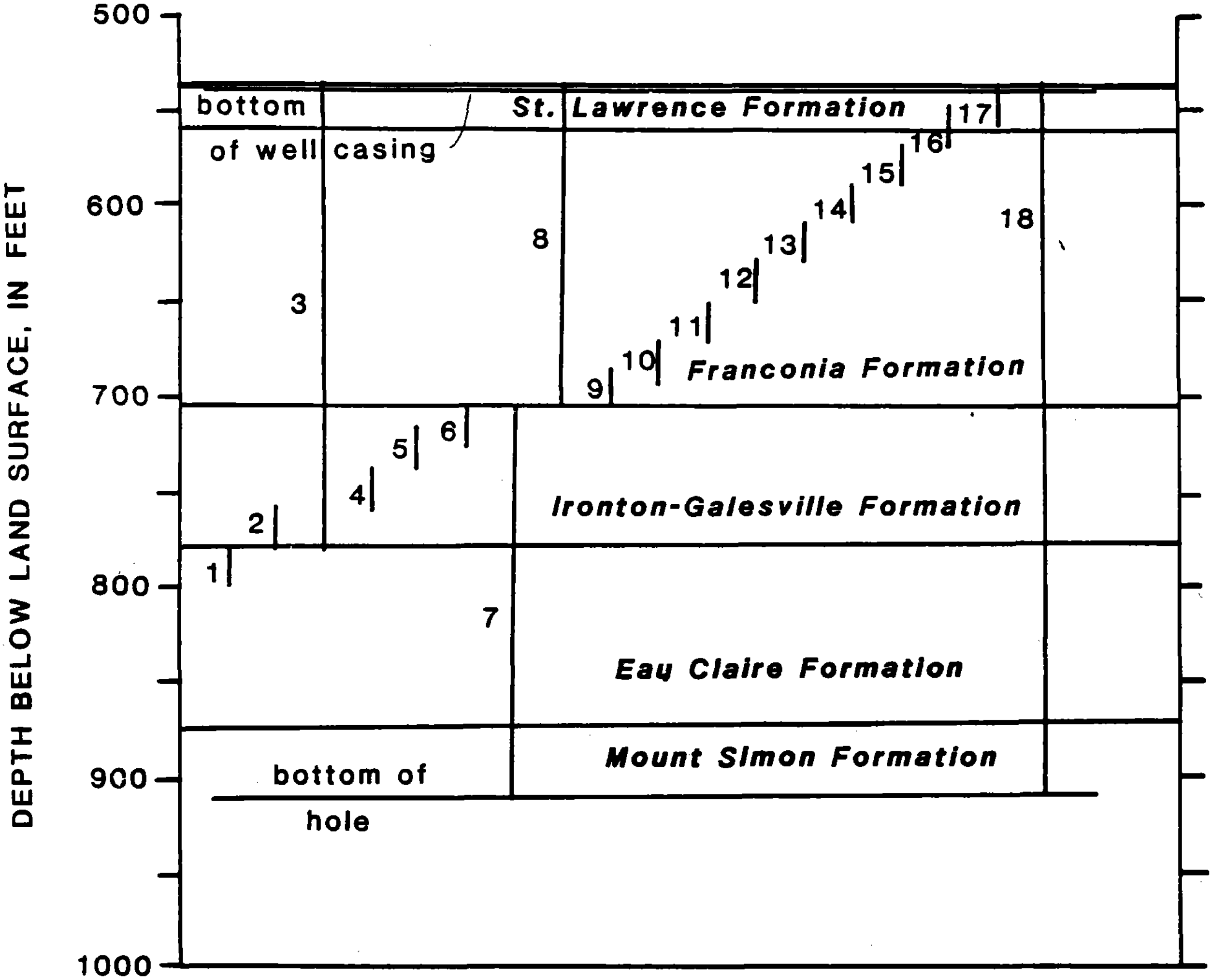


FIGURE 4.16. Position of Tested Intervals During Hydraulic Testing of Core Hole BC1

The current interpretation of the position and thickness of the six zones is shown in Figure 4.17. The hydraulic conductivity values assigned to each zone were chosen on the basis of analyses of time-drawdown data of packer tests on Holes AC-1 and BC-1, and from published aquifer-parameter data. The relative ratio between zonal parameters is probably correct, but the actual parameter value estimates could probably be improved with more detailed hydraulic testing. The transmissivity of the injection zone is probably between 200 and 350 ft^2/day.

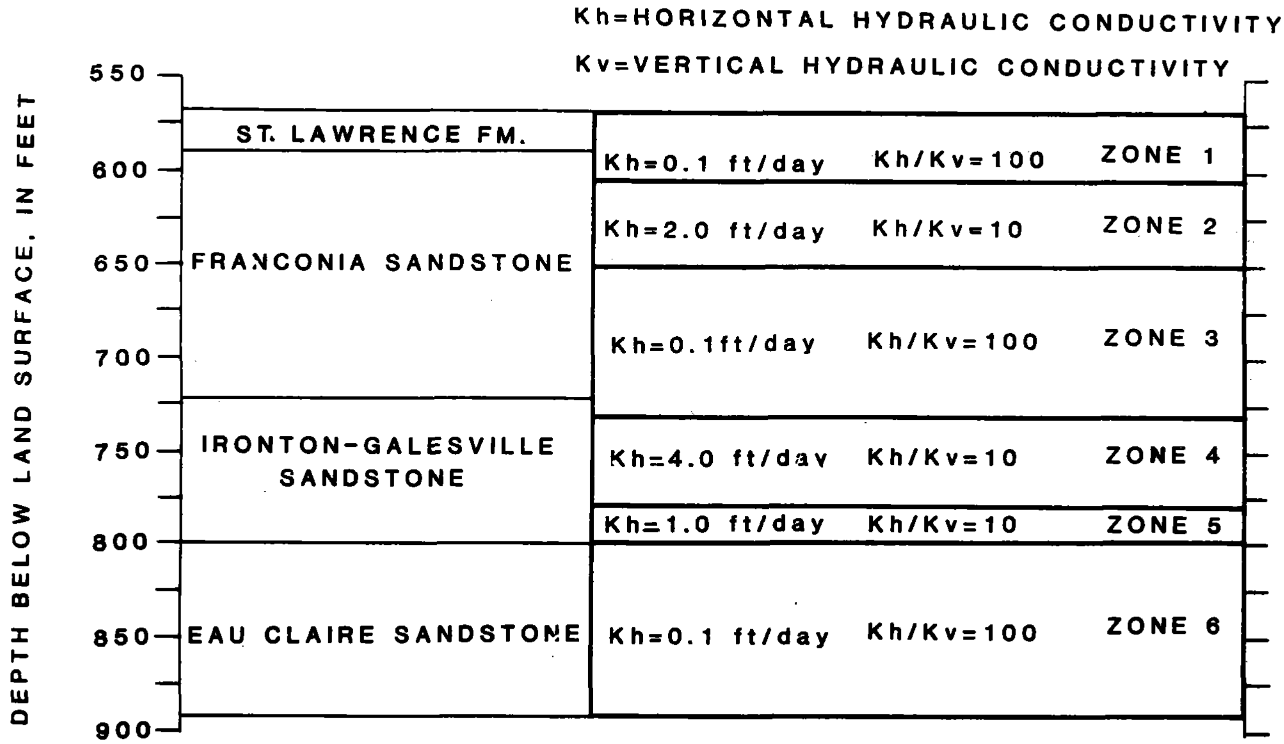


FIGURE 4.17. Hydrologic Zonation of St. Lawrence Through Eau Claire Formations Based on Interpretation of Core Holes AC1 and BC1

In anticipation of the hydraulic testing to be done on the two injection wells, both during their development and as part of the first phase of testing, when ambient ground-water temperature water will be used, several solutions to the equation of radial flow to a well in an extensive confined aquifer were calculated. The calculations were made using several values of aquifer transmissivity, well pumping rates, and single and doublet well systems. Table 4.6 shows the range of drawdown to be expected when pumping from a single well, and Table 4.7 shows the range of drawdown to be expected when the doublet well system is operating. Additional calculations for the doublet well system indicate that more than 95% of the 8-day head change occurs within the first 2 hours of pumping.

TABLE 4.6. Calculated Drawdown at Selected Distances from a Single Well Pumping at a Rate of 300 Gallons Per Minute for Several Values of Aquifer Transmissivity Storage Coefficient, and Pumping Times

Distance from pumping well, in feet	Time since pumping began, in days	Storage coefficient	Aquifer transmissivity, in ft^2/day					
			100	200	250	300	400	500
.5	1	$1x10^{-5}$	842	437	354	297	226	183
		$2X10^{-4}$	704	368	298	252	192	156
	2	$1X10^{-5}$	873	453	366	308	234	190
		$2X10^{-4}$	736	384	311	262	200	162
	4	$1X10^{-5}$	905	469	379	319	242	196
		$2X10^{-4}$	768	400	324	273	208	168
	8	$1X10^{-5}$	937	485	392	329	250	202
		$2X10^{-4}$	800	416	337	283	216	175
20	1	$1X10^{-5}$	503	267	218	184	142	115
		$2X10^{-4}$	365	198	163	139	107	88
	2	$1X10^{-5}$	535	283	231	195	150	122
		$2X10^{-4}$	397	214	176	149	115	94
	4	$1X10^{-5}$	566	299	243	206	158	128
		$2X10^{-4}$	429	230	188	160	123	101
	8	$1X10^{-5}$	598	315	256	216	166	134
		$2X10^{-4}$	460	246	201	170	131	107
45	1	$1X10^{-5}$	428	230	188	160	123	100
		$2X10^{-4}$	290	161	133	114	89	73
	2	$1X10^{-5}$	460	246	201	170	131	107
		$2X10^{-4}$	322	177	146	124	97	79
	4	$1X10^{-5}$	492	262	214	181	139	113
		$2X10^{-4}$	354	193	159	135	105	86
	8	$1X10^{-5}$	524	278	226	191	147	120
		$2X10^{-4}$	386	209	171	146	112	92

TABLE 4.7. Calculated 8-Day Drawdown at Selected Distances from the Discharging Well of a Doublet Well System using Several Values of Aquifer Transmissivity and Pumping Rates. The Doublet Sell Spacing is 830 Feet and the Aquifer Storage Coefficient is 0.00001

Pumping rates, in gallons per minute	Distance from center of pumping well, in feet	Aquifer transmissivity, in ft^2/day					
		100	200	250	300	400	500
300	0.5	682	341	272	227	170	136
300	20.0	340	170	136	113	85	68
300	45.0	263	131	105	88	66	53
200	0.5	454	227	181	151	114	91
200	20.0	227	113	91	76	57	45
200	45.0	175	88	70	58	44	35

The relatively large drawdown which will occur in the vicinity of the well bore may restrict the pumping rates which can be used during the aquifer testing and will affect the pumping rate that the well driller will use during the post-construction well development. The driller should be advised of the drawdown possibilities because it may affect his method of developing the wells.

Both axisymmetric radial and three-dimensional flow and energy transport numerical models have been constructed and most of the preliminary simulations have been made using the model that assumes radial symmetry. The computer code used for these simulations was developed by INTERCOMP Resource Development and Engineering, Inc. for the U.S. Geological Survey and will be referred to hereafter as the SWIP code. The code calculates a numerical solution to the finite-difference approximation of the partial differential equations describing 1) single phase fluid flow in the aquifer, and 2) energy transport by conduction and convection.

The preliminary simulation model was subdivided into four hydrostratigraphic units that correspond to the target injection zone (FIG aquifer) and the overlying and underlying confining beds. The model contained 16 layers and 21 columns and represented an aquifer cylinder with a 12-inch diameter well at the center and an external radius of 415 feet. The cylinder extends from 570 to 975 feet below land surface and the well is open between 615 and 810 feet below land surface. Water is assumed to enter the aquifer at a rate proportional to the hydraulic conductivity of the zone opposite the well screen. Because the well is to be operated as part of a doublet well system with a well spacing of approximately 830 feet, the external boundary was treated as a specified potential boundary. Table 4.8 summarizes the hydraulic and thermal properties used in the preliminary simulations.

Some of the preliminary simulations involved 24-day three part cycles where 300°F water was injected at a rate of 1200 gal/min for 8 days, stored for 8 days and then withdrawn at a rate of 1200 gal/min for 8 days. Figure 4.18 illustrates the position of the 100 and 200°F temperature fronts after selected times during the 24-day cycle. Model calculations also indicate that in the vicinity of the well bore aquifer heads will rise by as much as 200 feet during the injection phase and will decline by as much as 250 feet during the withdrawal phase.

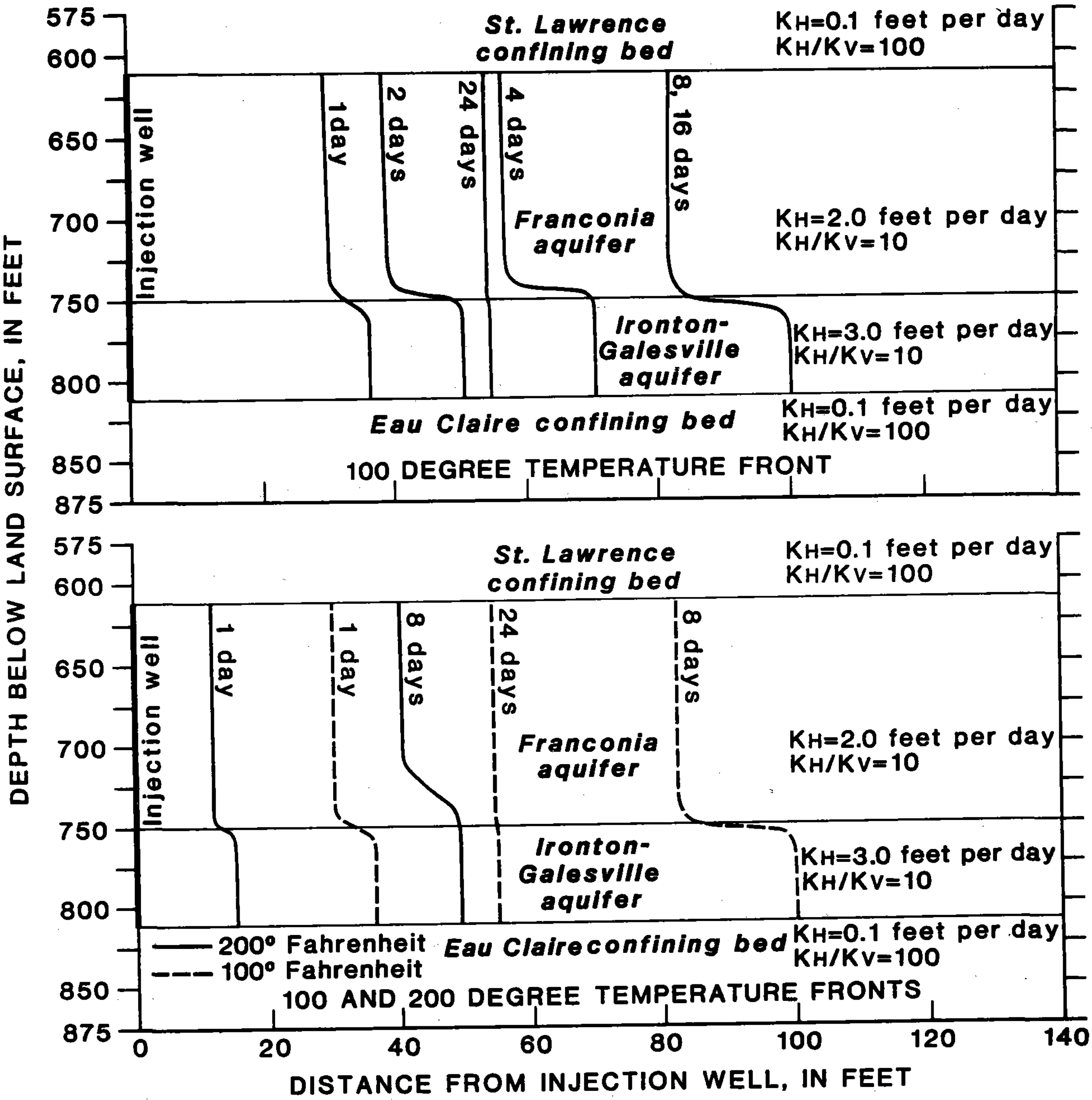
The revised aquifer cylinder would extend from 570 to 900 feet below land surface and the well would be open from 605 to 800 feet below land surface. Figure 4.19 shows the revised hydrologic zonation (rock and water thermal properties were assumed to be the same as before) and the positions of the 100 and 200°F temperature front after 8 days of injecting 300°F water at 1200 gal/min. Model calculations also indicate that in the vicinity of the well bore aquifer head will rise by as much as 375 feet during injection and will decline by as much as 450 feet during the withdrawal at 1200 gal/min. This calculation does not include vapor pressure of the well head.

The radial flow and energy-transport model was also used to evaluate the pressure changes and positions of the 200, 150 and 100°F temperature fronts during a 24 day (8-day inject, 8-day store, and 8-day withdraw) cycle.

TABLE 4.8. Summary of Hydraulic and Thermal Properties Used in Preliminary Simulations

Parameter	St. Lawrence Formation	Franconia Formation	Ironton-Galesville Formation	Eau Claire Formation
Thickness, feet............	45	135	60	165
Horizontal hydraulic conductivity, feet/day...	0.1	2.0	3.0	0.1
Vertical hydraulic conductivity, foot/day...	.001	0.2	0.3	.001
Porosity..................	.25	.25	.25	.25
Isotropic thermal conductivity, BTU/FT-DAY-DEG.F..................	35	35	35	35
ROCK HEAT CAPACITY, BTU/cu.FT-DEG.F.............	27	27	27	27

Water heat capacity	1.003 BTU/LB-DEG.F
Water compressibility	.000003/PSI
Rock compressibility	.000064/PSI
Water thermal expansion factor	.0002/DEG.F
Initial Reservoir fluid pressure	200 psia at depth of 615 feet.



EXPLANATION

K_H=Horizontal hydraulic conductivity
K_V=Vertical hydraulic conductivity

FIGURE 4.18. Position of 100 Degree Temperature Front After 1, 2, 4, 8, 16, and 24 Days During 8-Day Inject, 8-Day Store, and 8-Day Withdraw Cycles and Position of 100 and 200 Degree Temperature Fronts After 1, 8, and 24 Days During 8-Day Inject, 8-Day Store, and 8-Day Withdraw Cycles

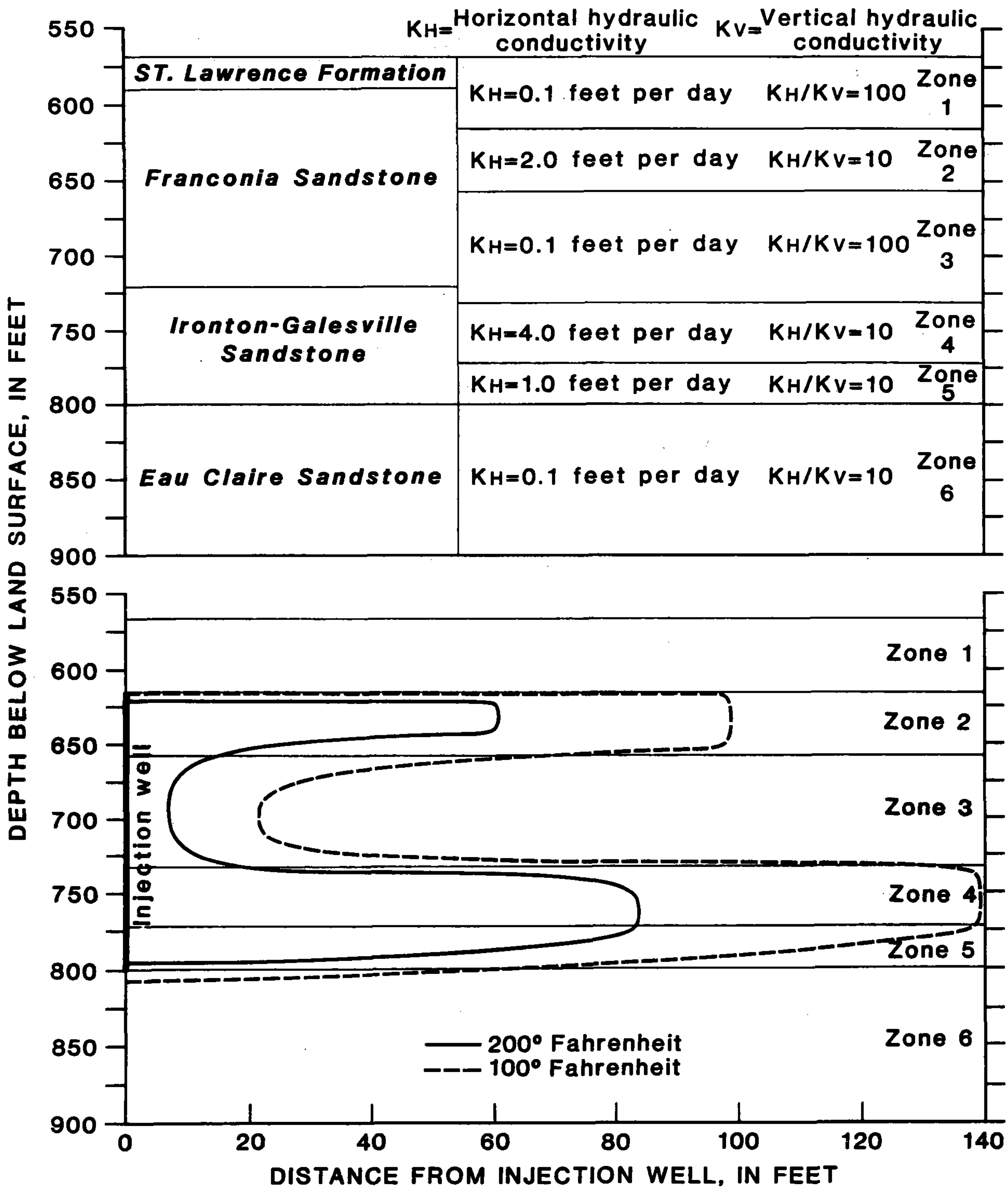


FIGURE 4.19. Hydraulic Zonation of St. Lawrence Through Eau Claire Formations Based on Interpretation of Core Hole AC1 and Position of 100 and 200 Detree Temperature Fronts After 8 Days of Injecting 300°F Water at 1200 Gallons Per Minute

For 10 simulations, the hydrologic zonation and aquifer parameters were identical to those shown in Figure 4.19 and the injection rates and temperatures were varied. The hydraulic and thermal properties used in these simulations are summarized in Table 4.9. An additional simulation was made to evaluate pressure change and positions of temperature fronts for an aquifer with a much smaller hydraulic conductivity and porosity than was used in the first 10 simulations. This simulation might represent the pressure and temperature changes that would occur in an aquifer which became severely clogged as a result of injection. Table 4.10 summarizes the hydraulic and thermal properties used in this simulation. The maximum pressure change and the furthest extent of the 200^o, 150^o, and 100^oF temperature fronts for each of these simulations is listed in Table 4.11.

Surface System Design and Instrumentation

Specifications and working drawings were prepared for bid advertisement on mechanical and electrical systems that provide the above interface between Site A and Site B, the injection and water supply site as well as the interconnection of that system to the existing University steam distribution system. The equipment was advertised for bidding December 23, 1980 with bid opening scheduled for January 13, 1981. These systems are designed for 300 gpm at 300^oF maximum. The pump motor and pump are included in this package as well as the remaining installation above ground related to instrumentation and the tape drive and uninterrupted power supply.

Institutional design was completed and equipment specified and ordered.

Legal and Institutional

Three state agencies in Minnesota have environmentally related responsibilities for the ATES project of the University of Minnesota. The Minnesota Pollution Control Agency (MPCA) has regulations governing water, air, land, and energy issues. The Minnesota Department of Natural Resources (MDNR) has jurisdiction over the state's water, land use, and wildlife, and the Minnesota Health Department (MHD) has purview over construction and operation of wells.

TABLE 4.9. Summary of Hydraulic and Thermal Properties Used in Simulations RAD 5A-1 to 10

Parameter	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Thickness, feet............	35	45	80	50	20	90
Horizontal hydraulic conductivity, ft/day.....	0.1	2	0.1	4	1	0.1
Vertical hydraulic conductivity, ft/day.....	.001	0.2	.001	0.4	.1	0.001
Porosity..................	.25	.25	.25	.25	.25	.25
Isotropic thermal conductivity, BTU/FT-DAY-DEG.F..................	35	35	35	35	35	35
ROCK HEAT CAPACITY, BTU/ FT^3-DEG.F..............	27	27	27	27	27	27

Water heat capacity	1.003 BTU/LB-DEG.F
Water compressibility	0.000003/PSI
Rock compressibility	.000064/PSI
Water thermal expansion factor	.0002/DEG.F
Initial Reservoir fluid pressure	200 psia at depth of 615 feet.

TABLE 4.10. Summary of Hydraulic and Thermal Properties Used in Simulations RAD 6A-4

Parameter	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6
Thickness, feet............	35	45	80	50	20	90
Horizontal hydraulic conductivity, ft/day.....	0.025	0.5	0.025	1	0.25	0.025
Vertical hydraulic conductivity, ft/day.....	.00025	.05	.00025	0.1	.025	.00025
Porosity..................	.10	.10	.10	.10	.10	.10
Isotropic thermal conductivity, BTU/FT-DAY-DEG.F..................	35	35	35	35	35	35
ROCK HEAT CAPACITY, BTU/ FT^3-DEG.F...............	27	27	27	27	27	27

Water heat capacity	1.003 BTU/LB-DEG.F
Water compressibility	0.000003/PSI
Rock compressibility	.000064/PSI
Water thermal expansion factor	.0002/DEG.F
Initial Reservoir fluid pressure	200 psia at depth of 615 feet.

TABLE 4.11. Summary of Pressure and Temperature Changes for Simulations RAD 5A-1 to 10 and RAD 6A-4

Simulation	Pumping rate, in gallons per minute	Temperature of injected water, °F	Maximum presssure change, in psi, during injection and withdrawal phases of 24-day cycle				Maximum extent of temperature fronts after 8 days injection		
			Injection		Withdrawal				
			Zone 2	Zone 4	Zone 2	Zone 4	200°F	150°F	100°F
RAD 5A-1	300	300	+55	+60	-60	-55	35	45	65
RAD 5A-2	300	250	+60	+65	-65	-60	21	35	60
RAD 5A-3	300	200	+65	+70	-70	-65	--	30	55
RAD 5A-4	200	300	+40	+40	-45	-40	30	40	55
RAD 5A-5	200	250	+40	+45	-45	-40	20	35	50
RAD 5A-6	200	200	+45	+45	-50	-45	10	25	45
RAD 5A-7	100	300	+20	+20	-20	-20	18	30	40
RAD 5A-8	100	250	+20	+25	-25	-20	11	25	45
RAD 5A-9	100	200	+25	+25	-25	-25	--	15	25
RAD 5A-10	1200	300	+198	+210*	-223	-215*	75	100	130
RAD 6A-4	300	200	+255	+270*	-295	-270	--	35	60

* Estimated.

Even though EPA's Underground Injection Control Program under the Safe Drinking Water Act classifies heat injection wells such as ATES as Class V wells which require no EPA permits, the State of Minnesota is among several states that consider heat as a ground water pollutant. Therefore, before Phase I ATES could proceed, the University of Minnesota had to apply for a temporary variance from MPCA's Rule WPC 22, from MHD's Rule 210-230, and a temporary Ground-Water Appropriation Permit from the MDNR.

The acquisition of these permits was a major action during 1980. For example, public comments submitted during the routine hearing for the WPC 22 variance precipitated the requirement for PNL and ATES Project personnel to prepare technical inputs to respond to the environmental concerns raised. The latter included clarification of biological/bacterialogical concerns, subsidence induced seismicity possibilities, and geochemical (mineral dissolution) changes potentially produced in the aquifer by the proposed closed-loop thermal injection activities.

These combined PNL and University of Minnesota team efforts during 1980 were successful in securing all the variances/permits necessary to implement Phase I aquifer characterization efforts. Specifically, in July 1980, the MPCA Board granted the University of Minnesota the Temporary Variance to WPC 22 for Phase I testing. In August 1980, a Temporary Variance to MHD's Rules 210-230 was granted with stipulations regarding testing of specific water quality parameters. A Temporary Water Appropriation Permit was filed with the Minnesota DNR in March 1980 and granted in September 1980.

Additional Work

In addition, visual examination of the cores from the FIG aquifer and upper and lower confining beds from Holes AC-1 and BC-1 is nearing completion. The detailed descriptions, now being typed, include sedimentary and diagenetic structures; joints, vugs and other voids; major mineral constituents; and other special features visible in a megascopic examination.

Also, the laboratory for water chemistry and rock dissolution experiments has been set up and is operational. Water samples were taken in October during packer testing of Hole BC-1, and core samples from Hole AC-1 are being examined for the kinetics of dissolution of aquifer materials.

4.1.2 Phase II Final Design, Construction and Operation

Contractor to be determined.

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

Bethel. The functional Design Criteria developed thus far does not indicate that the heat injection temperature can be sufficiently high to allow district heating temperatures of 80°C. Further investigation of stack gas heat exchangers and possible modifications to the building heat exchangers are required.

An aquifer of suitable capacity has been found. However, the limited thickness and the presence of clay lenses may restrict the efficiency of the aquifer for storage. Until the heat injection tests and modeling are completed this remains a potential hold on this project.

Stony Brook. The efficiency of the closed system may be limited by the relatively small temperature differential involved in the heat exchanger. Should the numerical simulation of the above-ground portion, which will follow the aquifer characterization, prove this to be a limiting condition, we may have to examine a semi closed system, as an alternative.

St. Paul, Minnesota. The lack of a High Temperature Test Facility as a precursor to the demonstration leaves many questions about the behavior of an aquifer at elevated temperatures (150°C) that will have to be resolved during the injection tests, modeling, and subsequent design effort.

The properties of the FIG aquifer discovered to date indicate the presence of a clay lens in the mid area which is causing an "hour-glass" effect in the permeability distribution curve. This condition will require some special effort in screening and modeling to determine the most efficient well configuration.

4.2 SEASONAL STORAGE TECHNOLOGY PROGRAM

The Seasonal Storage Technology (SST) 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 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 - Legal/Institutional Assessment
Task 2 - Economic Assessment
Task 3 - Environmental Assessment
Task 4 - Field Test Facilities
Task 5 - Compendia of Existing Technology
Task 6 - Physicochemical Analysis
Task 7 - Numerical Simulation
Task 8 - Nonaquifer Seasonal Thermal Energy Storage

4.2.1 Legal/Institutional Assessment

Pacific Northwest Laboratory

Objectives

The principal objective of this task is to catalog and analyze the legal, regulatory, and institutional issues that are likely to affect implementation of STES concepts. Issues are to be addressed at the federal, state, and, to a lesser extent, the local level of government. Initial effort is focused on the aquifer thermal energy storage (ATES) concept.

Technical Progress

A technical document containing the results of investigations to date under this study area was published in October 1980 (Hendrickson 1980). An updated and expanded version of this document is planned for publication at the end of CY-1981.

Regulatory Requirements Prior to Operation

Initiation of an ATES project will necessarily involve compliance with certain permits and regulatory requirements. In most western and some eastern states, a permit to withdraw ground water will be required from the appropriate state water resources agency. Most states have requirements related to well drilling, construction, and abandonment. In many states, a separate permit to reinject the thermally altered ground water will be required from the appropriate pollution control agency. A few states prohibit such reinjection, and a variance will be necessary if an ATES project is to be implemented. Eventually, a permit from a state agency or the U.S. Environmental Protection Agency under the underground injection control (UIC) program established by the Safe Drinking Water Act of 1974 will be required. This requirement will likely supersede existing underground injection requirements. Final UIC requirements for the well classification likely to include ATES wells will probably not be issued for several years. An ATES project may also trigger the need for an environmental impact statement (EIS) under the National Environmental Policy Act (NEPA) if a significant Federal action is involved in licensing or construction. Even if an EIS under NEPA is not required, about half of the states require an EIS for projects with significant environmental impacts.

Potential Liability

An ATES operator should be aware of several possible sources of liability. Liability is most likely for interference with the property rights of others in the storage aquifer. Interference with existing users of an aquifer as a potable water source is of greatest concern. Alleged interference would most likely be for increased water temperature, although it is also possible that an ATES operation could lead to some chemical or biological contamination of ground water. Liability is also possible to other existing ground-water users, to potential ground-water users in states (principally eastern states) recognizing overlying ground-water rights, and to mineral rights holders if mineral interests (including oil and gas) are interfered with. Subsurface storage rights and/or mineral rights may have to be purchased if significant liability is foreseen.

Surface drilling and injection activities can also potentially lead to liability through such things as noise, vibrations and fluid spills. Proper care in surface operations can minimize these possibilities.

Storage and Recovery

A central concern of the ATES operator will be assurance of the ability to store, protect, and recapture the thermal energy when desired. At a minimum, the ATES operator will need to purchase, or when necessary condemn, (assuming statutory authority) sufficient surface property rights to provide site access, drill needed wells, and provide adequate spacing from nearby land use activities. Acquisition of a subsurface energy storage easement may be needed if significant liability is foreseen or if intentional interference with the ATES operation by a surface owner/user is considered possible. Both of these contingencies are more likely if a relatively shallow aquifer is utilized for storage, although the likelihood of each can be rendered small by careful aquifer selection. The possibility that someone could drill with impunity into the energy storage bubble with the major purpose of capturing stored energy and/or interfering with an ATES operation is remote. This is true even if the ATES operator has not acquired any property interests.

Energy Delivery

Many legal, institutional, and regulatory issues will occur at the stage of heat or chill delivery. A principal issue is locating an entity with sufficient incentive to construct and operate an ATES and delivery system. It may be difficult to find an investor-owned entity with sufficient economic incentive; consequently, the responsibility may fall to a public body. A variety of other issues related to financing, rate setting, service areas, taxation, and other areas will require resolution. These issues are likely to be most complex for a residential district heating system.

Technical Problems

No problems were evident in the legal/institutional work during the reporting period.

4.2.2 Economic Assessment

General Electric-TEMPO (GE-TEMPO) and Pacific Northwest Laboratory

Objectives

The objectives of the economic assessment are: 1) to determine the economic performance of seasonal thermal energy storage concepts, 2) to estimate their market penetration potential, and 3) to provide economic expertise to the STES Program Office.

Tasks

The economic assessment work has five tasks:

1. Coordinate the development of an initial analysis of the Aquifer Thermal Energy Storage concept to serve as a focus for defining ATES investigations and as a general marketing document for the technology.
2. Develop a methodology for economic evaluation of ATES configurations.
3. Provide an initial economic evaluation of ATES heat and chill storage.
4. Initiate and monitor an external contract to develop a methodology for conceptual design and evaluation of ATES systems.
5. Provide analytical support to the ATES Demonstration Propram.

Technical Progress

Task 1 - Overall Analysis of ATES. The overall analysis of ATES was published in June 1980 as A Descriptive Analysis of Aquifer Thermal Energy Storage Systems (Reilly 1980). A brief summary of the results follows:

Seasonal storage of thermal energy in aquifers has the potential to make a significant near-term contribution towards relief of the national energy shortage. Winter chill, summer heat, and various forms of industrial waste heat can be stored for future demand, and can thus reduce the need for generating primary energy and lessen the nation's dependence on imported petroleum fuels. It appears that it is technically feasible to supply about 7.5% of the nation's total energy demand through aquifer thermal energy storage (ATES), with about a third of this energy initially supplied by industrial waste heat. This is purely a technical estimate, with no consideration given to cost effectiveness of ATES systems, or to institutional problems, including the need to amass very large amounts of capital for construction of ATES storage and distribution systems.

ATES appears to be the most promising of the several technologies proposed for long-term (or seasonal) storage of large amounts of thermal energy. A major key to ATES's attractiveness is its simplicity of design and construction. For many applications the installation can probably be designed and constructed using existing site-specific information and modern well-drilling techniques.

Another key to the attractiveness of ATES is its potential for cost-effective operation. The storage medium, water, is inexpensive. Well-drilling and equipment costs constitute the only capital storage expense, and so the cost of the storage container is essentially independent of the amount of energy to be stored. Therein lies the major advantage of ATES over other storage technologies, where cost of the container is typically proportional to volume stored. It is likely that initial storage efficiencies of 70% will be encountered for commercially-sized units. Efficiencies are expected to increase over time, possibly to the 90%+ range, as the aquifer heats or cools.

The potential for cost-effective implementation of ATES was investigated in the Twin Cities District Heating-Cogeneration Study in Minnesota. In the study, ATES demonstrated a net energy saving of 32% over the non-storage scenario, with an annual energy cost saving of $31 million. Discounting these savings over the life of the project, the authors found that the break-even capital cost for ATES construction was $76/kW thermal, far above the estimated ATES development cost of $23 to 50/kW thermal. It appears that ATES can be highly cost effective as well as achieve substantial fuel savings.

There are concomitant benefits. Large-scale ATES development has the potential for improvement of the environment, primarily due to reduced pollution from extraction, refining, and combustion of fossil fuels. Thermal pollution is reduced, and so is the cost of equipment presently required to treat that thermal pollution. The reliability of district heating systems is enhanced.

The potential for market penetration of ATES is immense. Aquifers are estimated to underlie roughly two-thirds of the nation. This figure probably understates ATES's potential because most applications will be in urban/industrialized regions, which are typically located near productive aquifers. Both winter chill and summer heat are technically feasible energy sources for many parts of the country, and the potential for electrical cogeneration and for capture of industrial waste heat is vast.

Widespread implementation of ATES is not without difficulties, however. The more exotic energy sources present technical problems, and work needs to be done to evaluate the implications of widespread heat storage at depth. Perhaps the most significant barriers to commercialization, though, are institutional. Since this is a new technology, numerous legal questions need to be addressed, including liability for thermal pollution of the aquifer and protection of the stored resource from capture by others. Because district heating of residential housing requires extensive pipelines, work needs to be done to develop the means to finance these highly capital-intensive ventures and to create incentives and/or leadership for such developments.

The existing body of information on ATES indicates that it is a cost-effective, fuel-conserving technique for providing thermal energy for residential, commercial, and industrial users. The negative aspects are minor and highly site-specific, and do not seem to pose a threat to widespread commercialization. With a suitable institutional framework, ATES promises to supply a substantial portion of the nation's future energy needs.

Task 2 - Development of a Methodology for Economic Evaluation of ATES. A computer code, AQUASTOR, has been developed to evaluate the economic performance of ATES configurations.

AQUASTOR combines demand, aquifer, and supply characteristics with climate, cost functions, and economic parameters in one systematic model. It provides the flexibility to individually or collectively evaluate the impact of different economic and technical parameters, assumptions, and uncertainties on the cost of providing heat (chill) from an aquifer storage system.

The model consists of two major parts: the aquifer resource submodel, and the distribution submodel. The resource submodel calculates the life cycle cost of energy production by simulating the exploration, development, and operation of an ATES system and the transmission of this energy to a distribution center. The distribution submodel calculates the life-cycle cost of delivered energy by simulating the construction and operation of a distribution system.

The code is extremely flexible and can simulate heating (with stored hot water), chilling (with stored cold water or with hot water and absorption chillers), or both (using hot water with absorption chillers). The distribution submodel will simulate large-scale district heating (cooling) networks, point demands, or various combinations. Each of the submodels is considered to be its own operating entity with a tailored financial configuration, including different tax rates and incentives, capital structure, and depreciation schedules.

AQUASTOR is designed in modular fashion with a large number of technical and economic subroutines. ASME steam tables are used throughout the design subroutines to calculate thermodynamic and physical properties of water (including pressure, temperature, enthalpy, specific volume, density, viscosity, and fluid quality), thereby enabling simulation of heat exchangers, transmission lines, and distribution systems.

Figure 4.20 is a block diagram that shows an overview of the logic used in AQUASTOR to simulate the ATES district heating system. Some important aspects of the two major submodels are described below:

Aquifer Storage Submodel

The storage submodel employs energy source characteristics, aquifer efficiency characteristics, and peak/annual demand flow requirements to design the storage and transmission systems. The code output provides estimates of the required number of wells, well field layout, pipeline lengths, and heat exchangers. The submodel optimizes transmission pipeline design (pipeline diameter, schedule, and insulation). Where supply is greater than demand, the system is sized to deliver any specified proportion of the demand, up to 100%. Where demand is greater than supply, the system is sized to deliver the full supply, with the deficit supplied by purchased thermal energy.

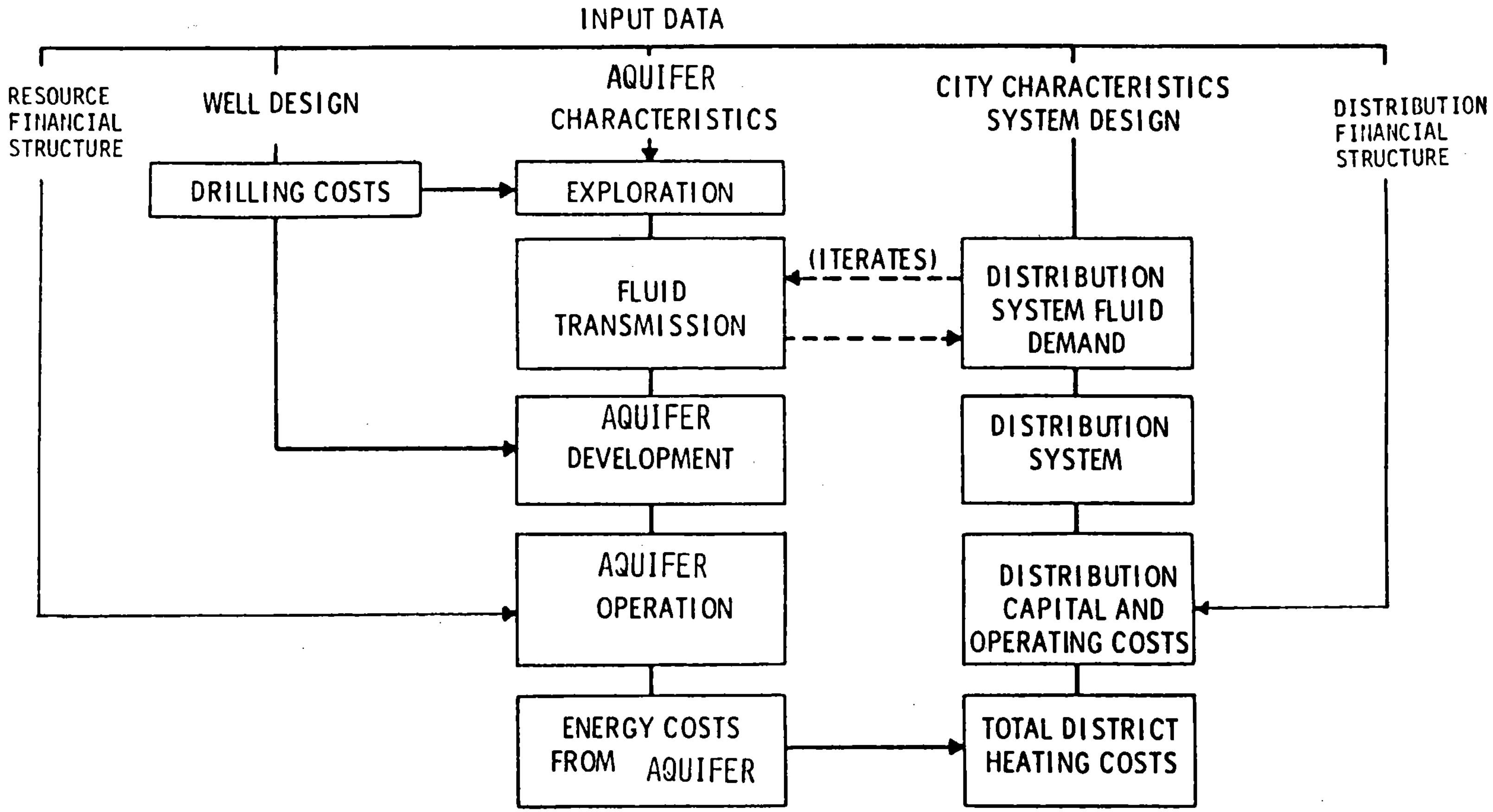


FIGURE 4.20. Logic Diagram for AQUASTOR Code

Distribution System Submodel

The distribution system submodel simulates the design and calculates the capital costs, operating costs, and maintenance costs of the district heating distribution system for a city. The input data to the distribution system submodel consists of the city characteristics, characteristics of districts comprising the city, design options for the distribution piping, insulation, and casing, and special options and adjustment factors (provision for growth, etc.).

The city is defined by its distance from the aquifer, climatic characteristics, and the number of districts within the city. The distances are used to design the fluid transmission lines and to calculate the fluid temperature and enthalpy entering the distribution center. The climatic parameters are used to determine the distribution of the heat demand, peak heat demand, average heat demand, the load factor, and supplemental heat requirements.

The city is disaggregated into districts. Each district is a contiguous area consisting of buildings of relatively similar heat demand and uniform density. Five district types, representing typical residential areas are identified and defined. There is a provision for defining additional user districts.

Task 3 - Economic Evaluation of ATES Heat and Chill Storage. Brief investigations were made into the cost of aquifer heat and chill storage. A summary of the results follows:

The Cost of Heat Storage

Levelized cost estimates were made for heat storage in aquifers (using the AQUASTOR code) for a number of different technical and economic assumptions.

The cost estimates include only storage costs. They do not include any purchase cost for the thermal energy, nor delivery and end-use costs. The capital budget includes purchase and installation of all hardware necessary for storage, from the heat exchanger where thermal energy is transferred to the aquifer water, to a second heat exchanger where thermal energy is transferred to the distribution fluid. The operation costs provide for all pumping energy (including both sides of both heat exchangers), maintenance on all equipment, financing charges (municipal utility @ 10% cost of capital), and administrative costs. A detailed listing of cost accounts is included.

The major assumptions used, and a brief explanation of each, are included below:

- System Size. Storage costs are investigated for three system sizes (100 MWt, 10 MWt, and 1 MWt). The 100 MWt refers to the peak demand at the end user (not including losses in the distribution system). The total energy delivered is, respectively, $8.97 * 10^{11}$, $8.97 * 10^{10}$, and $8.97 * 10^{9}$ Btu/yr, given the assumed load factor of 30%. Total energy stored is approximately 125% of the delivered energy, after storage and transmission losses are taken into account.
- Load Factor. A demand load factor (the ratio of average demand to peak demand) of 30% is assumed for all cases. This is equivalent to heating at peak delivery rate for 30% of the year, or at 30% of peak capacity continuously for 1 year, or some other combination. A supply load factor (the ratio of average energy supply to peak energy supply) of 25% is assumed, equivalent to 90 days of continuous energy storage.
- System Temperatures. Source temperature of $150^{\circ}C$ and $90^{\circ}C$ are used in the investigation. A $38^{\circ}C$ return temperature is used for the distribution system, since this is a typical return temperature for space heating systems. A natural aquifer temperature of $55^{\circ}F$ is assumed.
- Aquifer Thermal Efficiency. Two parameters characterize the aquifer thermal efficiency: fluid recovery factor, and thermal recovery factor. The fluid recovery factor defines how much water will be withdrawn before the temperature of the aquifer water drops too low to meet the demand. The thermal recovery factor defines the fraction of stored heat that is recovered (using an enthalpy balance, with the natural aquifer temperature as the reference temperature). Together, the two parameters

determine the average temperature of the water that is withdrawn from the aquifer. Ninety percent of the injected water and 80% of the injected heat are assumed recovered each cycle. The estimated average temperature of the distribution fluid is then 114°C for the 150°C source and 66°C for the 90°C source.

- Well Flow Rate. A maximum well flow rate of 500,000 lb/hr is assumed for this investigation. This is fairly high, but feasible. (Some geothermal wells are rated at over 1,000,000 lb/hr.) If the aquifer were unsuited to such a high delivery rate, then the cost of storage would increase quickly, since more wells, pumps, and connective piping would be required.
- Financing. A municipal financing structure with a 10% cost of capital is modeled. Field exploration and installation are assumed to take 4 years, with operations starting in year 5. Well and equipment lives are both assumed to be 30 years. Wells are replaced on a continuous basis such that all wells are replaced once over the life of the plant.

Discussion

Table 4.12 shows the results of the ATES Heat Storage Analysis. There is an apparent anomaly in the results due to parameter selection. A significant cost increase is to be expected with the reduction in source temperature, since the energy content of the delivery fluid from the 150°C source is about 2 1-2 times higher than from the 90°C source. Yet, the cost difference for the 1 MW system is only about 15%. The anomaly is due to the choice of well flow rate. Since well-flow rate was maintained at 500,000 lb/hr whereas in the 100 MW system, the wells are fully utilized. When the flow rates are increased to accommodate the 90°C source temperature, the 1 MW system does not require any additional wells (hence little additional capital cost), whereas the 100 MW system must increase the number of wells in proportion to increased flow rate. This factor is magnified in the cost estimates, since operation and maintenance costs are estimated as a function of capital cost.

In the system modeled, components were not optimized, and there is the potential for significant cost reduction through careful system optimization.

Table 4.12. Cost of ATES Heat Storage ($1979/MBtu)

1 MWt		10 MWt		100 MWt	
150°C SOURCE TEMPERATURE					
150 ft Wells					
$50/ft	$100/ft	$50/ft	$100/ft	$50/ft	$100/ft
8.37	8.63	1.62	1.65	0.97	0.98
1000 ft Wells					
10.28	12.03	2.31	2.31	1.78	1.91
90°C SOURCE TEMPERATURE					
150 ft Wells					
9.23	9.50	2.66	2.71	2.04	2.09
1000 ft Wells					
11.89	13.65	4.81	5.16	4.29	4.62

NOTE: $50/ft and $100/ft indicate well drilling cost, casing included.

The prime example of potential system improvement lies in selection of heat exchanger approach temperature (both at the energy source and at the user). A reduced approach temperature will reduce the number of wells, pipe diameter, pump size and pumping power required, while it will increase the size and operating cost of the heat exchanger itself. In an ATES system the energy is transferred sequentially through two heat exchangers, and the degree of temperature degradation can have tremendous leverage over the size and cost of other equipment required. In this investigation, approach temperatures were selected based upon a rough rule of thumb as a function of source temperature.

This investigation used two heat exchangers, one at the energy source, and one at the end user. It may be possible (where storage and withdrawal periods to not overlap) to use a single heat exchanger for both storage and withdrawal processes, with reduction in total capital cost. Of course, the same temperature degradation effects would occur.

Heat energy from the source was assumed to be available for a 90-day period, constraining the energy supply system (as opposed to the demand system) to a 25% load factor. Thus, wells and well-related equipment were sized for flow into the storage aquifer, rather than flow out of the aquifer. If energy storage had been allowed over a longer period, then well cost (and therefore, the cost of energy storage) could have been reduced.

A 30% demand load factor was assumed for evaluation of the cost of heat storage. This is reasonable for an industrial load, but rather high for a single-family housing district heating system. A Seattle district heating system might expect a load factor of 23%; in Minneapolis the expectation would be 18%. These estimates are for a system sized to meet the total peak demand of the district heating participants. Significantly higher load factors could be achieved by undersizing the supply system such that peak demands are met through supplementary heat.

The results indicate that there is little difference in the cost of energy when well-drilling costs are doubled from $50/ft to $100/ft (especially at shallow depths). At these drilling costs, most of the well-related capital cost is due to equipment such as pumps, valves, manifolds, and surface piping. There is, however, a marked increase in the cost of storage when deeper wells are required. This is attributable to three components: additional drilling expense, larger downhole pumps, and (most important) increased pumping energy requirements.

The Cost of Chill Storage

In order to perform a sensitivity analysis of the effects of a number of technical and economic parameters upon the cost of ATES cooling, a base case situation was developed, and a cost of cooling was calculated for that base case. Important input and derived parameters for this base are described below. (Input parameters are designated as (I).):

Demand: The air conditioning load for the ATES system was assumed to be a point demand with the following characteristics:

Annual demand	10^5 MBtu/yr (M = million)
Peak energy demand	57 MBtu/hr (I)
Load factor	0.2 (I)
Peak flow rate	4.2×10^6 lb/hr (8400 gpm)
Cooling water reject temperature	60^oF (I)

This annual cooling load is roughly 40% of JFK Airport's annual load; it is also equivalent to about 4,000 single family houses in the Ft. Worth, Texas climate.

Supply: The chill source is assumed to be a river running at 35^oF for a period of 3 months per year. The river water is isolated from the aquifer system by a heat exchanger at the river bank.

Heat exchanger approach temperature	10^oF (I)
River water in	35^oF (I)
River water out	50^oF (I)
River flow rate into heat exchanger	3.5×10^6 lb/hr (7000 gpm)
Aquifer water in	59.4^oF
Aquifer water out	45^oF
Aquifer flow rate	3.7×10^6 lb/hr

Storage: Storage is assumed to be in a productive, fairly shallow aquifer, since the temperature level does not require system pressurization. Because the storage bubble is relatively large and the temperature differential between the in situ water and the stored water is low, a moderately high storage efficiency is assumed.

Natural aquifer temperature	55^oF (I)
Aquifer thermal efficiency	80% (I)
Fluid recovery fraction	90% (I)
Well capacity	500,000 lb/hr (I)
Well cost	$100,000/well (including pump cost) (I)
Number of wells	18
storage well-field	9
supply well-field	9

Transport: The one way distance between the river and the air conditioning load is assumed to be 2,660 meters, with the aquifer somewhere in between. A layout of the system is depicted in Figure 1. The first 2,500 meters is laid on the surface; the remaining 160 meters at the load site is buried.

Schedule 10 steel pipe (seam-welded) in steel casing.

Supply lines insulated with 2 in. of polyurethane.

Financial: Both the supply and the distribution entities are assumed to be municipal utilities with the following characteristics:

Financing mode	100% bonds (I)
Bond rate	8%/yr (I)
Income tax rate	0% (I)
State revenue tax	4% (I)
Investment credits	0% (I)
Cost of electricity	$0.04/kWh (I)
Inflation rate	6%/yr (I)
System lifetime	30 years

Base Case Results

AQUASTOR calculated the levelized cost of cooling for the base case situation to be $14.28/MBtu (1979 price levels). Operating costs such as pumping power and maintenance, constitute 53% of total costs in the first year, and this fraction increases over system lifetime because of inflation.

Analysis of the Major Factors that Affect the Cost of ATES Cooling

A number of major factors were identified that affect the cost of ATES cooling. These were investigated on an individual basis in order to evaluate their relative importance and to demonstrate the relationship of the factors to total cost of cooling.

The data for each of the sensitivity investigations are presented in graphical form, with a brief discussion of the results and implications of the study. The data points generated are depicted on the curves, with the base case designated by the circle. The number above each of the data points represents the number of wells required for that particular case, thus providing an indication of the effect of the parameter on peak flow rates, since the number of wells is proportional to peak flow.

Demand Characteristics

System Size

A large range of system sizes was investigated, ranging from an annual load of 2000 Btu (2% of the base case) to 1,000,000 MBtu (10x the base case). Cost was found to vary inversely with system size in a nonlinear fashion, rising quickly at the smallest size and flattening out at the largest sizes (Figure 4.21). The major advantages captured by large systems are economies of scale in the storage and transmission systems. Storage capital cost is independent of total volume stored; rather, it is a function of peak flow rate. This is a major difference between ATES and other storage technologies where cost depends upon the size of the storage container.

It is likely that this inverse cost/size relationship is understated in the data since aquifer thermal efficiency (kept constant here) will typically increase with a larger annual storage volume, and decrease quickly as the storage volume decreases.

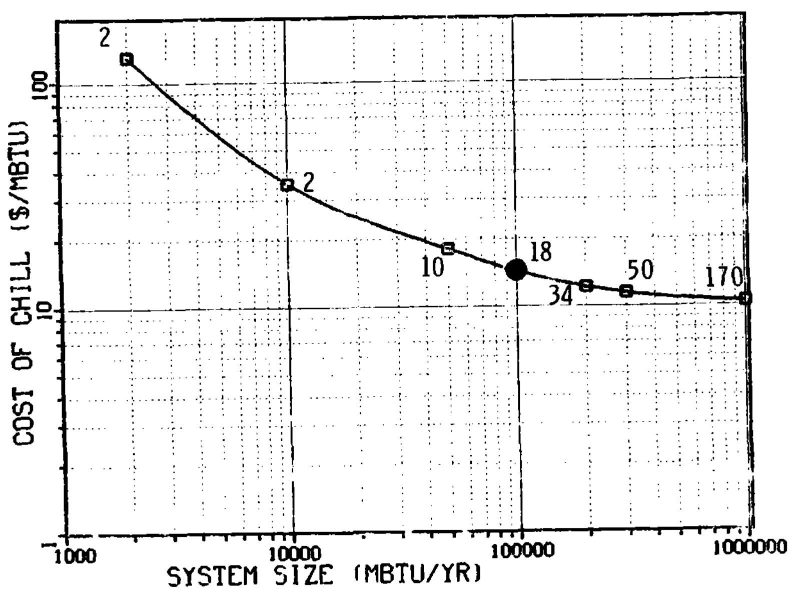


FIGURE 4.21. The Effect of System Size on the Cost of ATES Cooling

Load Factor

The load factor is defined as the ratio of average annual hourly demand to peak hourly demand. Load factors from 10%-30% were investigated. Since a large fraction of the ATES cooling cost is fixed, the cost of cooling increases rapidly as the load factor diminishes (Figure 4.22). Typical cooling load factors for single family dwellings are in the 10-15% range. For commercial and industrial space cooling applications that require some air conditioning throughout the year, load factors in the 20-30% range are not unreasonable. For a process chill application very high load factors might be expected. Because the cost of cooling rises so quickly at low load factors, employment of the ATES technology for capital-intensive district cooling of residential houses may be very expensive.

Transmission Distance

The cost of ATES cooling is highly dependent upon transmission distance. The relationship is roughly linear, since we have not assumed any economies of scale with extended length (Figure 4.23). One factor that tends to make the relationship nonlinear is heat gain in the pipeline, since additional water will be needed to meet demand, and eventually larger pipes will be required to

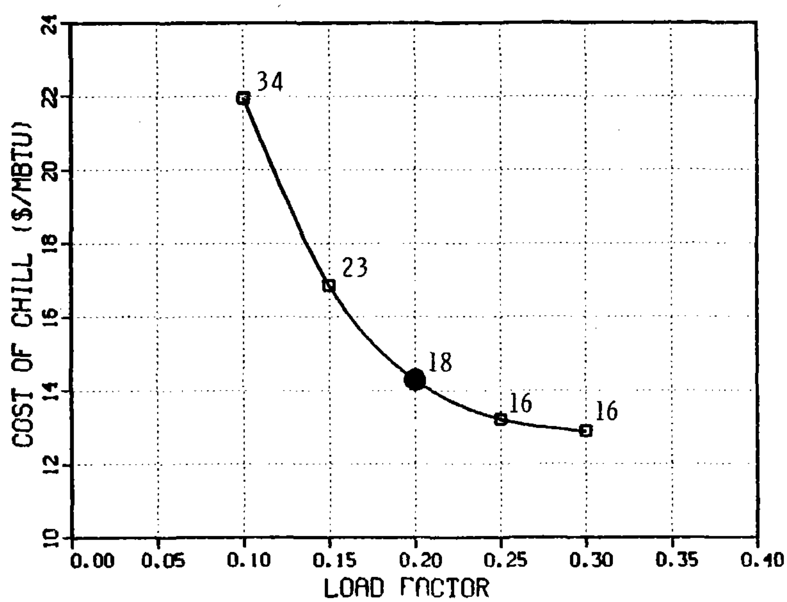


FIGURE 4.22. The Effect of Load Factor on the Cost of ATES Cooling

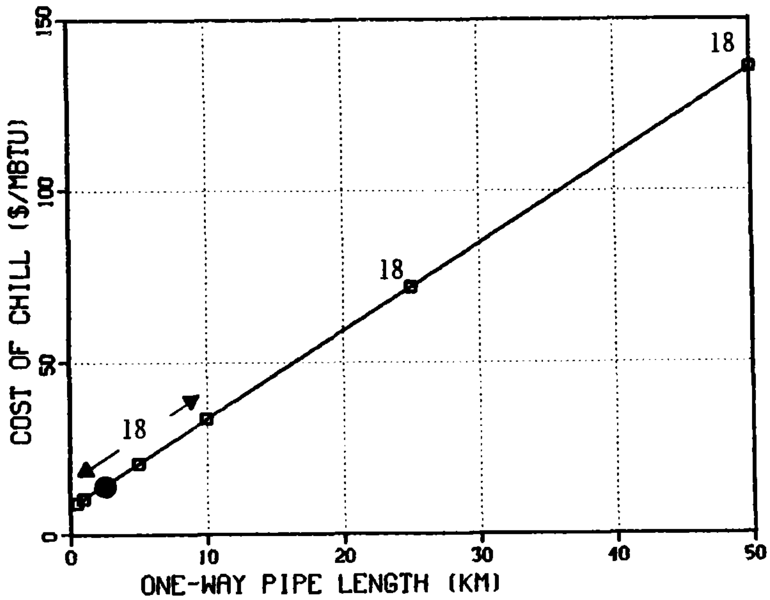


FIGURE 4.23. The Effect of Transmission Distance on the Cost of ATES Cooling

accommodate the larger flow. The reason that piping cold water for large distances is uneconomic is that its energy density is so low. To put this in perspective, oil has an energy content of 140,000 Btu/gal, chilled water only 120 Btu/gal. It is obvious that ATES cooling systems will necessarily be located on or near an aquifer and the chill source. A cooling load located above an aquifer could reduce its required transmission distance to almost zero by employing winter air as the chill source.

Load Reject Temperature

The temperature drop of the cooling fluid at the load determines the chill energy delivered. For a given chill delivery system, the higher the reject temperature from the load, the greater will be the energy delivered to the load, and the less expensive will be the energy delivered on a per-Btu basis. Thus, in the design of a particular ATES cooling system it will be necessary to balance the advantages of a higher reject temperature against the extra cost of the larger heat exchanger and delivery system required at the load. For the base-case system, increasing the reject temperature from 60°F to 65°F (which is not unreasonable for a 75°F air conditioning temperature) reduces the cost of cooling by 20% (Figure 4.24).

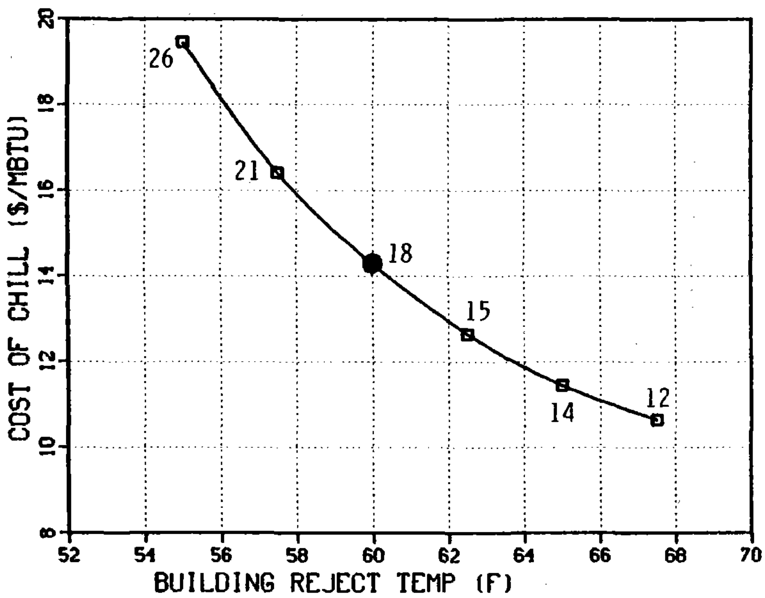


FIGURE 4.24. The Effect of System Reject Temperature on the Cost of ATES Cooling

Supply Parameters

Source Availability

The amount of time that the chill source is available is relatively unimportant to the cost of ATES cooling as long as two conditions are met: 1) the cost of the chill collectors is relatively small, and 2) the number of wells in the system is controlled by demand considerations rather than supply considerations. The number of wells required is determined by the greater of the peak flow rate out of the aquifer to the load (demand-controlled), or the flow rate into the storage aquifer from the chill source (supply-controlled). On the right side of Figure 4.25, peak demand controls the number of wells, and so the effect of changing source availability on total cost is minimal. The only additional costs are for a larger heat exchanger and slightly larger piping. The left portion of Figure 4.25 depicts the supply-controlled situation. Additional wells are required to store the total annual demand during the time that the source was available. The effect on the cost of cooling in this situation is very pronounced. It is evident that an ATES system does not require an extremely lengthy chill season for cost effective operation.

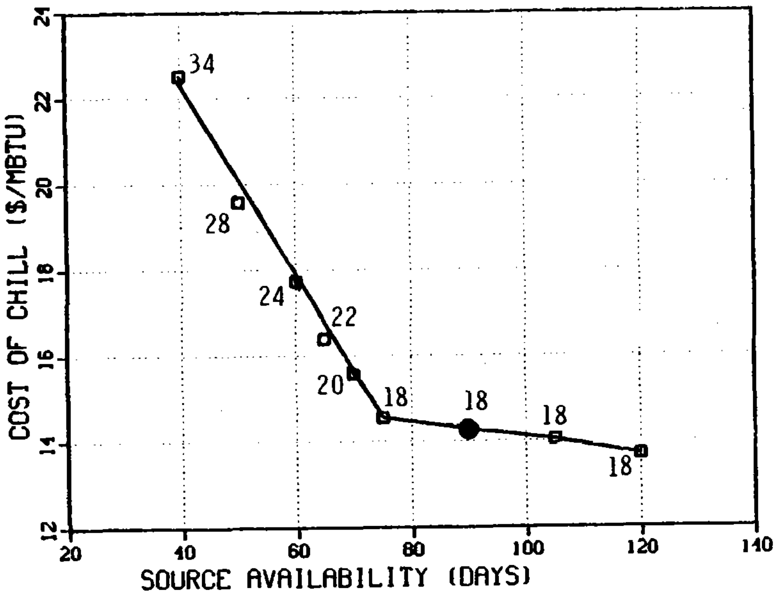


FIGURE 4.25. The Effect of Source Availability on the Cost of ATES Cooling

Source Temperature

The average temperature of the chill source is an important determinant of the cost of chill. In this simulation, as the temperature of the chill source rises, the temperature of the water delivered to the air conditioning load rises on almost a one-to-one basis (Figure 4.26). This reduces the energy content of the water delivered to the load, thereby requiring additional wells, increased pipe and pump sizes, and larger cooling devices at the load. Increasing the source average temperature from $35^{\circ}F$ to $40^{\circ}F$ increases the cost of cooling by almost 30% in this simulation. Since the gain at the load is the key variable controlling cost, a higher source temperature could be compensated for by a higher reject temperature.

Heat Exchanger Approach Temperature

Another method of compensating for a higher source temperature is to employ a larger heat exchanger with a smaller approach temperature in the chill collection subsystem. The approach temperature of the heat exchanger is the temperature difference between the incoming river water ($35^{\circ}F$) and the outgoing aquifer water temperature ($45^{\circ}F$). Conventional engineering judgment

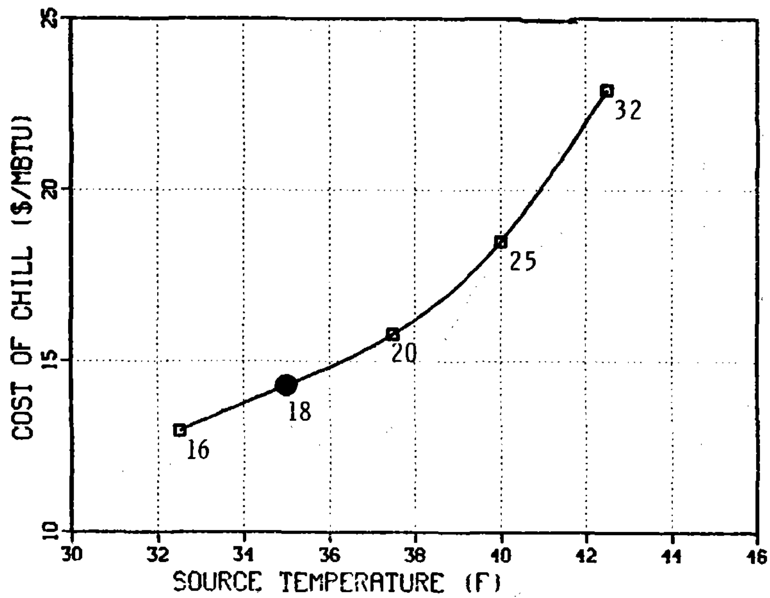


FIGURE 4.26. The Effect of Source Temperature on the Cost of ATES Cooling

would suggest a 10^{0}F approach temperature as a near optimum for industrial applications. For an ATES application, however, the leverage that the heat exchanger wields over the remainder of the system is substantial, and the additional capital costs and pumping costs incurred with a larger heat exchanger are quickly compensated for by savings in number of wells and pipe size. The scenario under investigation dramatically illustrates this point; as the approach temperature of the heat exchanger is lowered from 10^{0}F to 2.5^{0}F, the energy content of the fluid delivered to the load increases by about 50% (Figure 4.27). As a result, the number of wells required by the system drops from 18 to 12, and the total cost of the energy delivered is reduced by 20%. The optimum heat exchanger characteristics will vary from installation to installation, but it is likely that heat exchangers with rather small approach temperatures will be optimal for ATES cooling systems.

Aquifer Thermal Efficiency

Aquifer thermal efficiency, the ratio of energy recovered from the aquifer to energy injected (on an annual basis), is an important determinant of the cost of ATES cooling. It is dependent upon a number of factors, including: the rate of regional flow (which tends to carry input energy away from the well

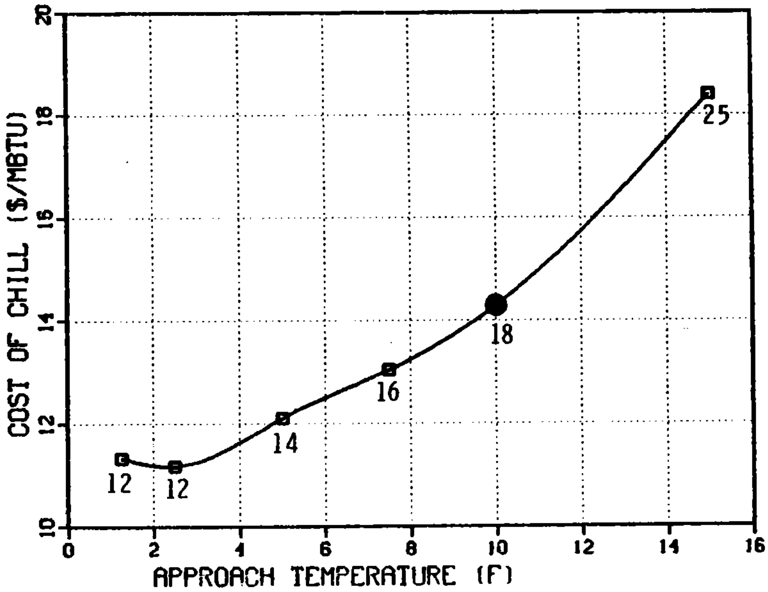


FIGURE 4.27. The Effect of Heat Exchanger Approach Temperature on the Cost of ATES Cooling

site), the temperature differential between the injected water and the in situ water, the total amount of water injected, and aquifer geometry. For a constant cooling load, a reduced aquifer thermal efficiency requires that more energy be injected, and hence a larger overall storage and delivery system is required. The relationship between aquifer thermal efficiency and cost is essentially linear (Figure 4.28). The scatter apparent in the figure is due to the fact that the number of wells required by the system is a step function.

Economic Parameters

Well Cost

The cost of cooling varies directly with the cost of wells (or more correctly, with the cost per unit flow rate) (Figure 4.29). Well costs constitute a significant part of the total capital cost, and so the cost of well drilling in a particular region may be the determining factor in the economics of a particular ATES installation.

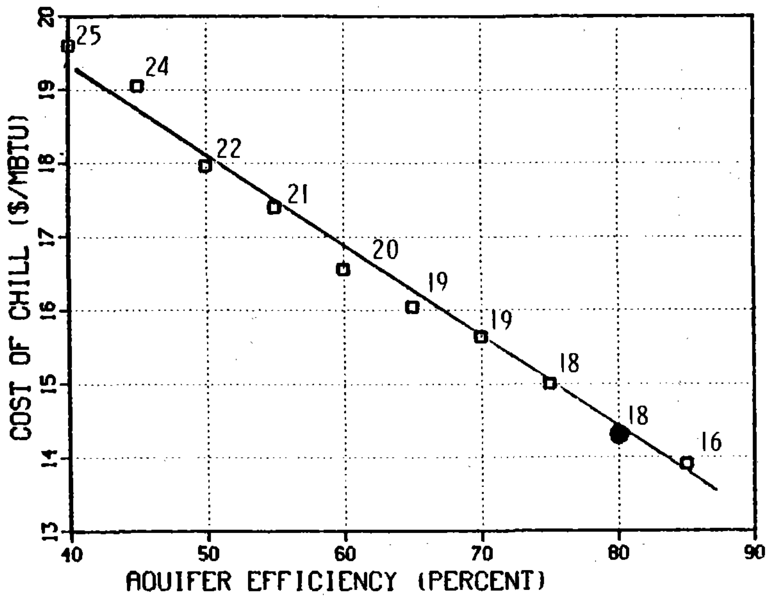


FIGURE 4.28. The Effect of Aquifer Thermal Efficiency on the Cost of ATES Cooling

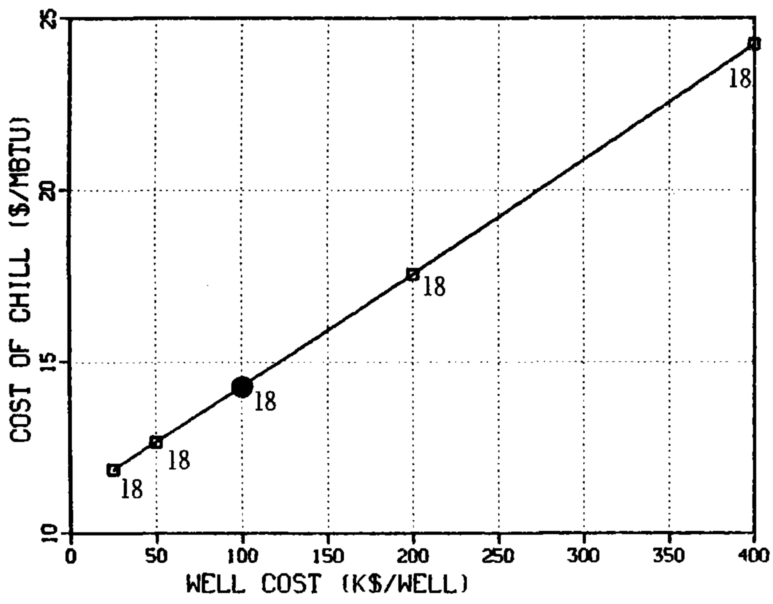


FIGURE 4.29. The Effect of Well Cost on the Cost of ATES Cooling

ATES cooling systems probably will not be subject to extremely high well costs in most parts of the country because the low temperature systems do not require deep, pressurized aquifers, and because temperature loss to the surface is less of a problem than with high temperature systems. Well costs will probably differ significantly between installations, however, for a number of reasons: 1) well drilling rates differ considerably in different parts of the country, 2) suitable aquifers may be found at widely varying depths, 3) aquifers can have varying productivities, and hence more wells may be required to deliver the same flow rates, and 4) some ATES systems may need to employ saline aquifers which require corrosion-resistant well materials and equipment.

Cost of Electricity

The cost of ATES cooling is relatively insensitive to the cost of electricity since the operation is capital intensive, with electricity used only for pumping (Figure 4.30). Doubling the cost of electricity only increases the levelized cost of cooling by about 5%. Thus, in areas with high electricity rates and high price escalation rates, ATES could prove quite cost effective.

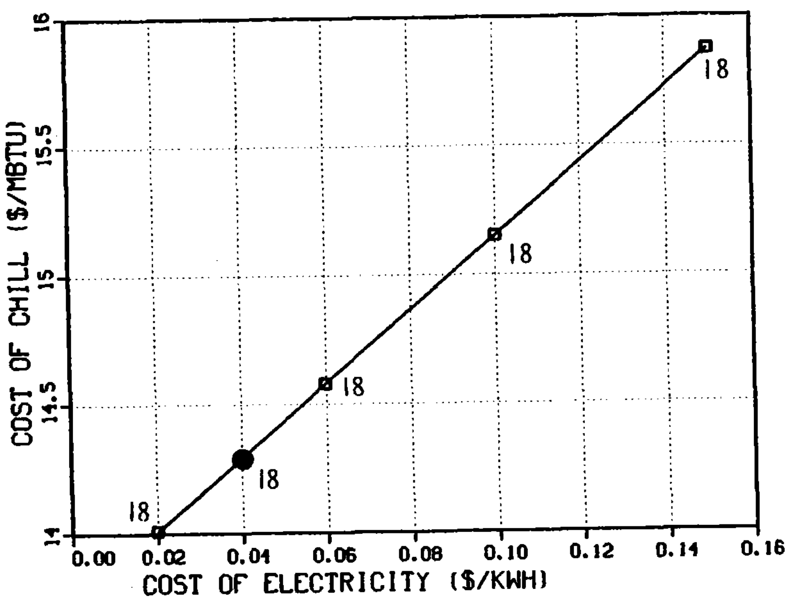


FIGURE 4.30. The Effect of Electricity Cost on the Cost of ATES Cooling

There are implications beyond direct cost to the user, however, in that electricity consumption is reduced (over electric compression cooling) during times of peak demand. The dollar savings from reduced capacity requirements in summer peaking locations could be significant.

Bond Interest Rate

Interest charges constitute a major initial cost of an ATES cooling system since ATES is capital intensive. However, the interest charges are fixed, and so over time (with a significant inflation rate) the cost of interest will drop as a fraction of total cost. In the base case it is apparent that small variances in the interest rate are rather inconsequential with respect to potential variances in other parameters (Figure 4.31). A 50% increase in the interest rate (to a municipal rate of 12%) results in only a 15% rise in the levelized cost of cooling.

Comparison with Other Cooling Techniques

Any economic analysis of an alternative cooling method must ultimately result in a comparison with conventional cooling techniques. The two types of cooling that are implemented on a widespread basis are electrically-driven compression chillers, and fuel-fired absorption chillers. The levelized cost

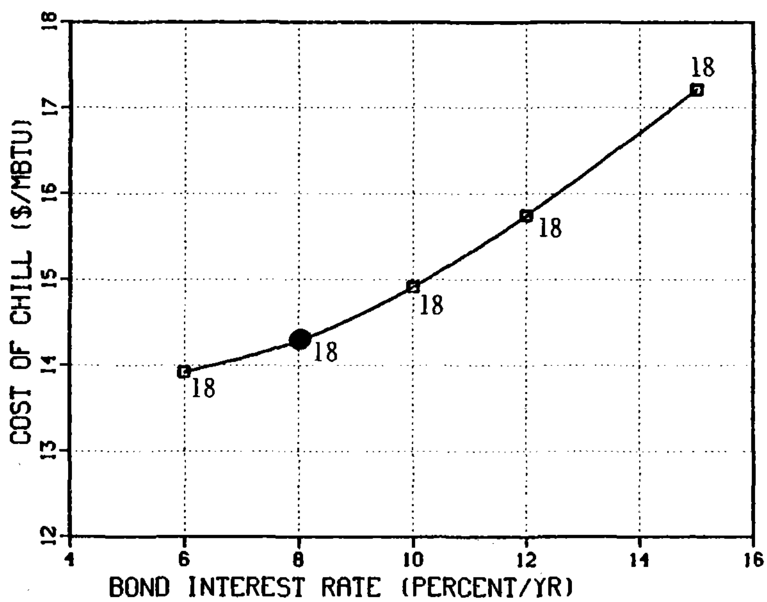


FIGURE 4.31. The Effect of the Cost of Capital on the Cost of ATES Cooling

of cooling was calculated for these systems using the same economic assumptions as used for the base case investigation of ATES cooling. Fuel was priced at $4/MBtu, with a 6% escalation rate. Cost and performance information for specific units was derived from vendor information. The levelized cost of chilling by means of electrically-driven compressive devices was calculated to be $10.26/MBtu. The cost for absorption chilling was calculated to be $18.00.

Although the cost of ATES cooling is more expensive than the cost of electric air conditioners, only slight changes in one or more of the base case assumptions would be enough to make ATES economically attractive. The base case parameters were selected so as to define a situation potentially attractive for ATES cooling, but they are not optimum conditions. For instance, substitution of a 2.5^{o}F-approach temperature heat exchanger for one with a 10^{o}F-approach temperature could reduce the cost of cooling significantly. Likewise, doubling the cost of electricity to $0.08/kWh would make ATES relatively more attractive: the ATES cost of cooling would rise a small percentage, whereas the cost of compressive cooling would significantly increase since its levelized cost is roughly 60% due to electricity.

Summary

The major outcome of the investigation conducted here is that the cost of air conditioning using chill energy supplied by an Aquifer Thermal Energy Storage system is extremely dependent upon site specific conditions. Under appropriate demand, supply, and geologic conditions ATES cooling can be competitive with both electric compression and absorption chiller devices. Under less favorable conditions, its cost of cooling could be an order of magnitude too high.

A few implications can be drawn for all ATES cooling systems. It will be uneconomical to pump chilled water for very long distances due to the low energy density of the fluid. Hence, an ATES system will typically be located on or near a suitable aquifer with the energy supplied by a nearby chill source (such as winter air collected at the site). In this investigation, schedule 10 piping in steel casing was employed. By using less expensive, non-cased, uninsulated pipe, the cost of piping can probably be reduced by about 30%.

Another implication of the study is that the temperature gain of the cooling water at the load site must be optimized. A few degrees variance in the delivery water temperature can markedly affect the cost of cooling. This temperature differential (between the cooling water supplied to the load and the reject temperature) is bounded on two sides: on the low side by the temperature of the chill source, or the freezing point, and on the upper side by the target temperature of the air conditioning system. Between these two bounds, the actual temperature differential is controlled by a number of parameters, including the approach temperatures of the heat exchangers at both the chill source and the load, pipe insulation, and aquifer thermal efficiency. Selection of these system components must be optimized based upon cost/performance tradeoffs.

Task 4 - Methodology for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage Systems. A contract was let with G.E. TEMPO to perform this task, and resulted in the October publication of Guidelines for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage, (Meyer, Hauz 1980).

The guidelines were prepared as a tool for those considering the use of ATES systems. The guidelines will assist in the preliminary design effort and in evaluation of the technical and economic feasibility of using the ATES technology.

Chapters 1 and 2 are an eight-page executive summary, describing the potential benefits of ATES, giving an overview of the technology and its applications, and providing rules of thumb for quickly judging whether a proposed project has sufficient promise to warrant detailed conceptual design and evaluation.

The balance of the 230-page document discusses the characteristics of sources and end uses of heat and chill which are seasonally mismatched and may benefit from ATES (industrial waste heat, cogeneration, solar heat, and winter chill, for space heating and air conditioning); describes storage and transport subsystems and their expected performance and cost as best these parameters are now known; presents a 10-step methodology for conceptual design of an ATES system and evaluation of its technical and economic feasibility in terms of energy conservation, cost savings, fuel substitution, improved dependability of supply, and abatement of pollution, with examples; and applies the methodology to a hypothetical proposed ATES system, to illustrate its use.

Appendix A discusses the flow of fluids and heat in aquifers, the design of ATES wells, and operational aspects of ATES, in greater detail than is found in the main body. Appendix B describes types of aquifers in the United States and their suitability for ATES. Appendix C gives formulas and tables for economic analysis, to supplement Chapter 5.

Task 5 - Provide Analytical Support to the ATES Demonstration Program. During FY-1980 only minor support was given to the ATES Demonstration Program. It is expected that activity in this area will increase in future years as economic information on the projects become available.

Technical Problems

There were no technical problems encountered during the reporting period.

4.2.3 Environmental Assessment

Oak Ridge National Laboratory, Resource Management and Assessment, 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). Current emphasis of this task is on a aquifer thermal energy storage (ATES) programmatic and site-specific documentation.

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 industrialization.

Task 3 - Environmental Advisory Assistance. This task provides assistance to the STES Program on all environmental matters associated with determining 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 proposals and assisting in the preparation of program-level reports and publications.

Technical Progress

Task 1. This task has received major emphasis during 1980 with activities being divided between programmatic (generic) documentation and site-specific environmental documentation requirements.

During 1980, with the assistance of the Oak Ridge National Laboratory and Resource Management and Assessment, this task completed the preparation and issuance of a draft Environmental Assessment (EA) for the ATES Program which fulfilled a FY-1980 milestone.

The comments received on the draft EA were extensive, as was anticipated. Reaching agreement on the EA contents required extensive coordination with the various organizational components of the Department of Energy (DOE) including the Office of Environment, NEPA Affairs Division (EV), Office of the General Counsel (OGC), Office of Advanced Conservation Technologies (ACT), Assistant Secretary for Conservation and Solar Energy (CS), and DOE Richland Operations (RL) as well as other concerned governmental agencies (Federal, state, and local). Revisions to the document in response to the comments were prepared and have been incorporated. As of the time of this writing, the revised EA is being fine-tuned prior to its publication in 1981.

Based on this EA, DOE has determined that the proposed ATES Program does not constitute a major Federal action signficantly affecting the quality of the human environment and therefore a programmatic environmental impact statement is not required.

The EA basically concludes that the environmental consequences of the ATES Program will be site-specific in nature. Potential adverse local environmental impacts could occur which may reduce aquifer permeability, alter ground water quality, and ground water microbiology. These potential impacts can be eliminated, however, if sites are carefully selected, systems are properly designed, and monitoring programs are included. Site-specific institutional issues related to water use are expected to be important for ATES type developments. Adverse impacts to surface water hydrology, aquatic ecology, terrestrial ecology, air quality and the host communities are not anticipated. Site-specific monitoring programs, which are comprehensive in scope, must be developed to ensure that mitigatory measures are adequate and to detect any unforeseen impacts. Potential environmental benefits are anticipated from reducing the amount of waste heat discharged to the environment and from reducing dependence on conventional energy sources for space heating and cooling. The ATES technology was assessed to be more developed for demonstration than its alternatives. The environmental consequences of the programmatic alternatives are not expected to differ from the proposed action to a great extent.

During 1980, discussions were held with appropriate DOE and non-DOE agencies/personnel to clarify NEPA compliance requirements associated with overall STES/ATES activities. These discussions resulted in the development of the tentative environmental documentation plan for STES Program shown in Figure 4.32.

The ATES Programmatic EA scheduled for DOE publication in FY 81 was described previously. With the guidance provided by this task during 1980, the three ATES Demonstration Contractors have:

- Finalized their Environmental/Institutional Plans,
- completed their preliminary environmental assessments for Phase I activities, and

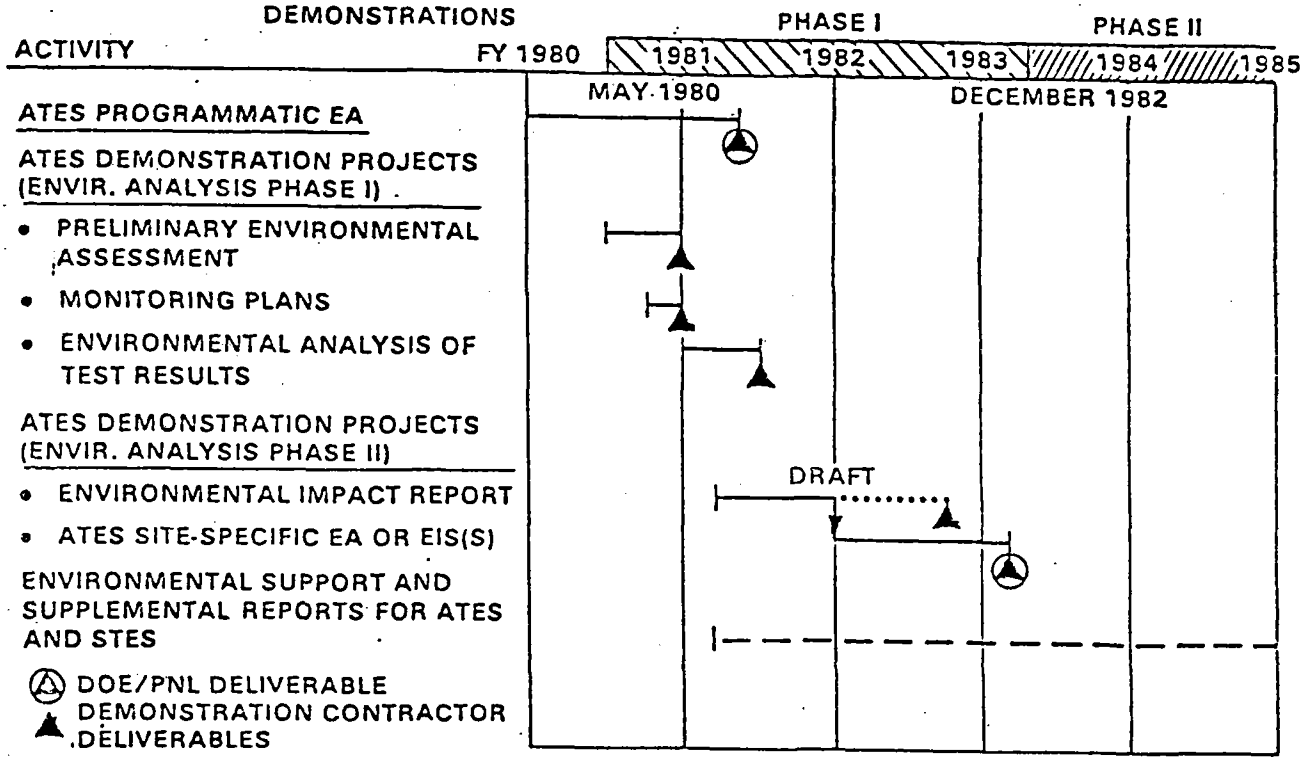


FIGURE 4.32. Scheduling for Environmental Assessment

- developed and implemented environmental monitoring procedures appropriate for their Phase I activities.

These environmental task actions which were all completed and approved during 1980, are considered to be important to the overall success of the ATES demonstrations for several reasons. First, the early inclusion of environmental concerns has resulted in the functional integration of the environmental and technology teams. This consolidation, during the planning stages, has resulted in a single field monitoring and data collection effort for site preparation, construction and testing activities that serves both environmental and technological objectives. Second, early environmental initiatives have minimized potential complexities associated with local environmental regulatory permitting requirements. Third, early environmental interactions directed toward educating the public and regulatory personnel should help prepare for the local environmental acceptance of expanded Phase II activities. And lastly, environmental activities throughout the program should ensure the development of environmental documentation and control technology to support operational and industrialization needs. The development of the three environmental reports assessing Phase II ATES Demonstration Projects' activities is the major requirement for this task during 1981 and 1982.

Task 2 - Environmental Research Assistance. To date, effort in this task area continues to be 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:

- Provided ATES Demonstration Project Support - Routinely provided assistance to ATES Program Manager in evaluating data and reports submitted by ATES contractors for environmental compliance and periodically coordinated with environmental specialists assigned to each project.
- Initiated coordination with other Federal agencies potentially interested in STES/ATES environmental efforts. During 1980, included EPA Office of Drinking Water, Water Resources Council, and DOE Offices of Environmental Assessment and Environmental Control Technology.
- Contributed to annual review of safety analysis for STES Program.
- Attended and presented environmental briefings at Consultant Review Team Workshop and Annual Contractors' Review.
- Prepared Draft Environmental Assessment for TVA's proposed ATES Project.
- Prepared Work Statement for external contractor to review and assess government regulations relevant to ATES developments.
- Contacted and interviewed several minority companies as potential external contractors in the environmental support area.

Technical Problems

The publication of the Environmental Assessment for the ATES Program in time to support planned field activities appears assured. However, the schedule for the development of the site-specific environmental documentation is very tight, especially if any EIS's are required. Accordingly, any demonstration project delays could seriously impact the environmental documentation development schedule.

4.2.4 Field Test Facilities

Sites are being identified and developed to obtain necessary engineering design and geohydrologic data and to conduct supporting research for the STES Program. This research includes the development of field test facilities to provide necessary guidance to the demonstration programs. Data collected at the field test facility (FTF) sites will provide required calibration and verification of advanced analysis methodologies being developed for site characterization and assessment. The FTF is designed to provide definition of the variables anticipated in ATES projects. Information developed through the FTF is made available to the ATES demonstration contractors. FTF activities are scheduled to continue through FY-1985 and will work in conjunction with the Demonstration Program.

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

Field 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 true doublet well field at the test site for the injection and monitoring of thermally enhanced ground water.

Task 2. Characterize the aquifer such that detailed data are available for use in the advanced methodologies task.

Task 3. Inject, store and recover ground water over three cycles at temperatures of 55°C, 90°C and 125°C, respectively.

Task 4. Monitor the movement of the thermal plume and supply data for computer analysis.

Technical Progress

Task 1 is nearing completion. The well field at the Mobile, Alabama site has been altered to provide data points for analyzing the true doublet test. New injection and supply wells have been drilled into the storage aquifer. Comprehensive testing of aquifer parameters is being carried out. A partially penetrating aquifer pump test was run to ascertain the ratio of horizontal to vertical permeability. Analysis of the test show the ratio to be 7:1. Fully penetrating aquifer tests have confirmed the horizontal permeability calculated from earlier experiments to within 1%. Table 4.13 shows the comparison of aquifer characteristics determined in 1976 and 1980. Experience with the nondoublet tests indicated a need for backup thermistors in the temperature monitoring wells; to accomplish this, dual strings of instruments have been installed. All surface equipment has been elevated 5 feet to provide flood protection. Surface flow equipment includes two large rapid sand filters which can be placed "on line" when deemed necessary. These filters will serve to remove clay and silt sized particles from the injection stream.

TABLE 4.13. Comparison of Aquifer Characteristics, 1976 Nondoublet Test and 1980 Doublet Test

Characteristic	1976	1980
Thermal Conductivity		
Aquifer	1.98 J/m.d.^{o}C	N.R.
Aquitard	2.21 J/m.d.^{o}C	N.R.
Hydraulic Conductivity (Horizontal)	44m/d	53.6 m/d[(a)] 53.4
Hydraulic Conductivity (Vertical)		7.66 m/d[(a)]
Aquifer Storativity	5 x 10^{-4}	4.9 x 10^{-4}[(a)]
Porosity	0.25	N.R.

(a) Result from 1980 partially penetrating test.
N.R. Paramerter determination not repeated.

A test to ascertain the despersivity of the aquifer has been designed and the necessary equipment installed. This test will utilize a NaBr (sodium bromide) tracer. This tracer will be injected at a constant rate and concentration and the arrival time and concentration of the tracer will be monitored at several sampling wells surrounding the injection well.

Injection of hot water for the first cycle of testing is currently scheduled for early February, 1981.

Field Test Facility

Tennessee Valley Authority

Objective

To locate and characterize a potential storage site within the TVA service area.

Technical Status

This effort was halted after a potential site was identified near Memphis, Tennessee. TVA was unable to identify internal funding to cooperatively develop this field test facility. Due to the nature of the proposed project, TVA's funding would have to come directly from pass through charges applied to the utility's customers as a rate increase.

There are currently no plans to reinstate this FTF activity.

Field Test Facility

Fugro, Inc.

Objective

To characterize a potential saline aquifer near Ferndale, Washington.

Technical Progress

Two test holes were drilled. One hole, on the property of the Thermal Reduction Company of Bellingham, Washington was drilled to a total depth of 505 feet at which depth it was ascertained that the drill had penetrated underlying Tertiary bedrock. Subsequently, the hole was backfilled and abandoned according to Washington State law. A second hole was drilled at a County Historical Park to a depth of 605 feet. Numerous problems were encountered during the placement of this well. Flowing artesian conditions in upper fresh water aquifers necessitated grouting of casing early in the project. Subsequent drilling activities damaged the grout seal and forced additional grouting. Following installation of casing, the hole was re-entered, during the cleaning operation a drill stem was twisted off at 488 feet. Recovery of the drill stem was attemped but proved unsuccessful. The hole was then backfilled and grouted to prevent contamination of the upper aquifers and abandoned. Re-assessment of the geohydrology of the Bellingham-Ferndale basin based on information from these drilling activities, indicates that the target Esperance sand unit is located further to the west, in deeper portions of the glaciated Nooksak Valley.

The project was terminated based on the legal, institutional and environmental difficulties associated with a hot water line crossing of the Nooksak River, and prohibitive costs associated with long distance transport of the heated water. Additional geohydrologic exploration would be necessary to prove the presence of the Esperance sand on the west side of the Nooksak River.

Field Test Facility

Pacific Northwest Laboratory

Objective

To locate and characterize a shallow unconfined aquifer suitable for storage of low temperature energy.

Technical Progress

Seven wells were drilled into the glaciofluvial sands and gravels within the Pasco Basin. Each of the wells penetrated the water table at a depth of about 50 feet. Wide variations in aquifer characteristics were noted between the several wells, with well yields ranging from less than 10 gpm to over 600 gpm. The site has been set aside as a potential place for testing the feasibility of gradient control in ATES systems. No work beyond initial drilling and testing of the wells was done during CY-1980.

Technical Problems

Auburn. There were minimal technical problems associated with the Auburn FTF. Those that were encountered centered around providing equipment capable of handling the proposed 125°C injection cycle. No difficulties were encountered in the drilling phase although costs exceeded expectations.

Bellingham. Major difficulties were evident in the exploratory drilling program at this proposed FTF site. The first drill hole penetrated bedrock before locating the target aquifer. This forced abandonment of that hole. Flowing artesian conditions at the second drill site necessitated extensive grouting of casing. Further down the hole, caving conditions forced the installation of additional casing. Upon re-entering the hole, after placing the casing, a drill bit was lost at 488 feet and proved to be irretrievable. The target Experance Sand aquifer was not penetrated in either drill hole.

4.2.5 Compendia of Existing Technology

Midwest Research Institute, Lawrence Livermore Laboratory, Oregon State University, Century West Engineering, Lawrence Berkeley Laboratory, David D. Hostetler, and Pacific Northwest Laboratory.

Objective

The objective of the Compendia Task is to collect, summarize, and transmit STES-related information. The task will provide a central source of information which will assist with the development of STES technologies and will also aid in the transfer of these technologies to the commercial sector.

Tasks

Task 1 - Library Establishment, Maintenance, and Development. Provide a useful library of STES-related information. Identify and procure new literature, enter bibliographic information in the computerized data base, distribute updated bibliographies, and maintain library operation.

Task 2 - Literature Reviews and Summary Papers. Review the literature and produce papers on topics that are pertinent to STES.

Task 3 - STES Newsletter Publication. Compile, edit, publish and distribute a quarterly STES Newsletter.

Task 4 - Production and Maintenance of the Aquifer Thermal Energy Storage Reference Manual. Produce and maintain a reference manual for the STES Program. Update individual sections of the manual as needed.

Task 5 - Development of the STES Technology Information System. Develop a computerized information system that will assist with the development of STES technologies and with the transfer of these technologies to the commercial sector.

Technical Progress

Task 1. Compendia task staff members have assembled a useful STES Library. The library now contains over 1700 documents with a wide range of key references on topics related to thermal energy storage. Library maintenance and development is being conducted via subcontract with Midwest Research Institute.

Bibliographic information from the STES Library has been entered into the computerized information system, called the STES Technology Information System (STES-TIS). Each library article is represented by a citation, which consists of a number of fields including author, title, publisher, publication date, keywords, abstract, etc. Each citation also contains fields that can be used by the STES librarian to keep a record of the status of the document represented by the citation. For example, each time a staff member checks out an article, the librarian can enter the name of the person and the date. Later, this information can be recovered to show which staff members have overdue articles. The ability to keep an on-line record of library transactions eliminates the need for maintaining voluminous hard-copy files.

The STES-TIS also provides the capability to conduct customized, on-line literature searches. A search can be conducted on any part of any field of the citation. For example, a search could be conducted to find all articles which contain the word "storage" in the title. Methods for searching the STES bibliographic data file have been documented in the User's Manual for the STES information system.

The bibliography is regularly updated, and a list of new articles is distributed every 2 weeks so that researchers on the STES Program are kept informed about the contents of the library.

During the past year, the existence of the library has been publicized, and researchers from foreign countries (including Sweden, Israel, Canada, France, and Germany) have heard about and have used the library.

Improvements made in the STES Library this year have resulted in a more useful, efficient operation.

Task 2. Several literature reviews and summary papers were completed during the past year. Topics covered include: Aquifer Thermal Energy Storage (ATES) site characterization methods, regional aquifer assessments, energy and mass transport in geologic media, and reinjection experience in ground-water cooling operations. All of these studies were conducted under subcontract. Technical progress on these studies is discussed in the following paragraphs.

A document on ATES site characterization methods was prepared by Mr. David Hostetler, a consulting engineer. This document contains information on the following: site selection and ambient temperature characterization; pre-operational thermal characterization and site evaluation; and subsurface facility design development. This is a draft report for internal use only.

Century West Engineering has conducted a regional aquifer assessment study. The objective of this study was to qualitatively describe the ATES potential of major aquifers throughout the United States. Century West Engineering has collected existing hydrogeological information for major U.S. aquifers. This information has been used to characterize each aquifer system. On the basis of its characteristics, each aquifer has been evaluated for its ATES potential.

The Department of Soil Science of Oregon State University (OSU) has completed part of a study on energy and mass transport in geologic media. The objective of the study is to identify soil and environmental conditions or parameters influencing the efficiency of an ATES facility. The study is primarily focused on energy transport mechanisms in the unsaturated zone of the unconfined aquifer system. During the past year, OSU completed a literature review and a preliminary parametric analysis. An annotated bibliography and an interpretive report have been delivered to PNL. Work is still being conducted under this subcontract, but technical adminstration has been transferred to the Numerical Simulation task of the STES Program.

Midwest Research Institute (MRI) has conducted a survey of ground-water reinjection experience in air-conditioning operations. Basically, the work consisted of three tasks: site identification, documentation of selected sites, and analysis of site data. The site identification task involved identifying sites across the United States where reinjection of cooling water is practiced. Selection of sites was based on availability of information and geographic location. The reinjection sites chosen for documentation were representative of different geographic locations and hydrogeologic environments. The second task involved site documentation. Documentation consisted of three parts: well system design, operational performance history, and analysis of the reinjection experience. The third task, data analysis, involved the identification of actual and potential problems with the reinjection operations of each site. The results of the study are contained in MRI's final report, which has been submitted to PNL.

A survey of ground-water source heat pump operations in the Portland, Oregon, area has been conducted by the Department of Mechanical Engineering of OSU. This study was intended to assess the use of ground-water source heat pumps for large-scale heating and cooling operations in the Portland area. Basically, the survey of ground-water source heat pump operations consisted of the following tasks: 1) identification of sites, 2) documentation of system designs, operational procedures, operational problems and overall system performance of each site, and 3) analysis of the heat pump operations. OSU also performed modeling to assess the potential benefit of using aquifer thermal energy storage in conjunction with ground-water source heat pumps. OSU submitted a final report containing the results of the study.

Task 3. The STES Newsletter was published quarterly during the past year. The scope of the newsletter was expanded to include articles on all types of seasonal thermal energy storage, not just on storage in aquifers. The newsletter has proven to be a valuable means for exchanging information with other researchers in the field of energy storage. The STES Newsletter is compiled, edited, published, and distributed by Lawrence Berkeley Laboratory under subcontract to PNL.

Task 4. The Aquifer Thermal Energy Storage Reference Manual was issued in August 1980. This manual contains a complete description of the work being performed under the STES Program. It will be updated as the Program progresses. The revisions will be distributed to all individuals holding a copy of the manual.

Task 5. Creation of the STES Technology Information System (STES-TIS) was initiated during the past year. The STES-TIS is a subset of the Technology Information System developed at the Lawrence Livermore Laboratory (LLL) under the sponsorship of the Department of Energy's Office of Advanced Conservation

Technologies. The Pacific Northwest Laboratory contracted with LLL to provide assistance in the development of an information system for the STES Program.

The STES-TIS has been designed to fill the informational needs of the STES Program by providing the capability to store and manipulate various types of data files and numerical models. In general, the STES-TIS contains four types of resources: 1) administrative, 2) bibliographic, 3) computational, and 4) communications.

Several administrative data files have been entered into the STES-TIS. One such data file is the conference data file, which contains information about various STES-related conferences. The file contains details about each conference, names of STES staff members who attended or presented papers, and information about the papers presented at the conference. The conference file is a useful managerial tool which is used by the STES managers to keep a running account of staff members' activities. Another administrative data file contains two types of news: 1) weekly highlights, which are short reports describing the important events of each week, and 2) newsletter articles, which are compiled, printed, and distributed on a quarterly basis.

The STES-TIS contains bibliographic data from the Seasonal Thermal Energy Storage Library. These bibliographic data were transferred into the computer from a text-processing system. The data were checked for validity and were converted to the proper format. The information contained in the data file was then checked by the STES librarian to ensure that it was complete and correct, and that it accurately represented the documents contained in the STES Library. The library data file now contains over 1700 citations and is updated regularly as new library articles are received.

In addition to data files, the STES-TIS can also accommodate numerical models. The STES Program is developing several models that could potentially be put into the system, including both economic and hydrologic models. Some of these models are too long and complex to reside on the small computer which houses the STES-TIS. However, in these cases, the STES-TIS can still be used as an automated gateway to other computer resources which can more easily accommodate them. This capability has already been used to implement one of the complex hydrologic codes on a large computer at the Solar Energy Research Institute, to which the STES-TIS can provide access.

Implementation of the STES models on the information system makes them available to a wider community of users, thereby encouraging transfer of energy storage information to the commercial sector. The project staff at LLL can also assist in converting the models from batch-mode to interactive, allowing users to run the models without having intimate knowledge of the codes. None of the STES models have yet been converted to interactive mode, although this task may be undertaken at some time in the future.

The STES-TIS offers a number of communications capabilities. The electronic mail program can be used to leave a message in the "mailbox" of another system user, who will be notified about the message the next time that he enters the system. The STES-TIS also has a conferencing capability, which allows a user to solicit responses to a message from a number of other users. Terminal to terminal communications are also possible, using the "write" and "link" commands.

These communication capabilities have proved invaluable to the STES Program, because they have allowed the Program Office at PNL to keep in close contact with all of the subcontractors. Use of the communication capabilities of the STES-TIS allows instantaneous transmission of messages and eliminates the delays caused when a letter is sent through the U.S. mail. Rapid transmission of information has led to more efficient management of the STES Program.

Technical Problems

No significant technical problems were encountered in any of the five tasks.

4.2.6 Physicochemical Analysis

Terra Tek, Inc. and Pacific Northwest Laboratory

Objectives

The objectives of this effort are to: 1) conduct laboratory tests on the physicochemical properties stability of aquifer materials subjected to Seasonal Thermal Energy Storage (STES) conditions, 2) develop laboratory and field facilities dedicated to the support of STES projects, and 3) develop geochemical modeling capabilities tailored to STES operational and environmental concerns.

Tasks

The physicochemical analysis work has three tasks:

Task 1 - Permeability/Creep Compaction Testing. It has been reported in the literature (Afinogenov 1969, Casse 1972, Danesh 1978, Goban 1980, Muhammadu 1976, Weinbrandt 1972) that the permeability of common aquifer materials decreases with increasing temperatures in the range of 25 to 150^oC. Permeability and compressibility tests on Massillon sandstone and Ottawa sand have been conducted at Terra Tek and PNL to determine the effects of temperature and time and to identify the contributing permeability damage mechanism(s), if any. The mechanisms investigated include: 1) pore volume reduction via consolidation of the porous material and/or thermal expansion of constituent sand grains into pore throats, 2) thermomechanical disaggregation and microcracking of the samples, 3) temperature-induced mobilization of fines with associated particulate plugging problems, and 4) anomalous fluid viscosities due to mineral dissolution. All tests were done with 150 bars (2175 psi) confining pressure, 60 bars (870 psi) pore fluid pressure, 25^oC to 150^oC temperature, 5.4 x 10.2 cm core samples, and deionized prefiltered water or a 2% by weight $CaCl_2$ brine.

Task 2 - Aquifer Properties Test Facility Development. This task involves management and technical overview of the design, construction, and installation of a STES laboratory flow loop and a field injectivity test stand. The laboratory system is designed to permit testing of aquifer materials under simulated STES conditions of temperature, pressure, flow direction, flow rates, and ground-water chemistries. The injectivity test stand is designed for onsite sampling of fluids being injected into the aquifer. Primary emphasis is on the suspended solids and how these particulates might impact injection well performance.

Task 3 - Geochemical Modeling. This task involves the development of a geochemical computer code modified specifically for STES applications. This includes mass transfer (mineral precipitation/dissolution), kinetic control for major aquifer minerals, and ground-water speciation compilations at temperatures from 25°C to 150°C. Another goal is the development of a package of acceptable field data collection and analyses techniques suitable for field site managers.

Technical Progress

Task 1 - Permeability/Creep Compaction Testing. All permeability/compressibility tests were done in the laboratory equipment shown schematically in Figure 4.33. Baseline experiments were done for Massillon sandstone and Ottawa sand with deionized, deaerated, prefiltered water as the permeating fluid. Composite results are shown in Figures 4.34 and 4.35. The permeability ratio (initial permeability/final steady-state permeability) is plotted at 25°C and 150°C. Based on this data alone, it would appear that permeability is temperature sensitive.

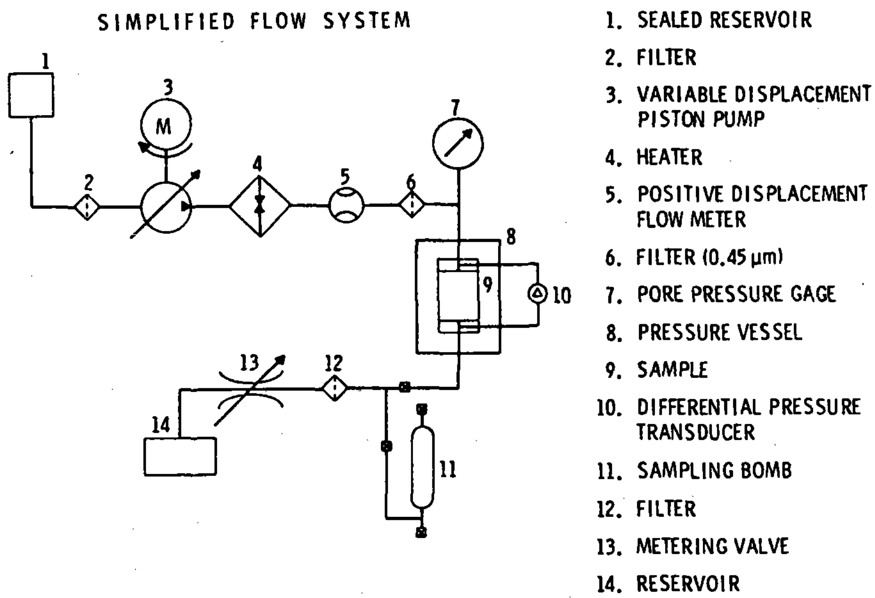


FIGURE 4.33. Flow Schematic

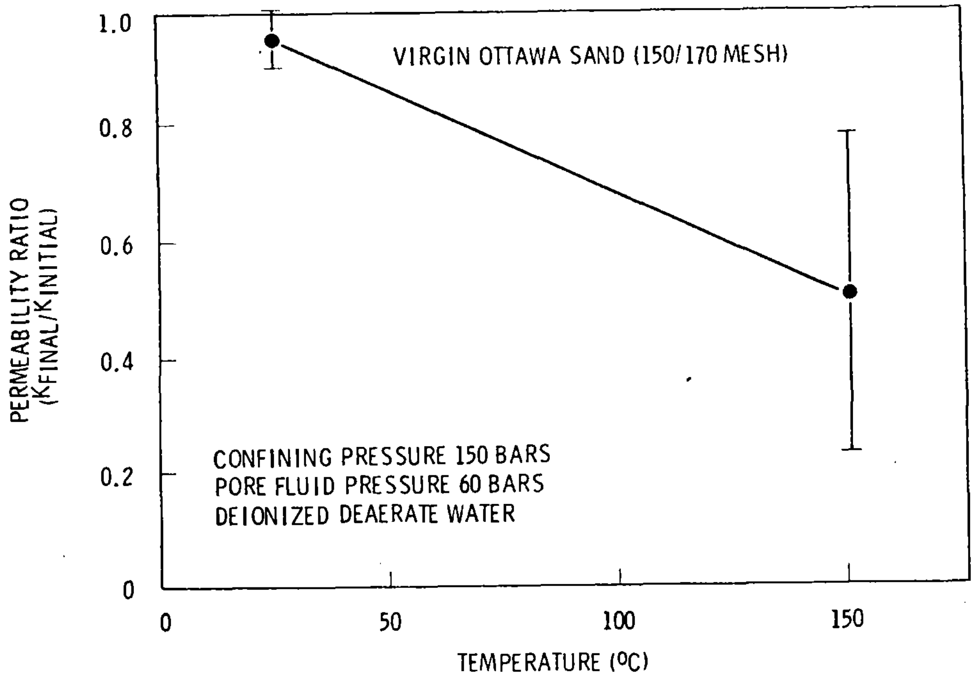


FIGURE 4.34. Ratio of the Final Permeability to the Initial Permeability at Each Temperature for Virgin Ottawa Sand (Error bars are ± one standard deviation)

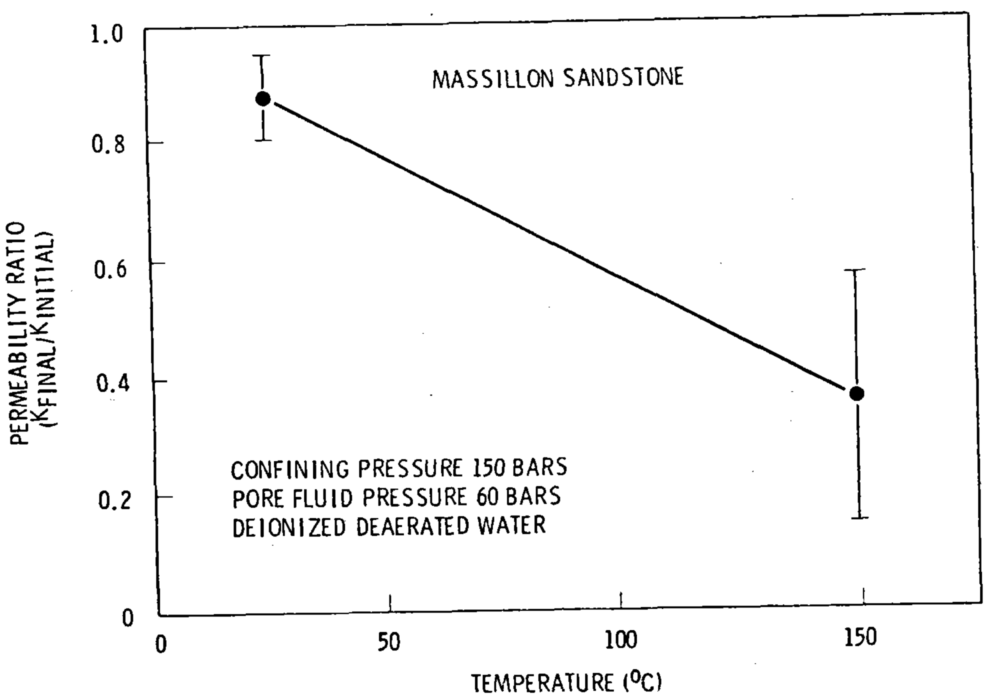


FIGURE 4.35. Ratio of the Final Permeability Value to the Initial Value at Each Temperature for Massillon Sandstone (Error bars are ± one standard deviation)

Pore volume reduction was investigated as a potential damage mechanism. Both the bulk compaction (densification) of the porous medium and thermal expansion of constituent sand grains into pore throats were considered. The amount of volume strain observed during the permeability experiments is depicted in Figure 4.36. The difference between the sandstone and sand curves as compared to the zero porosity single quartz crystal gives a reasonable estimate of the porosity reduction. For both Massillon sandstone and Ottawa sand, the pore volume loss was less than 0.5% on the average and therefore pore volume reduction (compaction or internal grain expansion) is not considered a significant permeability damage mechanism at 90 bars (1305 psi) effective load and temperature in the range from 25°C to 150°C. (The effective load represents the difference between the confining pressure on the outside of the rock sample and the fluid pressure inside the rock sample. The 90 bar effective load might represent a reservoir at a depth of 500 to 600 meters.)

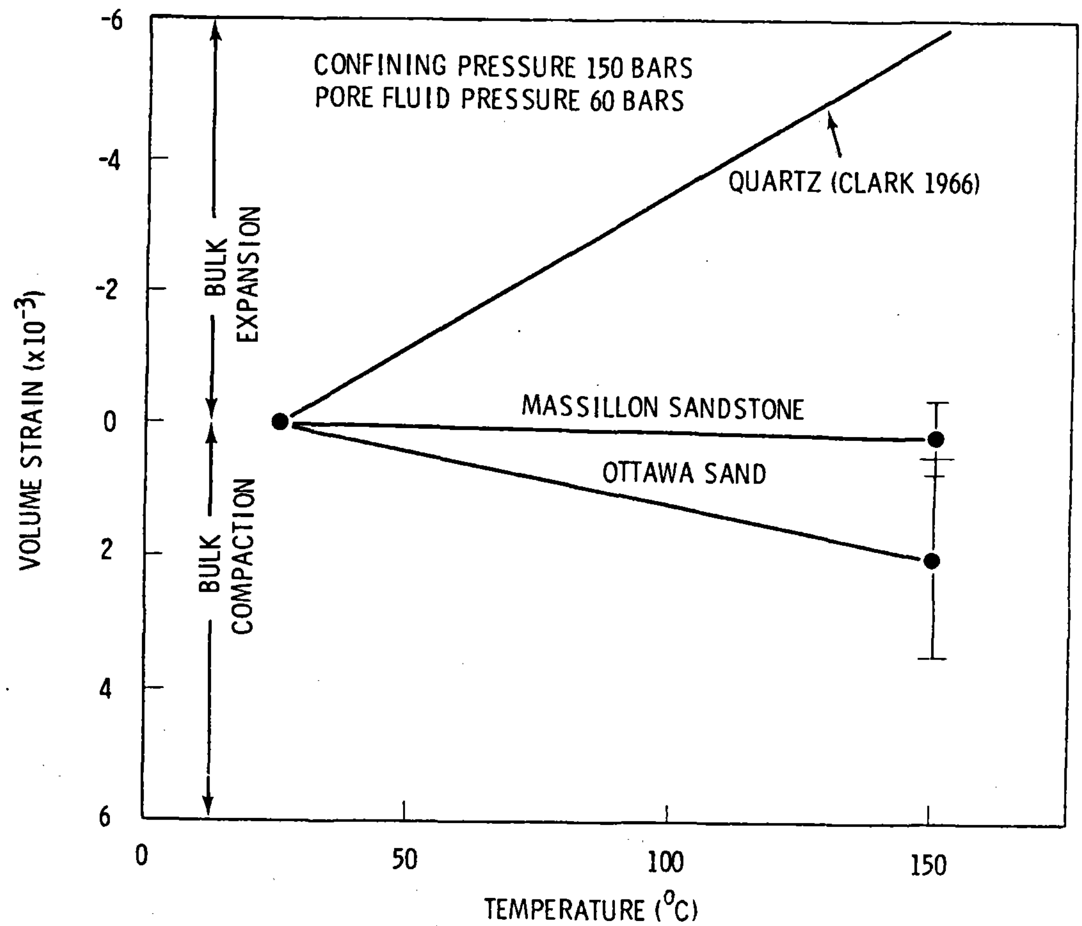


FIGURE 4.36. Volume Strain Versus Temperature for Massillon Sandstone and Ottawa Sand Under a 90 Bar Effective Load (Error bars are ± one standard deviation)

Viscosity perturbations due to mineral dissolution was also explored using a specially constructed capillary coil viscometer. Silica was found to be the only mineral increasing in concentration significantly during the permeability tests described in the previous section. Relative viscosity values were determined for deionized water, a 250 mg/liter silica solution, and a 15,000 mg/liter sodium cloride solution. As can be seen in Figure 4.37, the salt solution resulted in incrementally higher viscosity values as compared to the DI water. There was not observable difference between the silica-spiked water and the DI water, however. Therefore, it was concluded that an increase in the amount of dissolved silica in the water does not affect the viscosity and the "steam table" values for DI water are sufficient in intrinsic permeability calculations.

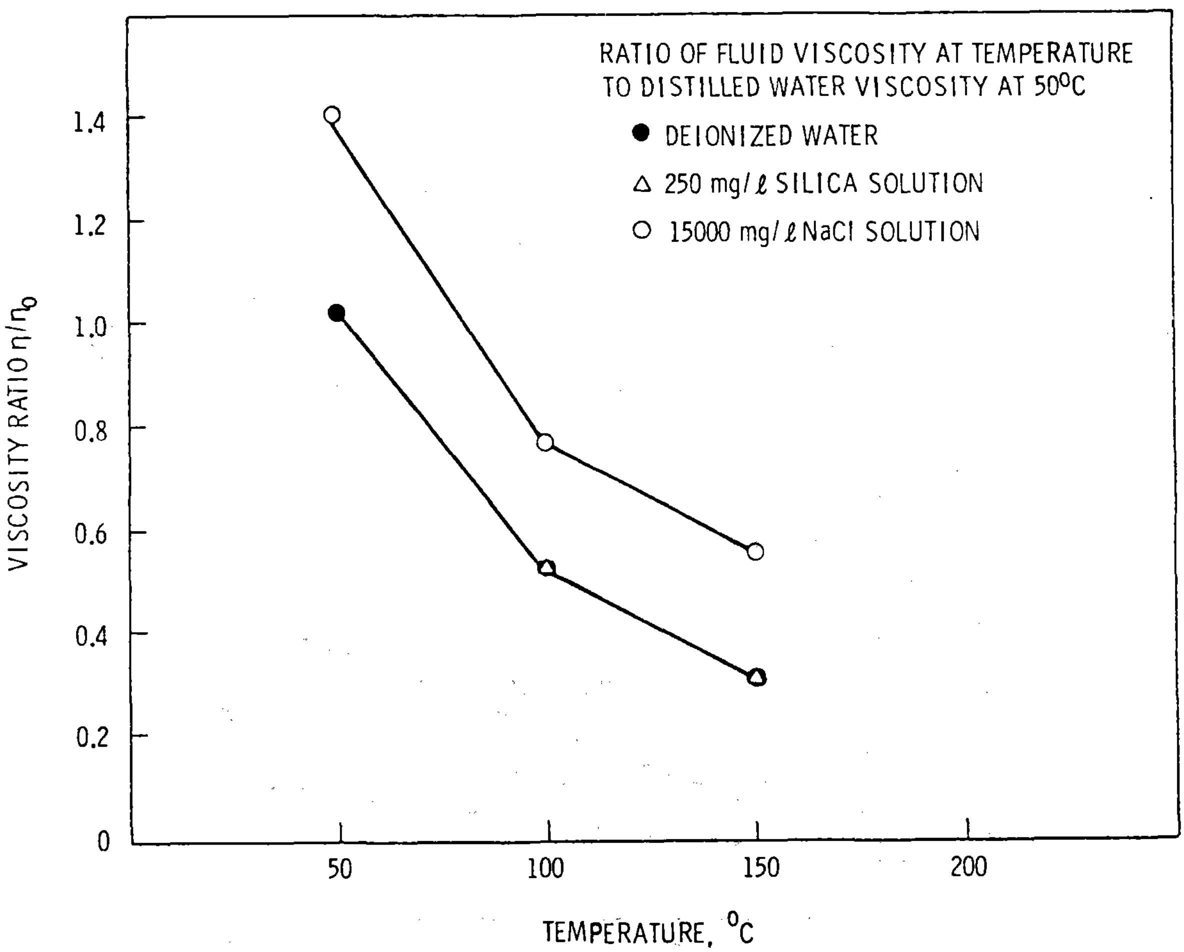


FIGURE 4.37. Viscosity Values for Deionized Water, Silica-Laden Water, and NaCl Brine Normalized to the Viscosity Value of Distilled Water at 50°C

This conclusion is supported by the short fluid residence time in the sand and sandstone cores (5 minutes), the once-through nature of the permeability tests, and the small observed changes in influent/effluent water chemistries (<15 mg/liter increase in silica).

Thermomechanical fragmentation was also considered. However, based on the fact that the permeability to dry nitrogen was not temperature sensitive and no statistically significant change in grain size distribution could be found between sand samples permeated with water at 25°C and 150°C, thermomechanical fragmentation is not considered a significant permeability damage mechanism at 90 bars effective load. The grain size distribution measurement technique was limited to 30 μm and therefore no conclusions are warranted concerning the thermomechanical generation of small fines.

Particulate plugging may be a significant permeability damage mechanism in aquifer materials. Fines can be dispersed by changes in salinity, pH, and temperature. (Mungen 1965, Hewitt 1963, Piwinski 1977). In the present study, a comparison was made between deionized water and a 2% $CaCl_2$ brine. Water (salinity) sensitivity was not observed for the sandstone and sand samples. Also, the pH of the influent and effluent waters did not vary appreciably during the permeability tests. However, more fines (particles) were flushed from the cores during the 150°C tests than for the 25°C tests (Figure 4.38).

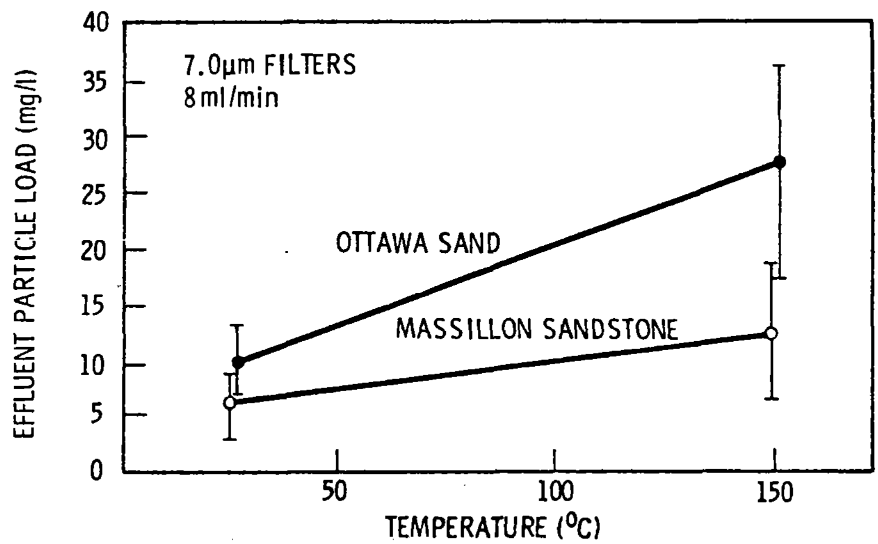


FIGURE 4.38. Effluent Particulate Load as a Function of Temperature for Massillon Sandstone and Virgin Ottawa Sand

The impact of thermally dispersed particulates on permeability was investigated by comparing carefully washed sand samples to virgin sand samples. The permeability was affected by the temperature-induced mobilization of internal fines, but by less than 10%. Thus, in the laboratory tests, particle mobilizatrion is not a significant permeability damage mechanism for the relatively clean Massillon sandstone and Ottawa sand. This must be explored further, however, because of the pathlength differences between the laboratory cores (10.2 cm) and field site (tens of meters). Example particles flushed from the cores at the higher temperature are shown in Figures 4.39 and 4.40. The fines are predominately kaolinite (clay mineral) and quartz fragments.

It now appears that sample compaction, thermal expansion of grains, anomalous viscosity, and temperature-induced particle mobilization were not responsible for the observed permeability degradation with temperature observed in the initial laboratory tests. Subsequent study has apparently revealed, however, that the permeability degradation may be caused by apparatus contamination, metal colloids derived from the laboratory equipment itself. This was determined by placing 2.0 μm and 0.45 μm filters immediately upstream of the rock cores. Example colloidal contaminants are shown via scanning electron microscopy in Figures 4.41 and 4.42. Based on energy dispersive x-ray scans, the particles appear to be predominantly zinc, iron, copper, and aluminum oxides or hydroxides presumably derived from corrosion and/or degradation of equipment components upstream of the sand and sandstone samples. The source of the contamination appears to be an aluminum gasket used in a pump filter, some brass valve bodies, and the stainless steel inline fluid heater rod. The insertion of the two filters immediately upstream of the sandstone and sand samples significantly attenuated the permeability degradation (Figure 4.43).

It is concluded that laboratory tests at temperature should be done in corrosion resistant vessels and include upstream filtration. With respect to field sites, operators of STES wells must investigate the nature of the suspended particle loads being injected into the reservoir. "Injectivity testing" should be conducted at all field sites where elevated temperatures are planned.

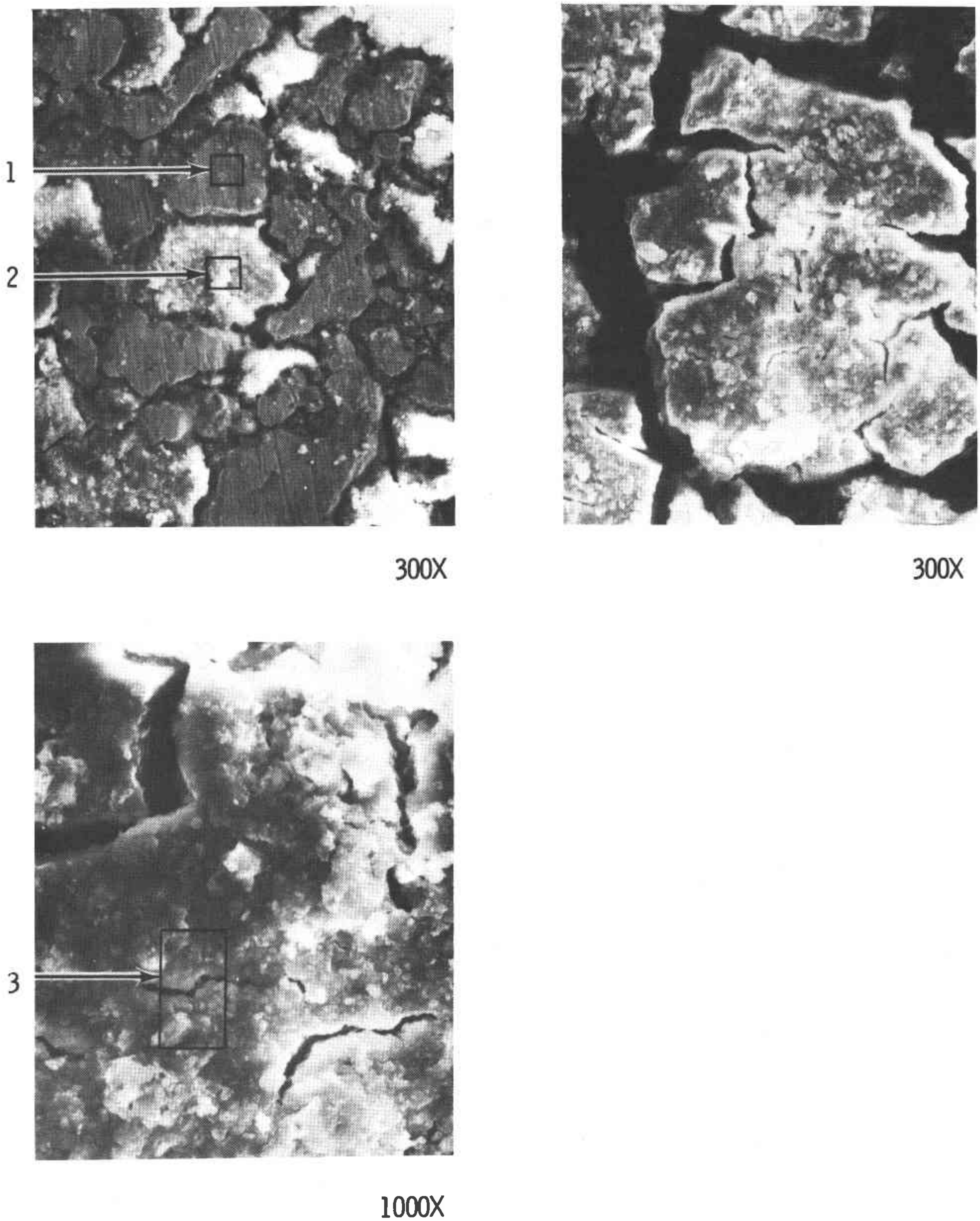
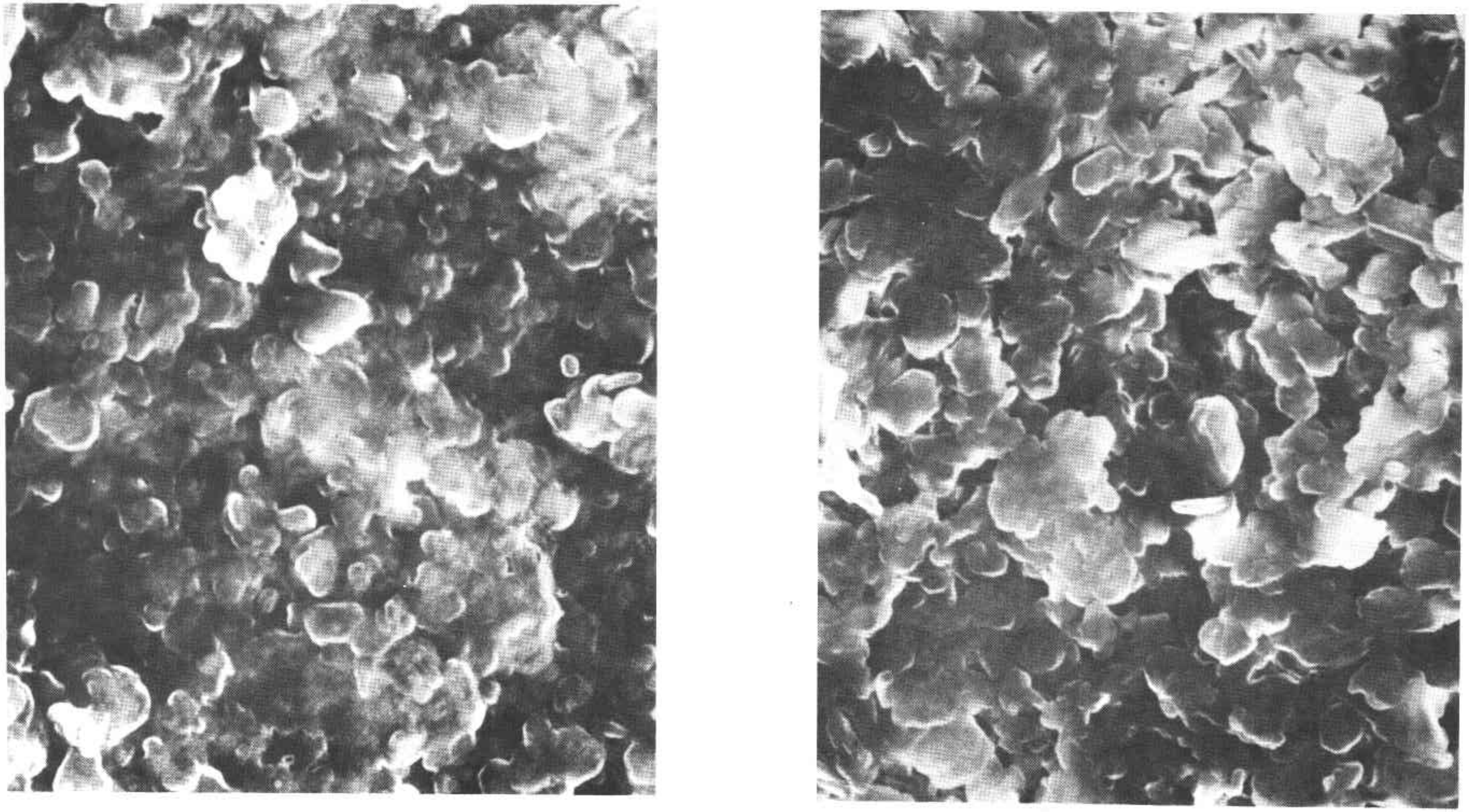


FIGURE 4.39. Particles Trapped by a 7.0 μm Filter During a Virgin Ottawa Sand Test



10,000X 10,000X

FIGURE 4.40. Kaolinite Particles Flushed from Ottawa Sand

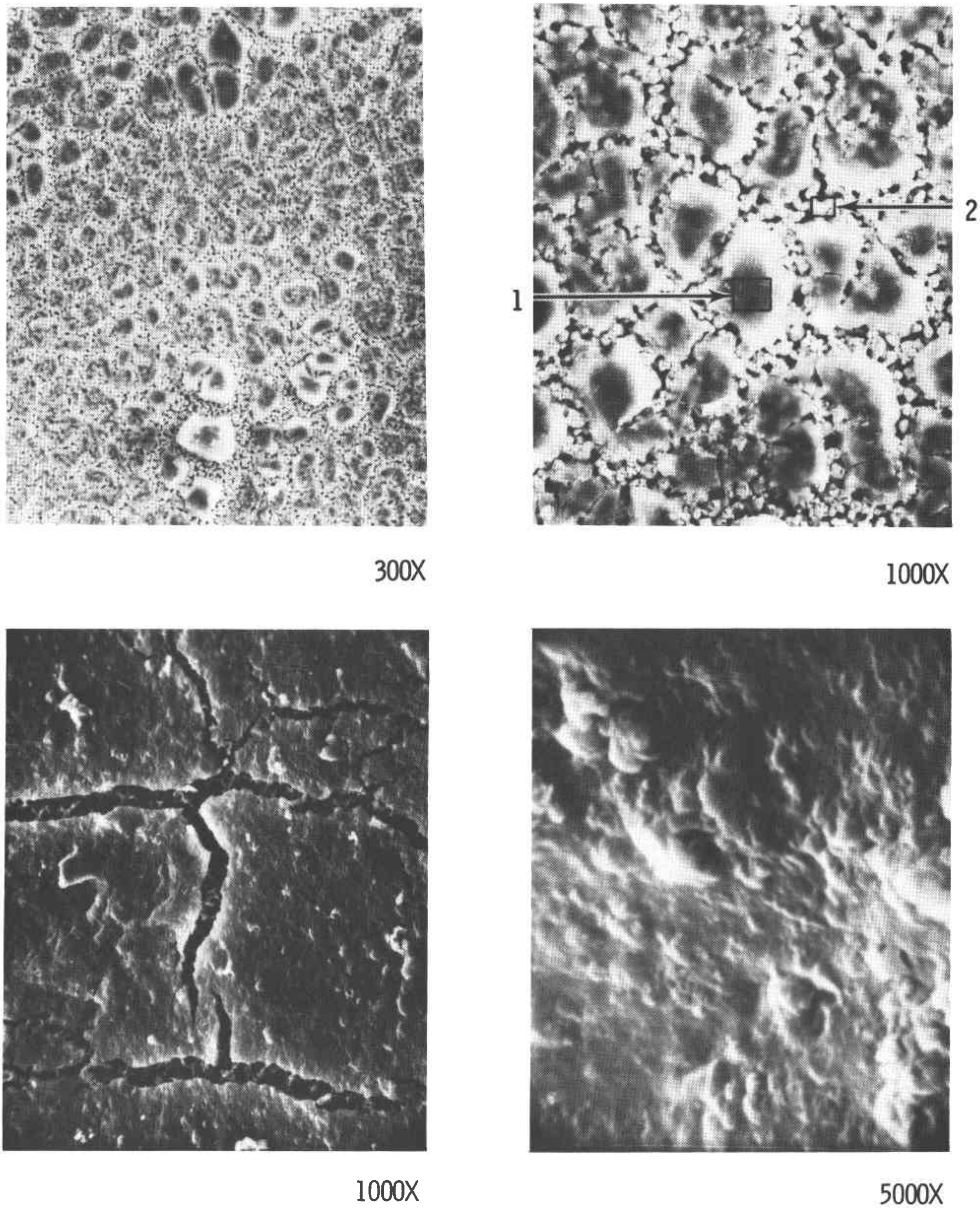


FIGURE 4.41. SEM Results from a 0.45 μm Upstream Filter Used in a 150°C Permeability Test

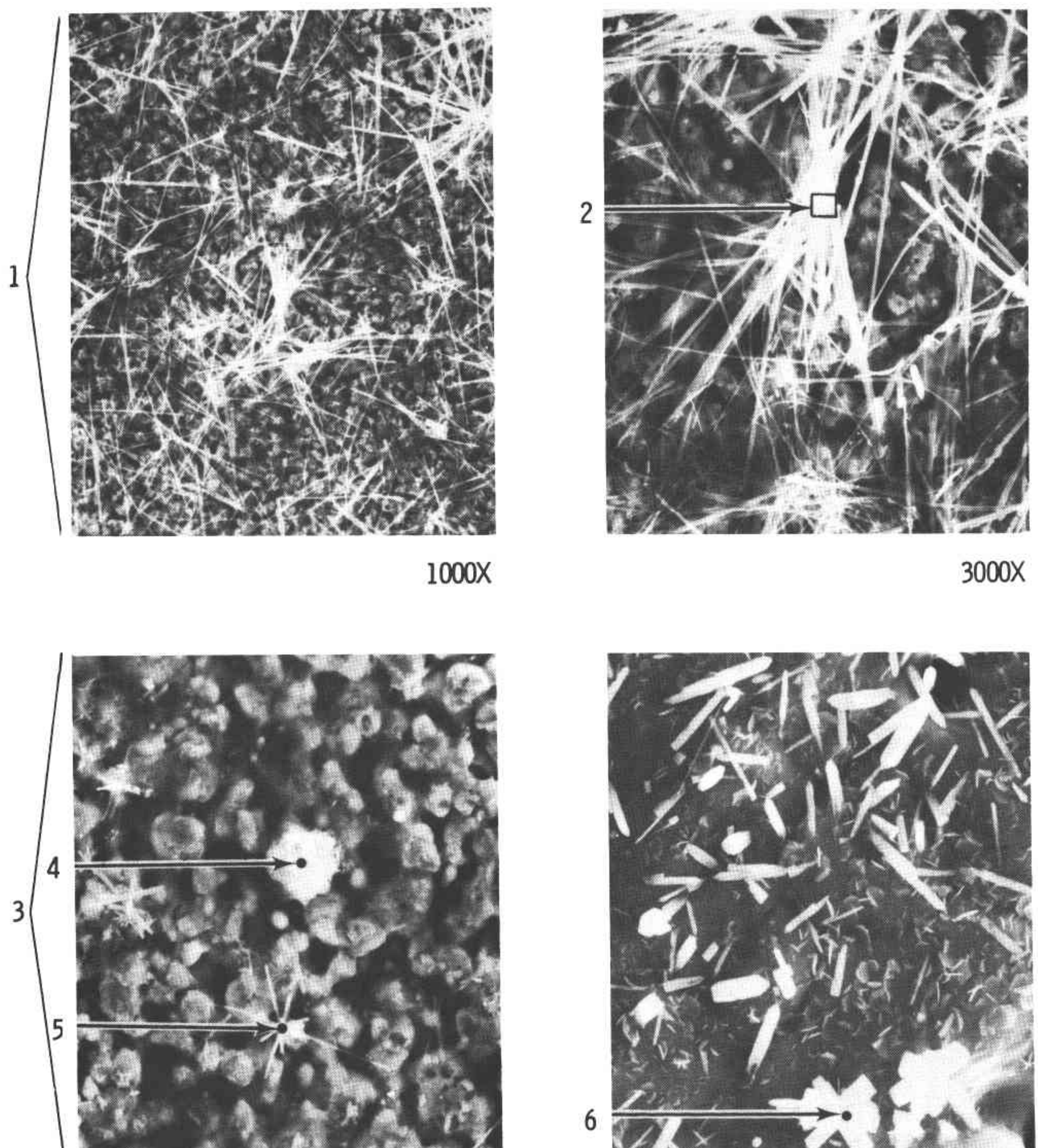


FIGURE 4.42. SEM Results from a 0.45 μm Upstream Filter Used in a 150°C Permeability Test

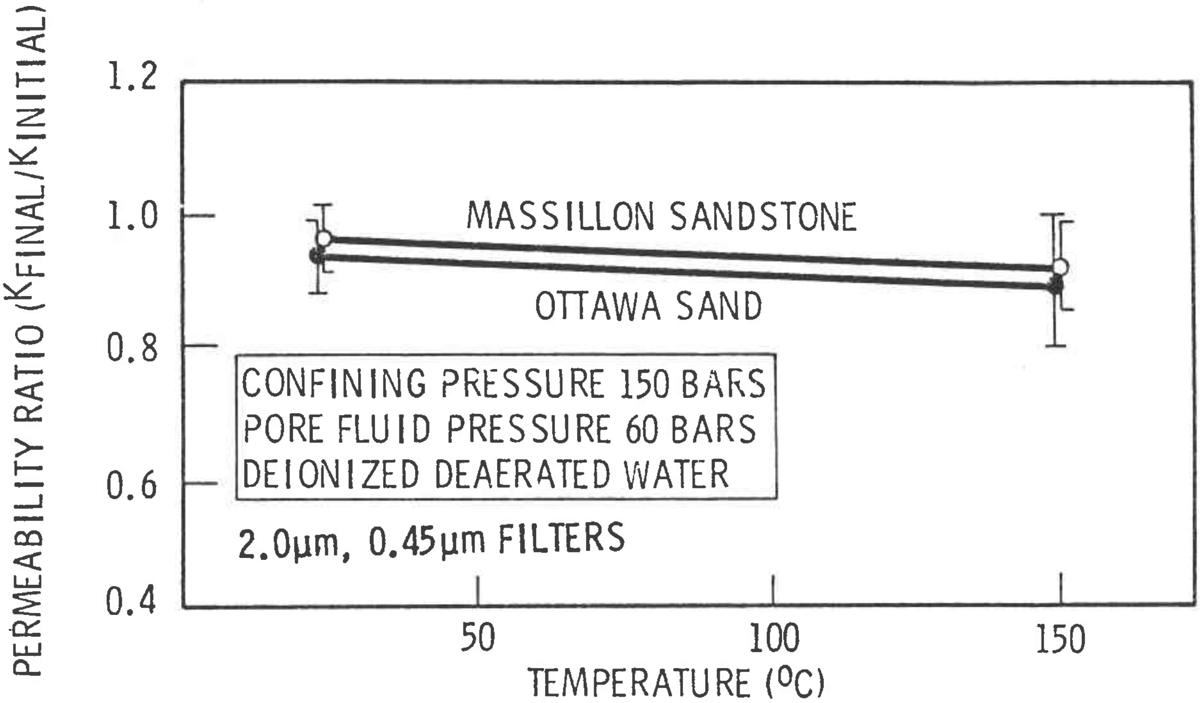


FIGURE 4.43. Permeability Ratio Versus Temperature for Massillon Sandstone and Ottawa Sand Tests with Upstream Filtration

It would appear from this study, that for low to moderate effective stress and temperatures less than 150°C, that Massillon sandstone and Ottawa sand permeabilities are not particularly temperature sensitive. Site-specific aquifer materials should be similarly tested. Furthermore, the potential effects of the small lab/field travel path ratio should be explored because of the apparent temperature-induced mobilization of natural fines internal to porous aquifer materials.

Task 2 - Aquifer Properties Test Facility Development. Development of specifications, a competitive bidding cycle, and selection of Terra Tek, Inc. as the subcontractor were completed. A photograph of similar equipment is shown in Figure 4.44. A list of capabilities is given in Table 4.14. As of the end of December 1980, engineering design for the entire system was 85% complete, system drawings 80% complete, and long lead items ordered. The equipment should be delivered to PNL in August and will be installed by the end of the fiscal year.

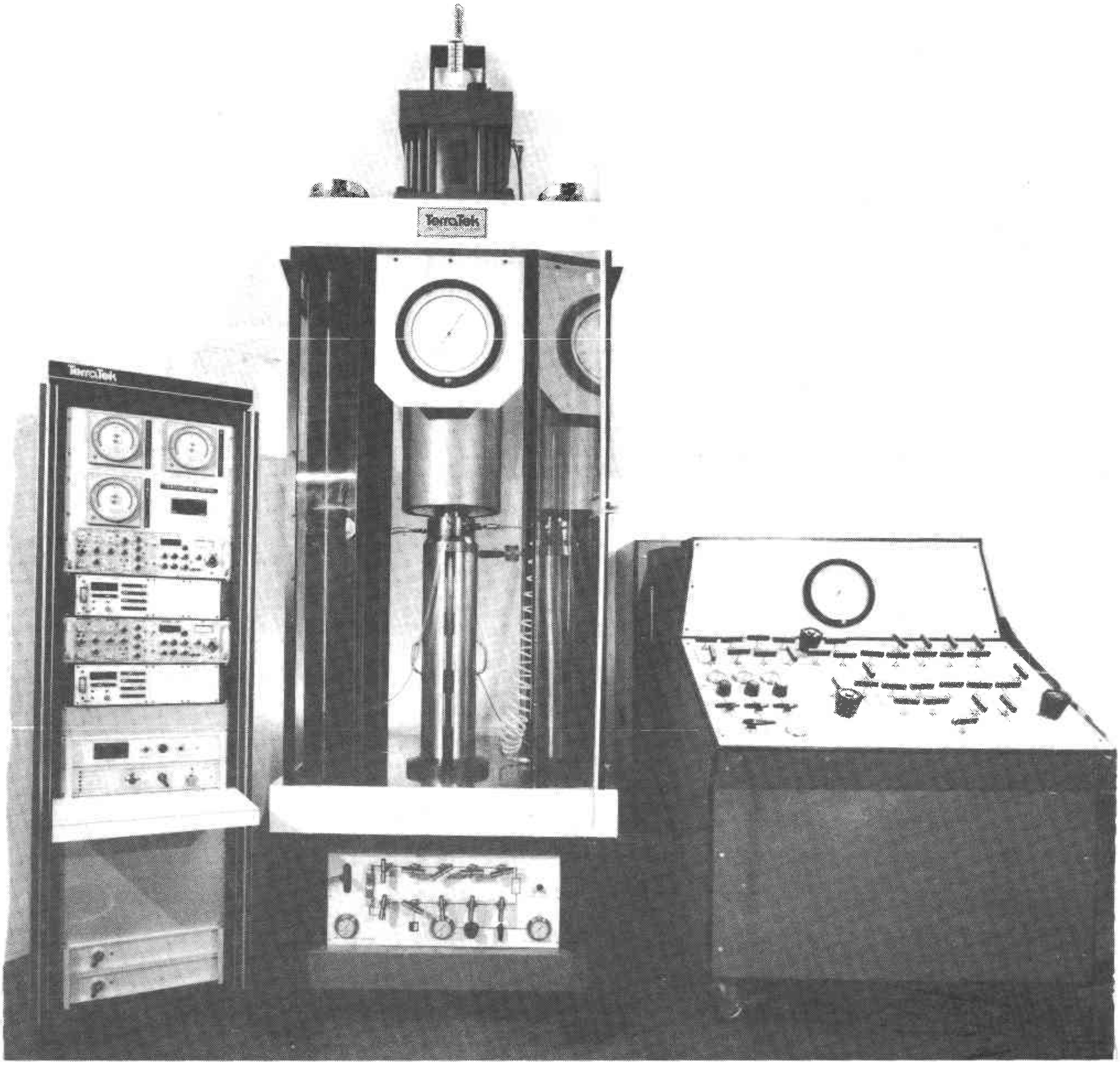


FIGURE 4.44. Photograph of Similar Equipment Developed for Dow Chemical Company

TABLE 4.14. Aquifer Property Test Facility Capabilities

• Axial Stress	172 MPa (maximum)
• Hydrostatic Stress	103 MPa (maximum)
• Pore Pressure	103 MPa (maximum)
• Pore Fluid	Light Brine, 10% Weight, NaCl
• Pore Fluid Flow Rate	0.02 ml/sec to 16 ml/sec
• Temperature	200°C (maximum)
• Pore Fluid Sampling	Via Pressurized Sampling Device
• Temperature Cycle	100°C Amplitude (maximum)
• Filters	Before and after the Sample
• Materials	Titanium, Inconel, Stainless Steel
• Primary Tests	Permeability Volume Strain Fluid Chemistry Changes Particle Mobilization Thermal Fatigue

The injectivity test stand has been designed and a schematic of the system is shown in Figure 4.45. The equipment will be mobile and therefore can be used at any STES field site. Injectivity test procedures have been adopted as well as the data reduction and interpretation schemes. The fabrication of the unit has been initiated. The equipment will be used initially at the Auburn field site.

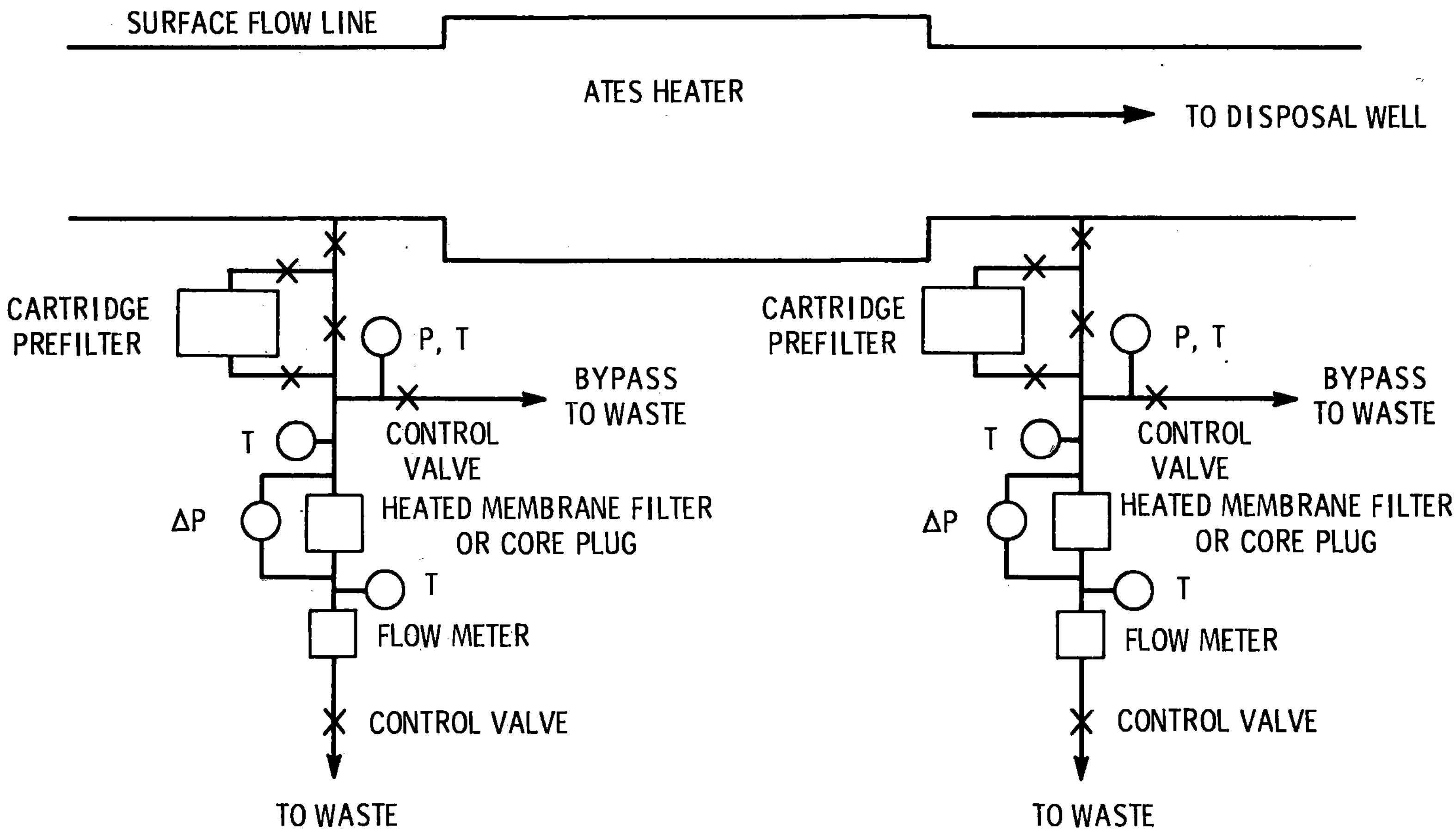


FIGURE 4.45. Schematic of the Injectivity Test Stand

Task 3 - Geochemical Modeling. Chemical modeling is a new task initiated in November 1980. The WATEQ4 model has been selected and is being modified to STES requirements. General capabilities are shown in Figure 4.46. Mass transfer (precipitation/dissolution) capabilities have been added to the code and progress is being made towards adding elevated temperature ($<150^{o}C$) capabilities in an equilibrium or kinetic mode. The data bank has been enhanced and a literature review on the kinetics of calcite, gypsum, silica, geothite, and ferrihydride is progressing. Field data collection and analysis techniques are being reviewed. Of particular interest are redox potential, cation concentrations (Ca, Mg, Na, K), anion concentrations (CO_3 + HCO_3 Cl, SO_4), and silica. Trace elements of interest include arsenic, barium, boron, cadmium, chromium, copper, lead, mercury, and nickel. Two reports are planned for FY-1981: 1) "A new geochemical code to simplify application and provide an equilibrium or kinetically-constrained mass transfer capability," and 2) "Development of an elevated temperature capability pertinent to STES."

Technical Problems

- There is a paucity of data concerning the effect of temperature and temperature cycling on the generation and adhesion characteristics of corrosion and precipitation scales in surface plumbing.
- Until the Aquifer Properties Test Facility is operational, there will be a lack of data concerning the long-term (>24 hr) response of samples to elevated temperatures.
- There is some uncertainty about the impact of temperature-enhanced mobilization of fines (small particles) on longer cores.
- Existing data limitations and thermodynamic inconsistencies limit geochemical modeling efforts. Additional laboratory studies and critical literature reviews are warranted, but even more importantly, field data at STES sites must be properly collected.

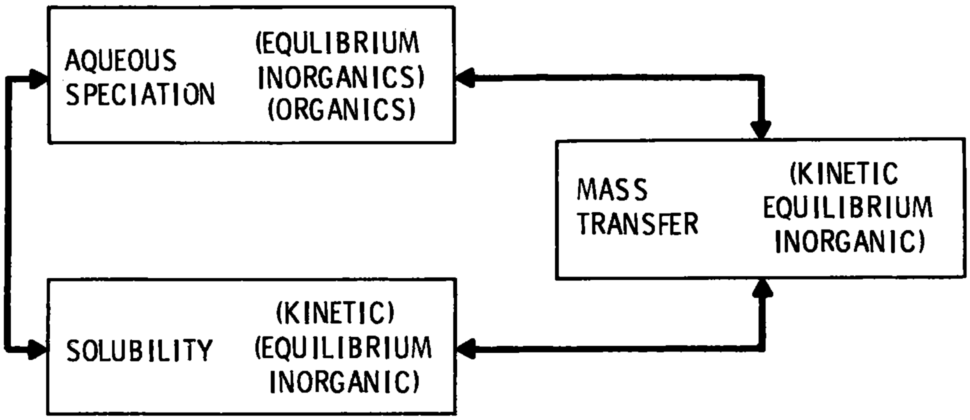


FIGURE 4.46. Geochemical Modeling Capabilities

4.2.7 Numerical Simulation

GeoTrans, Inc., Lawrence Berkeley Laboratory, Oregon State University, Washington State University, and Pacific Northwest Laboratory

Objectives

The objectives of this work are: to document the state-of-the-art with regard to numerical simulation of aquifer environments subject to thermal energy storage, and to develop and/or utilize simulation technologies capable of predicting the transport and retrieval of a thermal energy resource within the ground-water environment.

Tasks

Task 1 - State-of-the-Art. A document revealing the state-of-the-art of numerical simulation is deemed necessary for technology transfer to the engineering community. This document will include discussions of: the aquifer physics, their mathematical and numerical analogues, and representative values of aquifer parameters for a variety of aquifers.

Task 2 - Intera's Deep Well Disposal Model (DWDM). The DWDM code was developed for the USGS and first published by Intercomp in 1976. It is recognized as one of the candidate codes for simulation of ATES. The DWDM code is to be validated against data collected during a previous Auburn experiment.

Task 3 - Energy Transport in Unsaturated Media. An important aspect in determining the feasibility of ATES in unconfined aquifers is developing an understanding of the physics of energy transport in unsaturated media which overly any unconfined aquifer. Due to the potential availability of unconfined aquifers for ATES facilities, it is prudent to fine tune the physics while simultaneously developing a simulation capability based upon our current understanding of the phenomena.

Task 4 - Generic Simulations and Parameter Studies. Towards developing an understanding of the importance of competitive mechanisms within the ATES environment, a generic simulation and parameter sensitivity study was undertaken. A simplified technique is required for the economical analysis of a variety of aquifer parameters.

Task 5 - Site-Specific Analyses. State-of-the-art simulation codes are to be applied for the prediction of aquifer response to aquifer thermal energy storage.

Task 6 - Independent Analysis Capability. An independent and responsive analysis capability is to be developed for use by the STES Program Management in evaluating experimental results, facility design, and operational scenarios.

Technical Progress

Task 1 - State-of-the-Art. Towards meeting this needed documentation, the firm of GeoTrans, Inc., began a comprehensive search of the literature while simultaneously requesting current information from noted authors in this expertise area. At the close of the calendar year, GeoTrans has received responses from many of those contacted and had begun digesting the voluminous literature.

Task 2 - Intera's Deep Well Disposal Model (DWDM). Washington State University (WSU) has been contracted to supply a validation of the DWDM code. Modifications have had to be made to the code in order to run it on a restricted word size machine (e.g., IBM, UNIVAC, PDP computer hardware).

While some modifications required rewrite of coded segments, the major change has been the use of double precision for several arrays and associated computations. Details of the (1978-1979) Auburn experiment (e.g., design and data) have been supplied to WSU personnel and simulations are to be completed during the 1981 calendar year.

Task 3 - Energy Transport in Unsaturated Media. The physics of this transport process are currently being studied by members of the soils science faculty of Oregon State University (Stuart Childs). A literature review has been completed, and both a preliminary interpretive report and an annotated bibliography have been written. The OSU work is continuing to define the phenomena of greatest importance, and the soil and water parameter ranges which should be further investigated by laboratory experiments.

Using our current knowledge of the physics of nonisothermal flow in unsaturated media, Lawrence Berkeley Laboratory has undertaken the development of a simulation code for the coupled unsaturated-saturated nonisothermal ground-water environment. An isothermal code for the analysis of transient flow in unsaturated and saturated porous media (TRUST) is being expanded to include nonisothermal effects. Code development of this magnitude is a multi-year effort and work is continuing through 1981.

Task 4 - Generic Simulations and Parameter Studies. The objective of generic and parameter studies is to produce a graphical solution process which when given the aquifer and utilization parameters of the ATES facility can predict the response of the aquifer. Dimensionless parameter groups appropriate to the planning and design of practical projects have been defined and are being studied. Since many simulations must be made in a study of functional dependence, a simplified model has been employed. While as yet undocumented this model, known as the Steady Flow Model (SFM), has been verified for limiting cases against the Conduction, Convection and Compaction (CCC) model.

This model assumes a steady-state flow situation in an infinite, uniform aquifer. Buoyancy flow has been neglected in this code. Such an assumption is justified for storage in low permeability aquifers or scenarios which have a relatively low temperature difference between storage and ambient waters. A criterion taken from the recently issued publication (Hellstrom 1980) may be used to verify the applicability of this assumption. However, the results may still be applicable for cases of significant buoyancy flow. Results will be of an upper limit type and not a conservative estimate for such cases. Thermal properties of the system are assumed temperature-independent, hence the recovery factor will also be temperature-independent.

During 1980, this study has emphasized an understanding of the energy recovery factor (ERF) (i.e., the ratio of energy recovered to energy stored) as a function of aquifer properties and storage parameters. As the reader should recognize, values of ERF are heavily dependent upon when efforts to recover energy are halted. Recovery could be concluded at a temperature defined by the energy user, however, for our study equal volumes of fluid are injected and withdrawn. The recover factor has been calculated for a series of values of: aquifer thickness, cycle time period, velocity-dependent dispersion, and the number of cycles. Illustrations of some of the results are shown in Figures 4.47 through 4.49.

The energy recovery factor increases as the injected volume increases, and an optimal aspect ratio (thermal front radius/aquifer thickness) exists for which the factor is maximum for each volume. This optimal aspect ratio is dependent upon relative thermal properties of both aquifer and confining layers. Figure 4.47 reveals both the dependency upon volume and the optimal aspect ratio concept. The interweaving of constant thickness lines on this semilog plot of recovery factor versus volume (R_{TH}^2H) gives rise to the optimal aspect ratio. Lines of lesser and greater thickness underlie the thickness yielding the greatest recovery ratio for any given volume. Thus, for a constant volume and increasing thickness one finds a decreasing aspect ratio and a maxima or optimal recovery factor. Figure 4.48 displays the recovery factor as a function of the aspect ratio. The optimal concept is apparent here, however, of equal or greater importance is the influence of aquifer and aquitard thermal conductivity. As aquitard thermal conductivity decreases, energy losses to the aquitards decrease and the recovery factor increases.

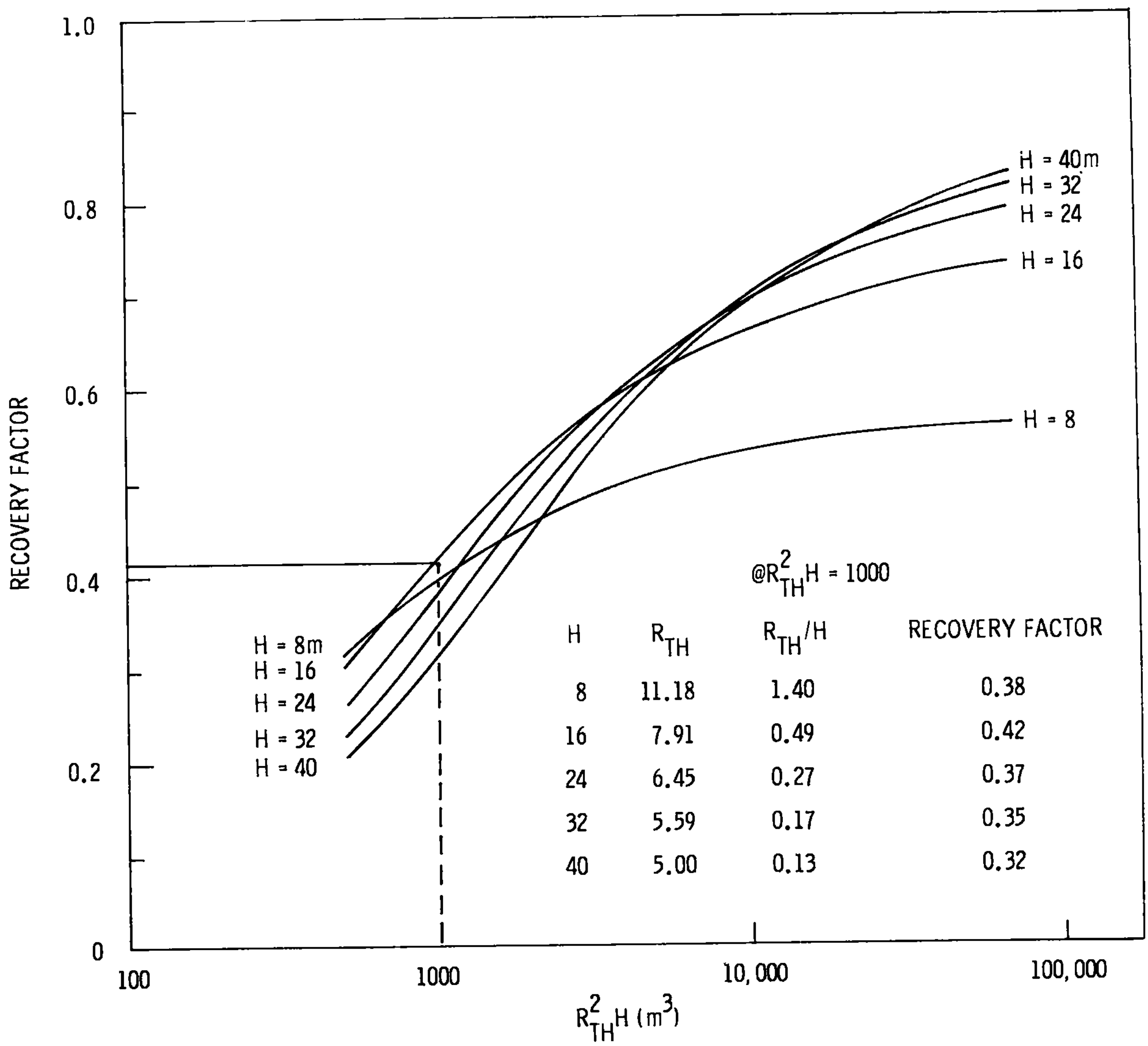


FIGURE 4.47. Recovery Factor as a Function of a Generic Volume Measure, $R^2_{TH}H$ (thermal radius squared times thickness)

Fundamental to STES is the concept of injection, storage and recovery. An operational scenario will define the relative length for each of these time increments, and Figure 4.49 displays the aquifer response to a single cycle for several different injected volumes. The aquifer thickness for each volume is such that the aspect ratio is optimal. Lines "a" show the results for a cycle with no storage period. Lines labeled "b" show the results for equal

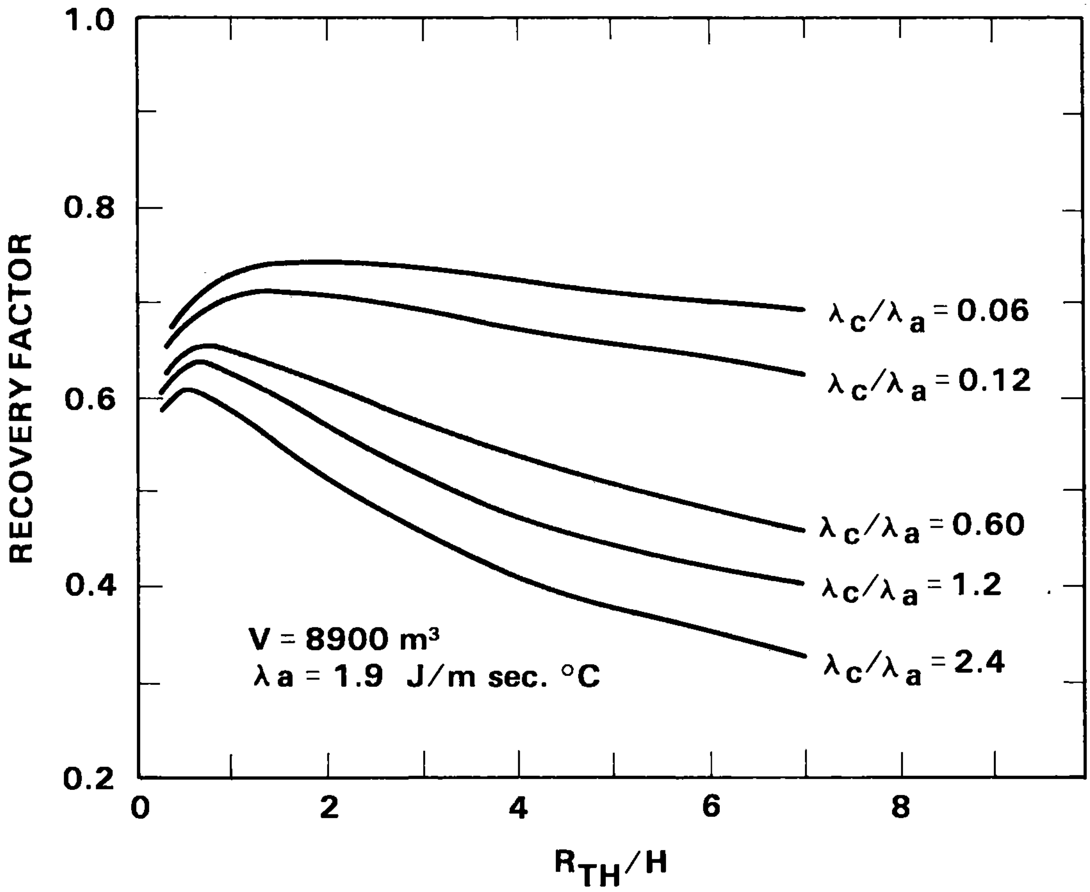


FIGURE 4.48. Recovery Factor as a Function of Aspect Ratios of Aquifer and Aquitard Thermal Conductivities (λ_a and λ_c)

injection, storage, and production periods. For the limiting case of instantaneous injection and withdrawal, the storage period becomes the entire cycle. Results of this hypothetical cycle are shown as line "c". One readily sees that increasing either the total cycle time or the storage period results in greater energy losses to the confining layers and aquifer. This, in turn, results in a reduction of recovery factor.

Task 5 - Site-Specific Analyses. Site-specific studies were undertaken for the Auburn University field test facility located at Mobile, Alabama. Three STES cycles are presently contemplated for the Auburn field test facility. Each will have a progressively higher injection temperature (55, 90,

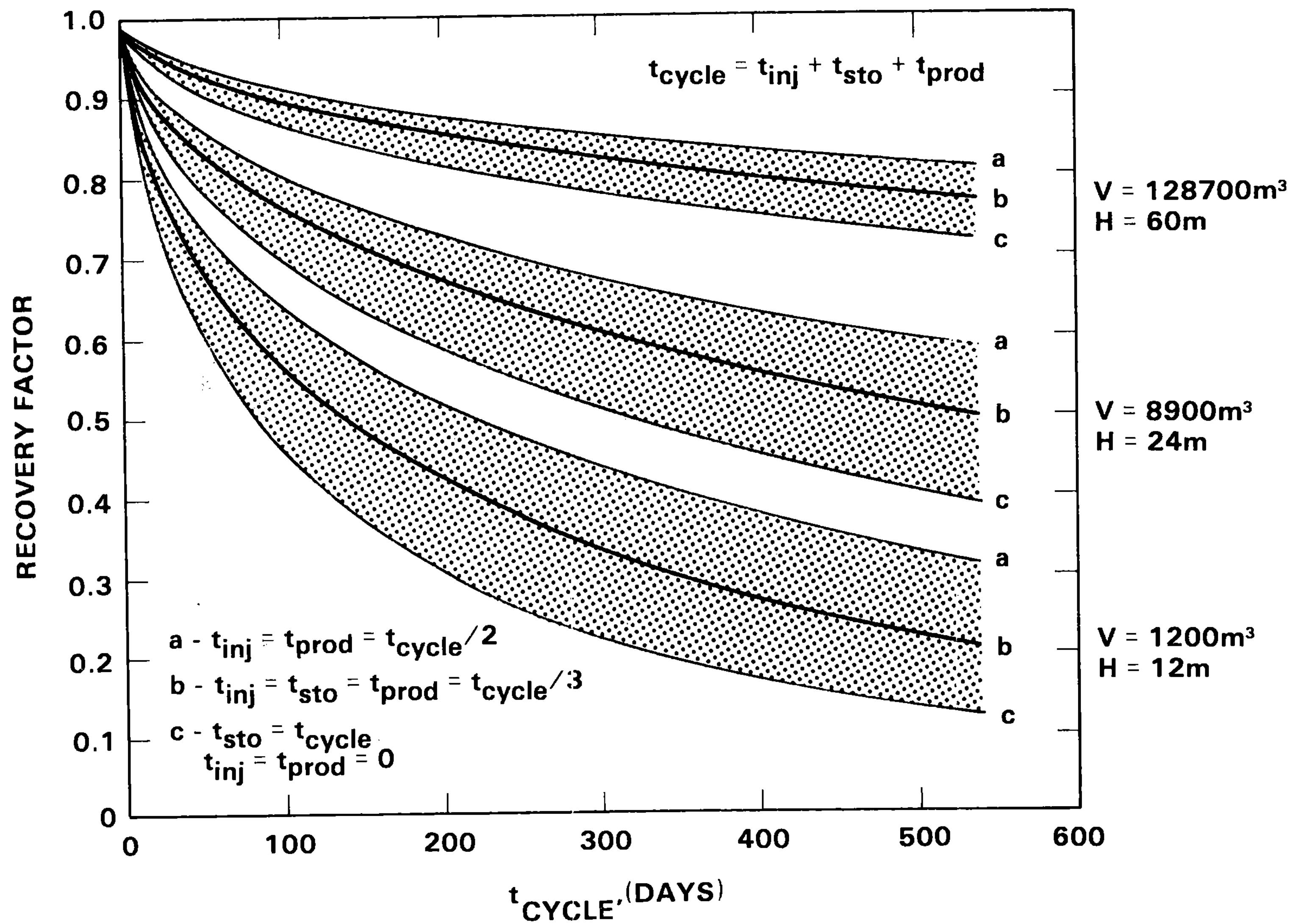


FIGURE 4.49. Recovery Factor as a Function of Total Cycle Time and Cycle Breakdown

125^{o}C). Simulations were undertaken to determine the: appropriate location of sampling wells, feasibility of fully versus partially penetrating recovery wells, and energy recovery prospects. Figure 4.50 shows the impact of a partially penetrating recovery well upon recovery temperature and factor for a 55^{o}C injection. One sees that the recovery factor is increased by 4%, and perhaps more significantly, the quality (temperature) of recovered energy is improved over a significant period of time. Results of a similar analysis for a 90^{o}C injection are shown in Figure 4.51. While the shape of the response curve is somewhat different, it is evident that both the quality and quantity of energy recovered is enhanced by the partial penetration concept.

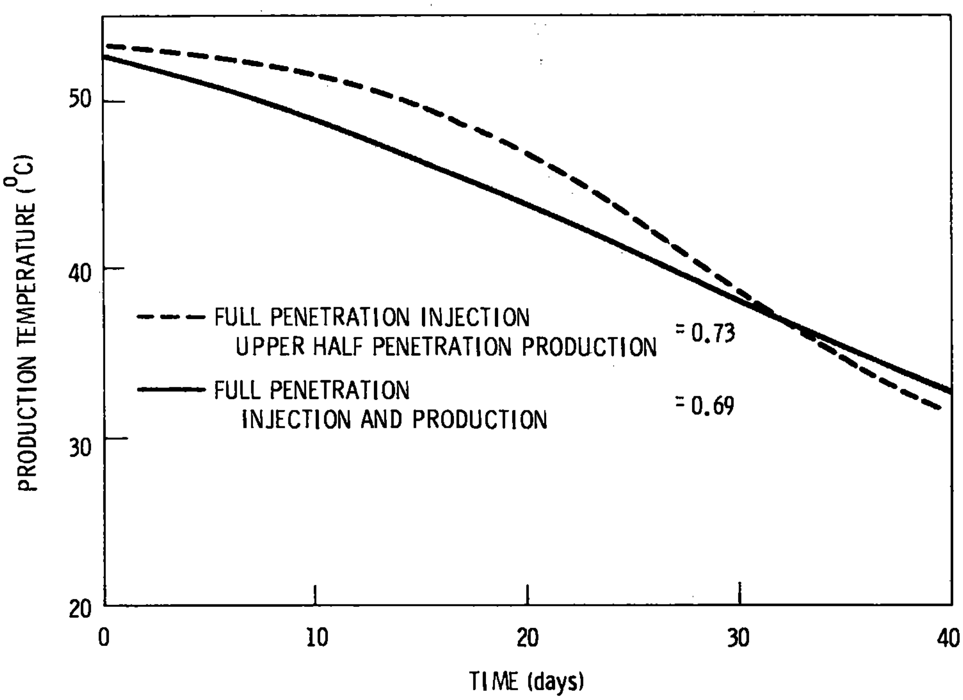


FIGURE 4.50. Production Temperature as a Function of time for 55^{o}C Injection Experiment (ε = recovery factor)

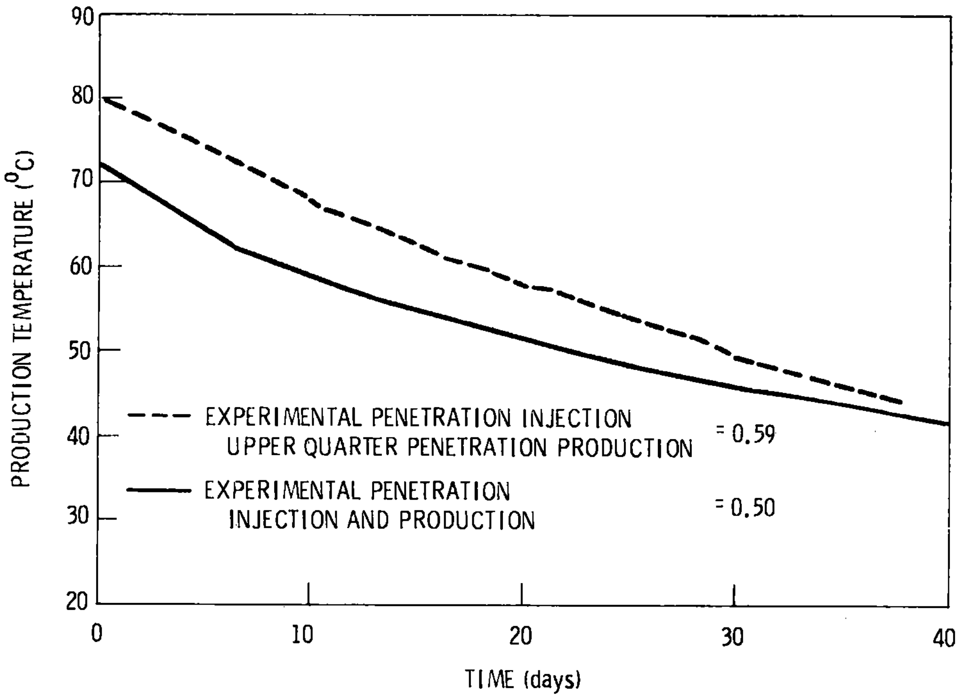


FIGURE 4.51. Production Temperature as a Function of Time for 90°C Injection Experiment

Task 6 - Independent Analysis Capability. Progress toward providing simulation capability of thermal-hydrologic events for the STES Program has continued on three fronts during the year. The finite element code CFEST (coupled fluid, energy, and solute transport) has yielded its first simulations of confined aquifers. Flownet and rectangular grids have been included in the automatic grid generation package. Finally, a data processing package has been developed to display and filter the raw field data from an aquifer thermal energy storage facility. Significant accomplishments were achieved in each of these three distinct efforts in the final quarter of CY-1980. Upon their final completion and documentation these three efforts will combine to provide STES management with an independent analysis capability for the near field aquifer environment. Future work efforts will focus upon testing the simulative ability of this near field package, and developing a far field analysis capability for the evaluation of energy lost to the environment.

The first version of the CFEST code is a standard Galerkin finite element algorithm for the multidimensional analysis of nonisothermal ground-water flows. The three partial differential equations are solved in a cyclical scheme with coupling provided through the density and viscosity parameters cast as functions of pressure, temperature, and solute concentration. Application of the model to the STES concept of a withdrawal/injection doublet penetrating a confined aquifer is shown in Figure 4.52. A withdrawal/injection rate of 900 m^3/hour has been superimposed upon an ambient flow field of 0.17 m/day. The axis joining the two wells is collinear with the flow direction and the wells are 300 meters apart. Dispersivity has been taken as zero, however, the stabilizing second order term is retained by virtue of a thermal conductivity of 1.7 kilo-calories per meter, degree centigrade, day. The seasonal concept of injection/storage/recovery is omitted in this early simulation and the upstream well is pumped continuously. Other simulations

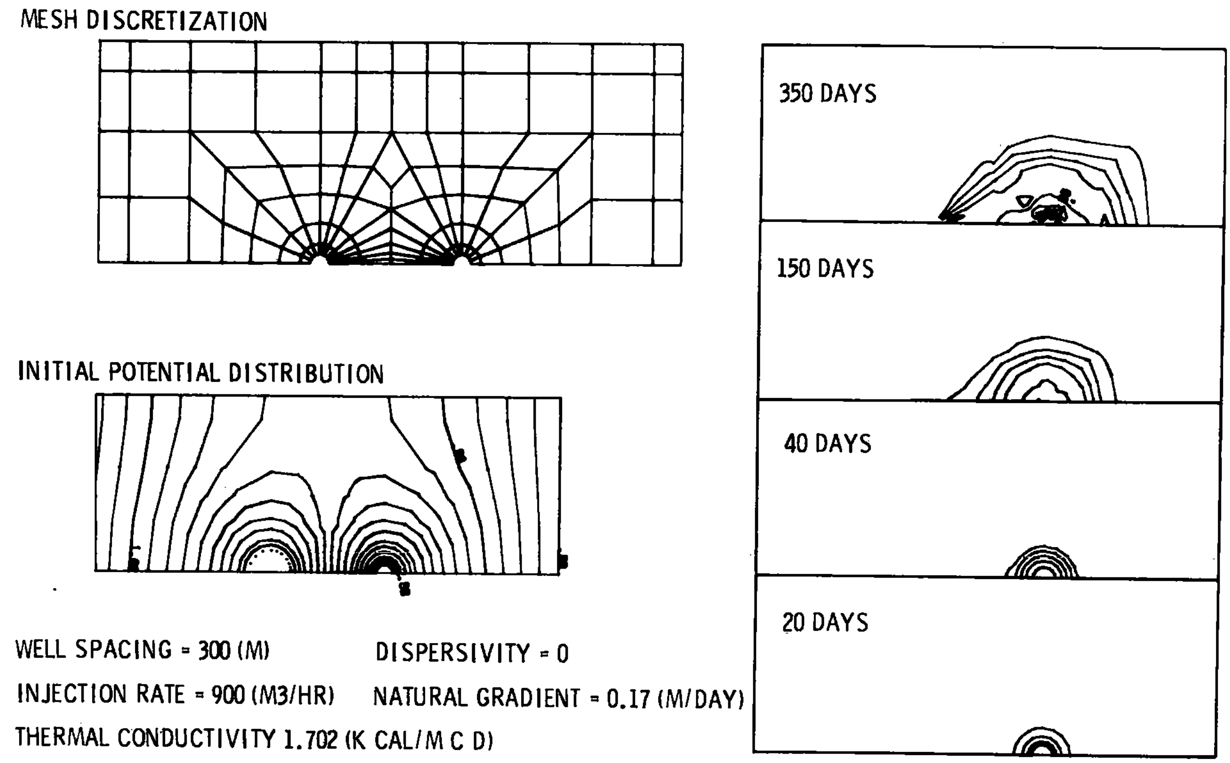


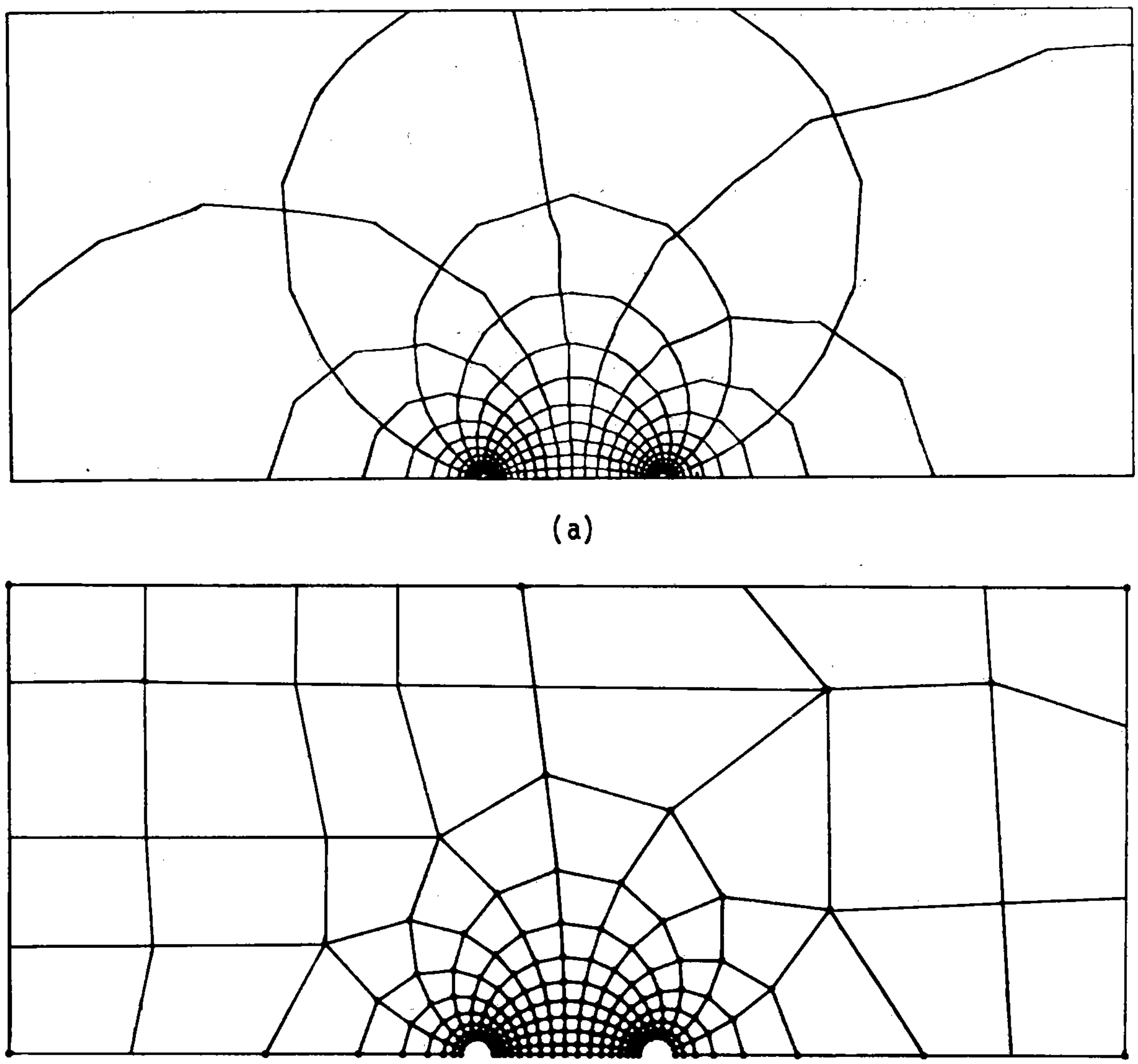
FIGURE 4.52. Computation Mesh, Potential Distribution and Thermal Plume as a Function of Time for an Injection/Withdrawal Doublet in a Confined Aquifer

where the regional flow is more significant have also been completed. Proper selection of mesh discretization and time step are being investigated further.

The most significant addition to the grid generation package has been the flownet grid. An analytical solution to the classical problem of a source and sink embedded in a uniform flow is used to create an isothermal approximation to the nonisothermal flow field of an aquifer storage zone. Newton-Raphson iteration is used to locate the intersections of velocity potential and stream lines. Thus, the appropriate density of quadralateral elements is automatically defined so long as thermal effects do not radically affect the distribution of fluids and their flow paths. Examples of the potential/streamline flownet and the resulting mesh are shown in Figure 4.53.

Raw data received from field test or demonstration facilities must be made acceptable to the simulation methodologies, and visualized for easy assimilation by members of the STES management group. Flow rate and injection temperature must be supplied to the model as piecewise constant values over increments of time. A data processing package which filters the data to provide such imput is necessary for economic reasons, and useful in locating erroneous data. Figure 4.54 is an example of the input and output of the mass and energy filtering scheme. Both mass and energy of the raw data are conserved over increments of time designated by the user.

Display of the recorded temperature data is made possible through a variety of horizontal and vertical plots as well as single probe (transducer) records. Use of these display capabilities will be necessary, for proper visualization of the fully three-dimensional data, and for comparison of simulations to recorded events. Horizontal contours and point values are displayed for the 20% plane in Figure 4.55. Various vertical profiles for these same wells are shown in Figure 4.56. One should note that vertical cross sections can be taken along any user specified line, and the inter-well option plots real distance between wells.



(a)

(b)

FIGURE 4.53. (a) Isothermal Potential/Streamline Flownet
(b) Flownet Mesh

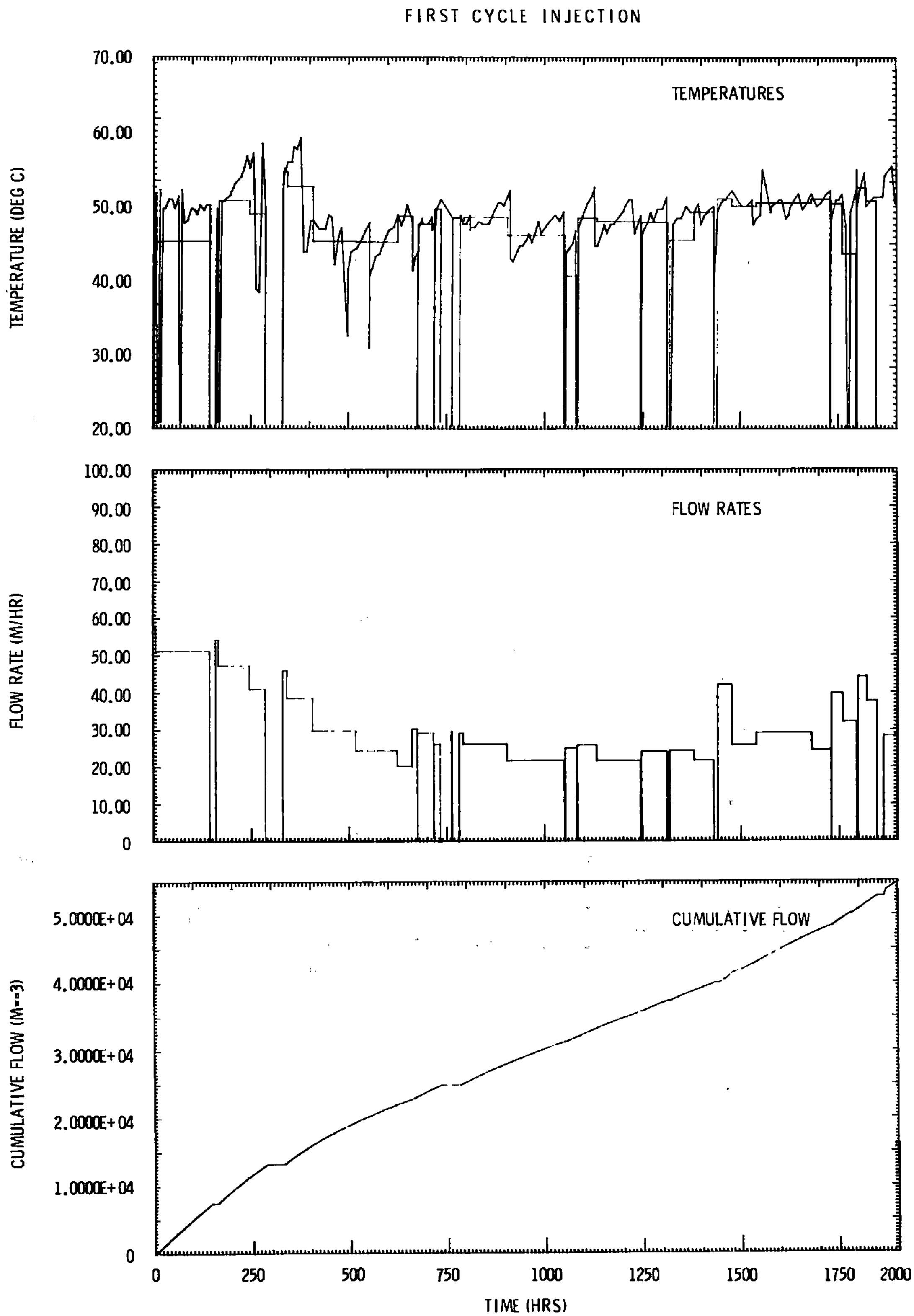


FIGURE 4.54. Input and Output of Mass/Energy Filter

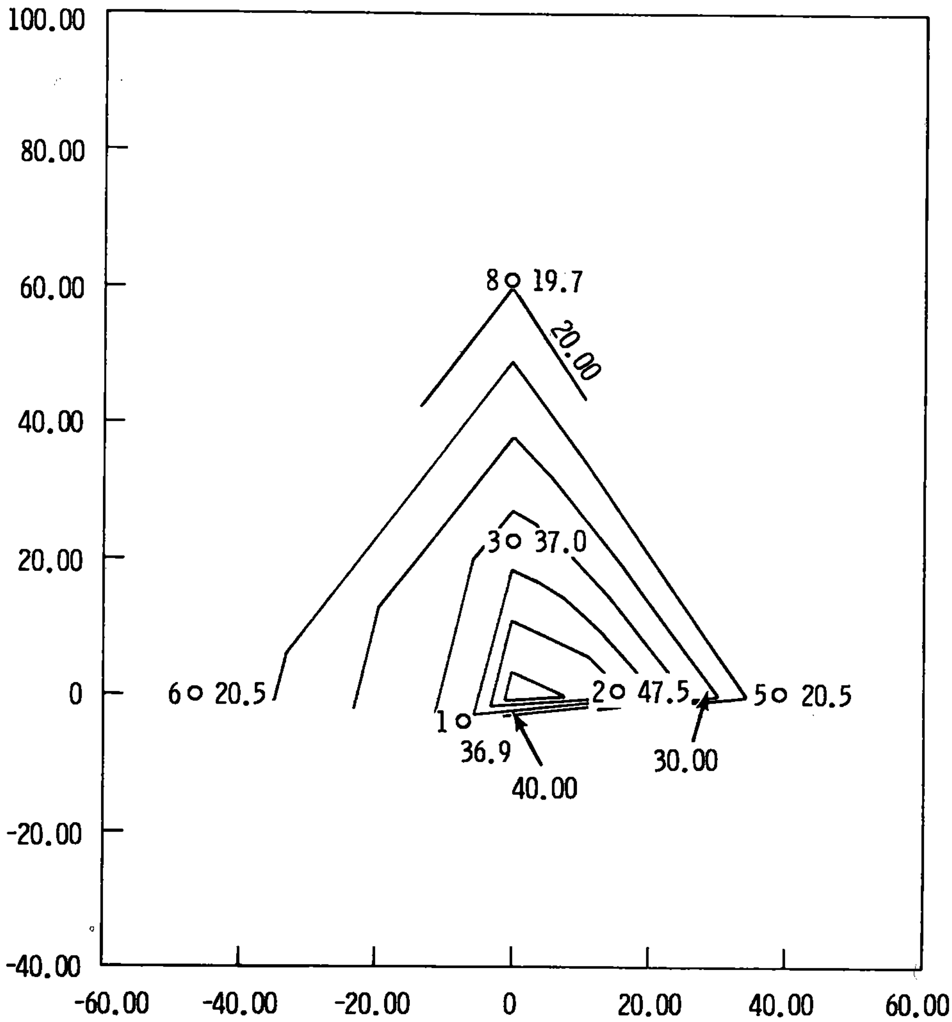


FIGURE 4.55. Point Values and Contours of Temperature @ 1000 Hours for the "Horizontal" Plane @ 20% Depth of Aquifer

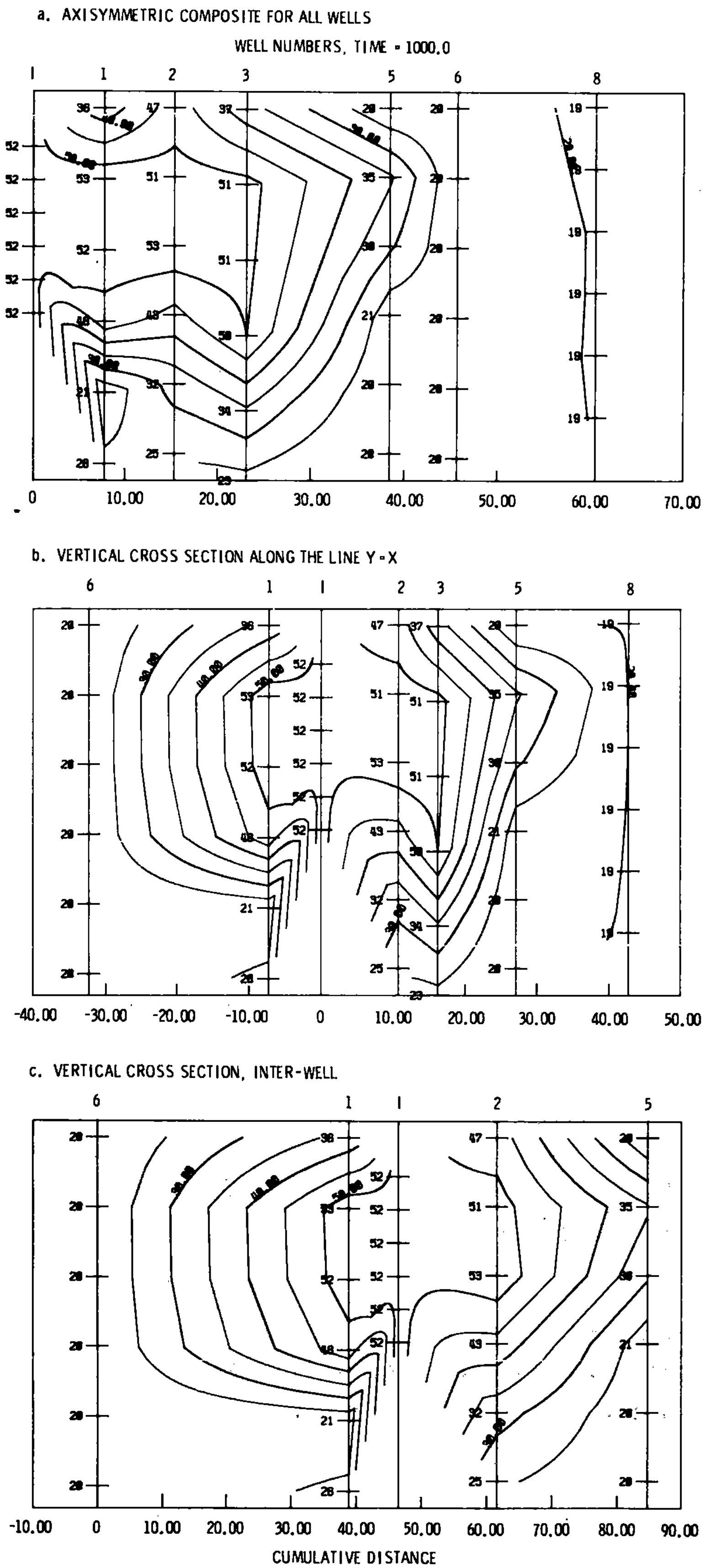


FIGURE 4.56. Visualization Options Describing the Vertical Distribution of Energy

Technical Problems

The development of a far field, long-term model of the distribution of energy lost to the aquifer environment poses the greatest technical problem of the coming year. All physical mechanisms must be examined and those that are most significant to the far field problem must be included in a simplified model of the aquifer environment. Environmental impacts will be judged by the quantity and distribution of energies lost to the environment. Hence, models to predict this distribution must include all potentially impacted areas for a considerable period of time. An extremely efficient and economical model must be formulated in a timely manner in order to answer the barrage of environment concerns on the horizon.

While being less pressing, the development of a coupled model of the saturated-unsaturated nonisothermal environment is a major technical problem. At present, the physics of the transport of energy exchange between the atmosphere and ground is not completely understood. European experiments employing shallow aquifers show significant communication between the aquifer and atmosphere. Until the transport processes are better understood, a safe depth will not be well defined for unconfined aquifer thermal energy storage. A nonisothermal code for the combined saturated-unsaturated environment will require considerable resources over a multi-year program of development, verification, and validation.

While not being a true technical problem, significant effort will be extended, in the coming years, to apply the available aquifer simulation codes to representative ATES facilities. The codes will be calibrated and subsequent predictive tests will be undertaken. Validation is essential at this point in time for the entire range of temperatures of potential ATES applications. This validation could demonstrate the sufficiency of those models presently available or indicate candidate areas for research with respect to numerical simulation of the aquifer environment.

5.0 REFERENCES

Blahnik, D. E. 1980. Preliminary Survey and Evaluation of Nonaquifer Thermal Energy Storage Concepts for Seasonal Storage. PNL-3625, Pacific Northwest Laboratory, November 1980.

Hellstrom, G., C. F. Tsang, and J. Claesson. 1980. Heat Storage in Aquifers: Buoyancy Flow and Thermal Stratification Problems. LBL-11059.

Hendrickson, P. L. 1980. "Legal and Regulatory Issues Affecting the Aquifer Thermal Energy Storage Concept." PNL-3437, Pacific Northwest Laboratory. Richland, Washington 99352.

Meyer, C. F. and W. Hausz. 1980. Guidelines for Conceptual Design and Evaluation of Aquifer Thermal Energy Storage, PNL-3581, Pacific Northwest Laboratory, October 1980.

Parr, A. D., F. J. Molz and J. G. Melville. "Field Studies of the Aquifer Thermal Energy Storage Concept." Auburn University, Department of Civil Engineering, Auburn, Alabama.

Prater, L. S. "Aquifer Thermal Energy Storage Reference Manual." Pacific Northwest Laboratory, Battelle, Richland, Washington. PNL-3471 UC-94e.

Reilly, R. W. 1980. A Descriptive Analysis of Aquifer Thermal Energy Storage Systems, PNL-3298, Pacific Northwest Laboratory.

Supkow, D. J. 1971. Temperature Measurements as a Means for Determining Aquifer Characteristics in the Tucson Basin, Pima County, Arizona. Unpublished PhD. Dissertation, University of Arizona.

Tsang, C. F., D. Hopkins and F. Hellstrom. "Aquifer Thermal Energy Storage: A Survey." Lawrence Berkeley Laboratory, Berkeley, California. 45 pp. LBL-10441.

Tsang, C. F., F. J. Molz and A. D. Parr. "Experimental And Theoretical Studies of Thermal Energy Storage in Aquifers." Lawrence Berkeley Laboratory, Berkeley, California. 5 pp. LBL-10889.

Tsang, C. F., T. Buscheck and C. Doughty. "Aquifer Thermal Energy Storage: A Numerical Simulation of Auburn University Field Experiments." Lawrence Berkeley Laboratory, Berkeley, California. 44 pp.

DISTRIBUTION

No. of
Copies

OFFSITE

A. A. Churm
DOE Patent Division
9800 S. Cass Avenue
Argonne, IL 60439

John J. Brogan
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

Arnold Epstein, Project Manager
CR-341, Forrestal Building
DOE
Washington, DC 20585

B. J. Gallagher
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

T. Levinson
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

G. F. Pezdirtz
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

Veronica Rabl
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

S. Strauch
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

J. H. Swisher
DOE Office of Advanced Conservation Technologies
Washington, DC 20585

No. of
Copies

228 Technical Information Center

Fred J. Molz
School of Engineering
Auburn University
Auburn, AL 36830

Donald Langmuir
Department of Chemistry and Geochemistry
Colorado School of Mines
Golden, CO 80401

Louis Stern
Dames & Moore
6 Commerce Drive
Cranford, NJ 07016

Howard E. Lowitt
Energetics, Inc.
2000 Century Plaza
Columbia, MD 21044

Walter Hausz
4520 Via Vistosa
Santa Barbara, CA 93110

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

Chin Fu Tsang
Bldg 90, Room 1012-H
University of California
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

Victor E. Hampel
Integrated Information Systems
Computation Dept., L-275
University of California
Lawrence Livermore Laboratory
P.O. Box 808
Livermore, CA 94550

No. of
Copies

L. Lorenz
Internorth
2223 Dodge St.
Omaha, NE 68102

Charles H. Lee
Midwest Research Institute
425 Volker Blvd
Kansas City, MO 64110

Matt Walton
Minnesota Geological Survey
319 15th Avenue S.E.
Minneapolis, MN 55455

National Aeronautics
and Space Adminstration
Asst Adm for Energy Programs
Washington, DC 20546

National Science Foundation
Division of Advanced Energy
Research and Technology
Room 1140
1800 G Street, NW
Washington, DC 20550

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

J. F. Martin
Oak Ridge National Laboratory
P.O. Box Y
Oak Ridge, TN 37830

Douglas D. Huxtable, Director
Energy R&D
Rocket Research Company
York Center
Redmond, WA 98052

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

No. of
Copies

L. Radosevich
Sandia Laboratories, Livermore
P.O. Box 969
Livermore, CA 94550

W. G. Wilson
Sandia Laboratories, Livermore
P.O. Box 969
Livermore, CA 94550

Sandia Laboratories
Technical Library Div. 3141
Albuquerque, NM 87185

Frank Baylin
Solar Energy Research Institute
1536 Cole Blvd
Golden, CO 80401

Charles Wyman
Solar Energy Research Institute
1536 Cole Blvd
Golden, CO 80401

Allan Michaels
Solar Thermal Storage Programs
Argonne National Laboratory
Building 362
9700 South Cass Avenue
Argonne, IL 60439

John F. Spencer
Department of Ecology
State of Washington
Olympia, WA 98504

J. M. Cherne
TRW
One Space Park
Redondo Beach, CA 90278

William Waldrop
Assistant Branch Chief
Water Systems Development Branch
Division of Water Management
Tennessee Valley Authority
P.O. Drawer E
Norris, TN 37828

No. of
Copies

Craig Cooley
Terra Tek
University Research Park
400 Wakara Way
Salt Lake City, UT 84108

Donald L. Reddell
Agricultural Engineering Dept.
Texas A&M University
College Station, TX 77843

U.S. Army Corps of Engineers
Attn: Library
P.O. Box 59
Louisville, KY 40202

U.S. Department of Energy
Attn: Chief, APMBR
Division of Energy Storage Systems
Washington, DC 20545

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

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

Kevin Billings, Legislative Assistant
Office of Congressman Sid Morrison
1330 Longworth Building
Washington, DC 20515

Robert D. MacNish,
District Chief
Arizona District
U.S. Geological Survey
Federal Building
Tucson, AR 85718

No. of
Copies

Union Carbide Corporation
Nuclear Division
Attn. Library
Y-12 Plant
P.O. Box Y
Oak Ridge, TN 37830

Stanley N. Davis
Department of Hydrology and Water Research
University of Arizona
Tucson, AZ 85705

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

James W. Crosby III
Geology Department
Washington State University
Pullman, WA 99164

David L. Schreiber, Ph.D., P.E.
Consulting Hydraulic Engineer
P.O. Box 1087
(c/o The Colony)
Coeur d'Alene, ID 83814

ONSITE

2 DOE Richland Operations Office

D. K. Jones
H. E. Ransom

78 Pacific Northwest Laboratory

M. A. Beckwith
D. Blahnik
C. H. Bloomster
S. M. Brown
D. B. Cearlock

No. of Copies		No. of Copies	
	R. N. Coy		J. E. Minor
	D. E. Deonigi		S. L. Montgomery
	T. J. Doherty		D. A. Myers
	J. R. Eliason		M. E. Olson
	K. Fox		J. R. Raymond
	W. A. Frier		R. W. Reilly
	D. L. Gale		W. D. Richmond
	A. F. Gasperino		L. S. Prater
	P. L. Hendrickson		J. A. Stottlemyre
	R. K. Johnson		T. L. Willke
	C. T. Kincaid		G. E. Wukelic
	L. D. Kannberg		STES Library (40)
	W. W. Laity		Technical Information (5)
	W. V. Loscutoff		Publishing Coordination MI(2)
	R. P. Marshall		

NOTICE

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

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

Price: Printed Copy $______*; Microfiche $3.00

*Pages	NTIS Selling Price
001-025	$4.00
026-050	$4.50
051-075	$5.25
076-100	$6.00
101-125	$6.50
126-150	$7.25
151-175	$8.00
176-200	$9.00
201-225	$9.25
226-250	$9.50
251-275	$10.75
276-300	$11.00