Underground Energy Storage Program

1981 Annual Report

Volume II Technical Summaries

June 1982

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

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

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

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

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

UNDERGROUND ENERGY STORAGE PROGRAM
1981 ANNUAL REPORT
VOLUME II: TECHNICAL SUMMARIES

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

June 1982

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

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

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

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

Volume II presents the amplified technical summaries of individual tasks and projects conducted during this reporting period. The activities of the authors reporting herein were actually broader in scope than may be reflected by the mini-reports. Readers wishing additional information on specific topics are invited to contact individual authors.

The work described in this report represents one segment of a continuing effort to encourage development and implementation of advanced energy storage technology. The results and progress reported here rely on earlier studies and will, in turn, provide a basis for continued efforts to develop the STES and CAES technologies.

L. D. Kannberg
Program Manager
Underground Energy
Storage Program

ACKNOWLEDGMENTS

The efforts of many contributors are represented in the two volumes of this report. Progress achieved during the March 1981 to March 1982 reporting period is attributed to multiple subcontractors working with the Underground Energy Storage Program staff. These included Terra Tek, Inc., of Salt Lake City, Utah; FluidDyne Engineering Corporation, Minneapolis, Minnesota; S. W. Childs of Oregon State University, Corvallis; C.-F. Tsang of Lawrence Berkeley Laboratory, Berkeley, California; A. F. Fossum from RE/SPEC, Inc., Rapid City, South Dakota; J. Istvan of PB-KBB, Inc., Houston, Texas; R. L. Thoms of Louisiana State University, Baton Rouge; W. E. Soderberg, University of Minnesota, Minneapolis; and F. J. Molz, Auburn University, Auburn, Alabama.

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

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

CONTENTS

PREFACE.	iii
ACKNOWLEDGMENTS.	v
FIGURES.	xv
TABLES	xviii
1.0 INTRODUCTION.	1
PART I - SEASONAL THERMAL ENERGY STORAGE Aquifer Thermal Energy Storage	
2.0 NUMERICAL MODELING.	3
2.1 OBJECTIVE.	3
2.2 TASKS.	3
2.2.1 Task 1. State-of-the-Art Review.	3
2.2.2 Task 2. Simulation Capability Verification . . .	3
2.2.3 Task 3. Site-Specific Analyses	3
2.2.4 Task 4. Design and Operation Optimization of ATES Facilities	4
2.3 TECHNICAL PROGRESS	4
2.3.1 Task 1. State-of-the-Art Review.	4
2.3.2 Task 2. Simulation Capability Verification . . .	5
2.3.3 Task 3. Site-Specific Analyses	7
2.3.4 Task 4. Design and Operation Optimization of ATES Facilities	12
2.4 TECHNICAL PROBLEMS	13
2.5 PUBLICATIONS	13
2.6 REFERENCES	14

3.0	LABORATORY/FIELD ANALYSIS	17
3.1	OBJECTIVES	17
3.2	TASKS.	17
3.2.1	Task 1. Permeability/Creep Compaction Testing. .	17
3.2.2	Task 2. Aquifer Properties Test Facility Development	18
3.2.3	Task 3. Geochemical Modeling	18
3.2.4	Task 4. Injectivity Studies.	18
3.3	TECHNICAL PROGRESS	19
3.3.1	Task 1. Permeability/Creep Compacting Testing. .	19
3.3.2	Task 2. Aquifer Properties Test Facility Development	21
3.3.3	Task 3. Geochemical Modeling	22
3.3.4	Task 4. Injectivity Studies.	25
3.4	REFERENCES	25
4.0	FIELD TEST FACILITIES	27
4.1	OBJECTIVE.	27
4.2	MOBILE FIELD TEST FACILITY	27
4.2.1	Tasks	27
4.2.2	Technical Progress.	28
4.3	ST. PAUL FIELD TEST FACILITY	31
4.3.1	Tasks	31
4.3.2	Technical Progress.	32
4.4	STONY BROOK DEMONSTRATION PROJECT.	48
4.4.1	Chilled Water Injection Test.	49
4.4.2	Aquifer Characterization.	51

4.4.3	Cost Estimate for Aquifer Thermal Energy Storage Alternatives.	55
4.4.4	Injection Well Plugging Study	60
4.5	REFERENCES	60
PART II - SEASONAL THERMAL ENERGY STORAGE		
Nonaquifer Thermal Energy Storage		
5.0	NONAQUIFER SEASONAL THERMAL ENERGY STORAGE.	61
5.1	OBJECTIVE.	61
5.2	TECHNICAL PROGRESS	61
5.2.1	Technology Assessment	61
5.2.2	Store Sizing.	62
5.2.3	Capital Cost.	63
5.2.4	Inventory Turnover Effect	64
5.2.5	Thermal Effectiveness.	65
5.2.6	Advantages.	66
5.2.7	Disadvantages	68
5.2.8	Heat Pump	68
5.3	CONCLUSIONS.	69
5.4	RECOMMENDATIONS.	70
6.0	SEASONAL THERMAL ENERGY STORAGE ECONOMIC ASSESSMENT	71
6.1	OBJECTIVES	71
6.2	TASKS.	71
6.3	TECHNICAL PROGRESS	71
6.3.1	Task 1. Development of a Methodology for Economic Evaluation of ATES	71
6.3.2	Task 2. Detailed Economic Evaluation of ATES Heat Storage.	76

6.3.3 Task 3. Nonaquifer Chill Storage Analysis. . . .	80
6.4 REFERENCES	81
PART III - COMPRESSED AIR ENERGY STORAGE Reservoir Stability Studies	
7.0 STABILITY CRITERIA FORMULATION.	83
7.1 OBJECTIVE.	83
7.2 TASKS.	83
7.3 TECHNICAL PROGRESS	83
7.4 PUBLICATIONS	84
8.0 PREDICTION OF THE THERMOHYDRAULIC PERFORMANCE OF POROUS MEDIA RESERVOIRS FOR CAES IN SUPPORT OF THE FIELD TEST AT PITTSFIELD, ILLINOIS.	85
8.1 OBJECTIVE.	85
8.2 FIELD TEST ANALYSIS.	87
8.2.1 Reservoir Description	87
8.2.2 Bubble Development.	87
8.2.3 Air Cycling	91
8.2.4 Water Coning.	92
8.2.5 Thermal Development	94
8.2.6 Dehydration	96
8.3 SUMMARY.	98
8.4 REFERENCES	98
9.0 POROUS MEDIA EXPERIMENTAL TASKS	101
9.1 OBJECTIVE.	101
9.2 SUBTASK DESCRIPTIONS	101
9.2.1 Subtask 1. Equipment Development and Acceptance Testing.	101

9.2.2	Subtask 2. Porous Media Experimentation.	102
9.3	TECHNICAL PROGRESS	102
9.3.1	Subtask 1. Equipment Development and Acceptance Testing.	102
9.3.2	Subtask 2. Porous Media Experimentation.	103
10.0	AQUIFER FIELD STUDY AT PITTSFIELD, ILLINOIS.	109
10.1	OBJECTIVES	109
10.2	TASKS.	110
10.2.1	Project Management and Technical Support . . .	110
10.2.2	Permitting	110
10.2.3	Exploration.	111
10.2.4	Surface Facility Development	111
10.2.5	Well Field Development	111
10.2.6	Water Sampling	112
10.2.7	Subsurface Instrumentation	112
10.2.8	Air Injection to Develop Storage Bubble. . . .	113
10.2.9	Cyclic Air Injection and Withdrawal.	113
10.2.10	Post-Test Coring, Core Analysis, and Disposition.	113
10.2.11	Decommissioning and Site Restoration	113
10.2.12	Technical Reporting, Interpretation, and Data Transmittal	114
10.3	TECHNICAL PROGRESS	114
10.3.1	Project Management and Technical Support . . .	115
10.3.2	Permitting	115
10.3.3	Exploration.	116

10.3.4	Surface Facility Design, Procurement, and Construction	117
10.3.5	Well Field Development	119
10.3.6	Water Sampling	122
10.3.7	Subsurface Instrumentation	122
10.3.8	Bubble Development	125
10.3.9	Air Cycling.	126
10.3.10	Post-Test Coring and Core Disposition.	127
10.3.11	Decommissioning.	128
10.3.12	Technical Reporting, Interpretation and Data Transmittal	128
10.4	CONCLUSIONS.	128
10.5	PUBLICATIONS	129
11.0	LABORATORY TESTS OF SALT SPECIMENS SUBJECTED TO LOADINGS AND ENVIRONMENTAL CONDITIONS APPROPRIATE TO A COMPRESSED AIR ENERGY STORAGE RESERVOIR	131
11.1	GENERAL OBJECTIVES	131
11.2	TASKS UNDERTAKEN	131
11.2.1	Task 1. Laboratory Cyclic Thermal and Mechanical Testing of Salt	131
11.2.2	Task 2. In Situ Slant Borehole Pressure Cycling Testing.	131
11.2.3	Task 3. In Situ Permeability Measurements	132
11.2.4	Task 4. Development of Stability Criteria	132
11.2.5	Task 5. Reporting	132
11.3	TECHNICAL PROGRESS	132
11.3.1	Task 1. Cyclic Thermal and Mechanical Testing of Salt.	132

11.3.2	Task 2. In Situ Borehole Pressure Cycling Testing.	137
11.3.3	Task 3. In Situ Permeability Measurements . .	142
11.3.4	Task 4. Development of Stability Criteria . .	143
11.3.5	Task 5. Reporting	143
11.4	PUBLICATIONS AND PRESENTATIONS IN TECHNICAL MEETINGS .	143
PART IV - COMPRESSED AIR ENERGY STORAGE Second-Generation Concepts Studies		
12.0	DESIGN STUDY FOR SECOND-GENERATION CAES CONCEPTS	145
12.1	OBJECTIVE.	145
12.2	TASK DESCRIPTION	145
12.3	PROGRESS	145
13.0	COMPRESSED AIR ENERGY STORAGE THERMAL ENERGY STORAGE MATERIALS SCREENING TEST	147
13.1	OBJECTIVE.	147
13.2	TASK DESCRIPTION	147
13.3	TECHNICAL PROGRESS	148
13.3.1	Test Facility.	148
13.3.2	Test Conditions.	152
13.3.3	Bed Materials.	153
13.3.4	Test Results	155
13.4	CONCLUSIONS.	168
14.0	ADIABATIC CAES DEVELOPMENT, THERMAL/CHEMICAL SCREENING TESTS.	171
14.1	OBJECTIVE.	171
14.2	TECHNICAL PROGRESS	171
14.2.1	Material Selection	171

14.2.2	Thermal/Chemical Test Systems.	171
14.2.3	Material Evaluation.	172
14.2.4	High (896°F) Temperature Exposure.	173
14.2.5	Dew Point (290°F) Temperature Exposure	174
14.3	CONCLUSIONS.	177

FIGURES

1.1	Underground Energy Storage Program Structure	2
2.1	First Cycle Prediction Results	8
2.2	Second Cycle Prediction Results.	10
3.1	Permeability and Compaction Test	20
3.2	Sand Pack Efficiency Test.	20
3.3	Thermal Fatigue Test	21
4.1	Water Recovery Temperature	29
4.2	Temperature Distribution at End of Storage Period.	30
4.3	Temperature Distribution at End of Recovery Period	31
4.4	Location of St. Paul FTF Test and Monitor Wells.	33
4.5	Pressure Change with Time for Values of Base Permeability and Two-Thirds the Base Permeability and a Constant Injection Rate of 660 gpm.	35
4.6	Well Efficiency for St. Paul Production Well B	37
4.7	Well Efficiency for St. Paul Production Well A	39
4.8	Drawdown for Observation Points in Well AM2.	41
4.9	Summary of Lithologies and Hydrologic Zones of the Franconia-Ironton-Galesville Aquifer and Confining Beds, St. Paul Field Test Facility	44
5.1	Home Equivalent Capacity Required.	63
5.2	Approximate Capital Cost (Single Inventory Turnover)	64
5.3	Approximate Costs Versus Inventory Turnover (Storage Only).	65
6.1	Major Submodels and Order of Execution in AQUASTOR	72
6.2	A Comparison of the Cost of ATES Against Conventional Technology	79

6.3	Aquifer Thermal Energy Storage Component Cost Breakdown.	79
8.1	Water Coning During Reservoir Extraction Cycle	86
8.2	Reference Relative Permeability Functions.	89
8.3	Reference Capillary Pressure Functions	89
8.4	Volume Flow Rate Versus Time for 275 psi Constant Pressure Air Injection	90
8.5	Lines of Constant Saturation (50%) Versus Radius for Different Time Periods During Bubble Development	91
8.6	Water Coning: 50% Saturation Front.	93
8.7	Thermal Development: Radial Temperature Profiles After Final Weekly Extraction Cycle.	96
8.8	Radial Saturation Profiles at Various Times During the Simulation	97
9.1	Gas Permeability Versus Depth, Yakley #1	104
9.2	Drying Curve for St. Peter Sandstone	106
9.3	Permeability Versus Temperature.	106
10.1	Injection/Withdrawal Well Design	120
10.2	Location, Elevations and Bottomhole Deviations of Pittsfield Wells	121
10.3	Cross Section of Closed-Instrument Wells	124
10.4	Sampling/Logging Well Design	125
11.1	Long-Term Triaxial Extension Test with Cycling Loads	135
11.2	Permeability of Jefferson Island Rock Salt	136
11.3	Typical Borehole for In Situ Tests	137
11.4	Air Pressurization of Borehole in Salt Mine.	139
11.5	Instrumentation and Apparatus for High-Pressure Oil Tests.	140
11.6	Hydraulic Fracturing for Boreholes in Salt	141

13.1	Test Vessel Schematic.	150
13.2	Test Loop Process Schematic.	150
13.3	Load Simulator	151
13.4	Typical Bed Axial Temperature Profile.	154
13.5	Isothermal Pressure Loss Comparison.	156
13.6	Typical Axial Pressure Loss Data, Thermocycling Test . . .	157
13.7	Elutriated Particle Emission Comparison.	157
13.8	Approximate Comparison of Size Distribution.	159
13.9	Post-Test Denstone	162
13.10	Post-Test Iron Oxide	163
13.11	Post-Test Dresser Basalt	164
13.12	Typical Time-Wise Bed Temperature Profile.	166
13.13	Temperature Across Top of Bed.	166
13.14	Egg Crate Assembly for Radial Flow Distribution.	167
14.1	Simulated TES Material Environment Reaction Column	173

TABLES

2.1	Parameters Used in the First-Cycle Prediction Numerical Simulation.	8
2.2	Parameters Determined by Comparing Experimental and Calculated Temperature Fields During the First Cycle. . . .	9
2.3	Second-Cycle Summary.	12
4.1	Drawdown in St. Paul Well B for Various Discharge Rates	37
4.2	Drawdown in St. Paul Well A for Various Discharge Rates	39
5.1	Nonaquifer STES Concept Technology Assessment	62
5.2	Heat Recovery Potential and Quality	66
5.3	Nonaquifer STES Concept Main Advantages and Disadvantages .	67
8.1	Reservoir Description	88
11.1	Stress Conditions for Tests	133
11.2	Tests Performed According to Table 11.1	134
13.1	Test Conditions	153
13.2	Compressive Strength Test (ASTM E-382) Results.	159
13.3	Tumble Test (ASTM E-279) Results.	160
13.4	Miscellaneous Physical Data	168
14.1	Changes in Candidate TES Materials After Exposure to Dry 896°F Air	175
14.2	Changes in Candidate TES Materials After Exposure to Moist 280°F Contaminated Air.	176
14.3	Hygroscopic Tendencies of Nonmetals	178

UNDERGROUND ENERGY STORAGE PROGRAM
1981 ANNUAL REPORT
VOLUME II
TECHNICAL SUMMARIES

1.0 INTRODUCTION

This second volume of the two-volume 1981 Annual Report presents technical summaries of the individual efforts conducted as part of the Underground Energy Storage (UES) Program during the period March 1981 to March 1982. Under Pacific Northwest Laboratory (PNL) management as lead laboratory for the U.S. Department of Energy (DOE), the UES Program was organized as shown in Figure 1.1.

The organization of this report essentially follows that of the UES Program. The volume is subdivided into four parts corresponding to the Program's four main components:

- Part I - Seasonal Thermal Energy Storage, Aquifer Thermal Energy Storage
- Part II - Seasonal Thermal Energy Storage, Nonaquifer Thermal Energy Storage
- Part III - Compressed Air Energy Storage, Reservoir Stability Studies
- Part IV - Compressed Air Energy Storage, Second-Generation Concepts Studies

The technical summaries of individual projects and tasks appear as main sections behind the appropriate volume part designation page.

FIGURE 1.1. Underground Energy Storage Program Structure

PART I
SEASONAL THERMAL ENERGY STORAGE
Aquifer Thermal Energy Storage

Work in this part of the program was performed in three areas. Numerical modeling efforts are documented in Section 2.0. Section 3.0 discusses the laboratory/field analyses of physical and geochemical properties characteristic of aquifers. Research at two field test facilities and one ATES demonstration site is described in Section 4.0.

2.0 NUMERICAL MODELING

C. T. Kincaid

Pacific Northwest Laboratory

Numerical modeling work has been performed by Lawrence Berkeley Laboratory, Pacific Northwest Laboratory, GeoTrans Inc., Oregon State University, Washington State University, and Maddox and Associates.

2.1 OBJECTIVE

The objective of this work is to develop new, or utilize existing, simulation technologies capable of predicting the transport and retrieval of a thermal energy resource within the ground-water environment, for designing and evaluating aquifer thermal energy storage systems.

2.2 TASKS

The numerical modeling work was subdivided into four tasks.

2.2.1 Task 1. State-of-the-Art Review

Documentation is to be developed that presents the state-of-the-art with respect to numerical simulation techniques applicable to ATES. These reports will serve to both transfer technology to the engineering community, and guide the direction of the program with respect to numerical simulation of ATES.

2.2.2 Task 2. Simulation Capability Verification

Those codes representing the best available simulation technology for the aquifer environment of an ATES facility will be verified against published analytical and semi-analytical solutions. Verified codes will subsequently be validated against the data sets collected at the Mobile, Alabama Field Test Facility.

2.2.3 Task 3. Site-Specific Analyses

The best available simulation technologies will be applied to the analysis of the Alabama and Minnesota field test facility experiments.

These codes will be used in designing and evaluating experiments conducted at the field test facilities.

2.2.4 Task 4. Design and Operation Optimization of ATES Facilities

Methodologies for determining optimal time distribution of both the quality and quantity of energy recovered will be developed as a function of system design, flow rates, and injection temperatures.

2.3 TECHNICAL PROGRESS

2.3.1 Task 1. State-of-the-Art Review

Two efforts were completed under this task during the year. In the first, GeoTrans Inc. completed a review of simulation techniques for saturated environments (Mercer et al. 1981). A second effort completed by Stuart Childs of Oregon State University reviewed the literature on heat and mass transport in the unsaturated porous media overlying an unconfined aquifer (Childs and Malstaff 1982). Brief summaries of both reports are given below.

2.3.1.1 Saturated Environments (Mercer et al. 1981)

"In general, available models of the saturated ground water environment are adequate to address most concerns associated with ATES; that is, design, operation, and environmental assessment."

Assuming that codes are applied appropriately, the primary limitation on calculations is the data base used to construct the model. Numerical transport models are limited by the uncertainty of subsurface data and the lack of long-term historical data for calibration. Geochemical models are limited by the lack of thermodynamic data for the temperature ranges applicable to ATES. Model applications undertaken with data collection activities on ATES sites should provide the most important contributions to the understanding and utilization of ATES . . . the primary conclusion of this review is that model application to field sites in conjunction with data collection activities is essential to the development of this technology.

2.3.1.2 Unsaturated Environment (Childs and Malstaff 1982)

In addition to reviewing the literature, the work of Childs and Malstaff was designed to identify, via a parametric analysis, those parameters of greatest importance with respect to the feasibility of unconfined ATEs.

In order to establish the parameters appropriate for study, a comprehensive literature review was made. It was found that flow systems in the temperature range between 50 and 90°C have not been studied; the analysis presented (in Childs and Malstaff 1982) is therefore in the position of extrapolating existing data to the temperature range of interest for unconfined ATEs. Although water vapor fluxes are seldom as large as saturated medium liquid water fluxes, they are important under unsaturated conditions. The major heat transport mechanism for unsaturated porous media at temperatures from 50 to 90°C is latent heat flux. This mechanism is nonexistent under saturated conditions but may well control design of unconfined aquifer storage systems.

The parametric analysis reported by Childs and Malstaff treats the detailed physical phenomena that occur as one-dimensional (vertical). Their results demonstrate the temperature and moisture dependence of the transport coefficients of importance. "The question of design of an unconfined ATE site is also addressed by considering the effects of aquifer temperature, depth to water table, porous medium flow properties, and surface boundary conditions." Chill storage is shown to have the best response for the three soil types investigated (silt loam, fine sandy loam, clay). It appears that for a 90°C ATE application the soil type does not affect the relatively large heat loss from a shallow unconfined aquifer. For a less extreme application (65°C), soils with intermediate vapor and liquid water flow characteristics exhibit high heat loss. Hence, for these applications the soil type will play a role in evaluating the feasibility of unconfined ATEs.

2.3.2 Task 2. Simulation Capability Verification

Two activities were directed toward documenting simulation capability verification during the past year. The first effort was to

convert the Survey Waste Injection Program (SWIP) code (INTERCOMP 1976) to a short word length (e.g., IBM) computer and verify it against published solutions. This was completed and the results published by Washington State University (Ichimura 1982). The second activity involved PNL staff and Dr. S. K. Gupta, a consultant to PNL, in the verification of the Coupled Fluid, Energy and Solution Transport (CFEST) code. Primary documentation for CFEST has been prepared and will be published upon receipt of clearance.

2.3.2.1 Survey Waste Injection Program Verification (Ichimura 1982)

Simulations were conducted with the SWIP code installed on an AMDAHL 470V/8 machine using an IBM OS/VS2 operating system and FORTRAN IV G1 Release 2.0 compiler. This data structure is the same as employed on the large mainframe IBM 370 series computers. Minor errors in the algorithms computing mass and energy balances were corrected to yield comparable accuracy between IBM and CDC machinery. Several other minor alterations to the code are also discussed in Ichimura (1982). Verification simulations reported include comparison to Theis (1935), Hoopes and Harleman (1967), Avdonin (1964), and Gringarten and Sauty (1975). Finally, the SWIP code is validated against the Mobile, Alabama data collected in 1978 and 1979 and its results are compared to those published by Lawrence Berkeley Laboratory (Tsang et al. 1981). Both the SWIP and CCC (newly renamed PT) codes slightly overpredict the efficiencies of recovery for these experiments.

2.3.2.2 Coupled Fluid, Energy and Solute Transport (CFEST)

During the past year, the initial verification of the CFEST code was completed. Documentation was prepared, and includes sections on the conservation equations employed and their numerical analogues, the input data requirements, and the completed verification studies. In addition to the four papers cited above, CFEST has been verified against published solutions by Coats and Smith (1964), Hantush (1959), and Nelson and Schur (1978).

The CFEST code was initially applied to the 1978-1979 experiments conducted at Mobile, Alabama. It was also applied to the aquifer storage problem defined by the International Energy Agency. The formal reporting of these validation exercises has been deferred pending completion of the Mobile, Alabama (1978-1979) applications.

2.3.3 Task 3. Site-Specific Analyses

Concurrent with the first two cycles of the ATES field experiment at the Mobile FTF, Lawrence Berkeley Laboratory (LBL) did numerical simulations based on field operating conditions to predict the outcome of each cycle before its conclusion.

2.3.3.1 First Cycle Prediction

During the first cycle, 25,000 m³ of water at an average temperature of 59°C were injected over a period of one month into an aquifer 21 m thick with a permeability of about 63 darcies. It was then stored for one month and subsequently produced. The injected water was obtained from a supply well perforated in the same aquifer 240 m away from the injection/production well. The LBL research team was provided with the basic geological, well-test, injection flow rate, and injection temperature data.

The well-test data and geological information were studied and analyzed to obtain reservoir parameters and their range of uncertainty. The parameters used in the LBL numerical simulation are listed in Table 2.1. Because the supply well is 240 m from the injection/production well, and the thermal radius is only about 25 m, it was decided that a radial calculation mesh would be adequate. Based on the injection flow rates and temperatures provided, LBL employed the numerical model PT (formerly called CCC) to calculate production temperature and energy recovery factor for a given production flow rate schedule. The result is presented as curve A in Figure 2.1, where the experimental result is also plotted. The experimental results were made known to LBL after their numerical simulation was completed. The predicted energy recovery factor is 0.620 compared to the experimental value of 0.552. This agreement is satisfactory.

TABLE 2.1. Parameters Used in the First-Cycle Prediction Numerical Simulation

Thermal conductivity:	Aquifer	2.29 J/m.s.°C
	Aquitard	2.56 J/m.s.°C
Heat capacity of rock		1.81×10^6 J/m ³ .°C
Aquifer horizontal permeability		63 darcies
Aquifer vertical to horizontal permeability ratio		1:7
Aquitard to aquifer permeability ratio		10^{-5}
Porosity:	Aquifer	0.25
	Aquitard	0.35
Storativity:	Aquifer	6×10^{-4}
	Aquitard	9×10^{-2}

FIGURE 2.1. First Cycle Prediction Results

2.3.3.2 First Cycle: Detailed Comparison Between Theory and Experiment

Next, a series of parameters studies was made comparing the experimental and calculated temperature fields at various times during the first cycle. These studies led LBL to hypothesize that the aquifer is vertically stratified into three layers, the middle layer having a permeability 2.5 times that of the upper and lower layers. Table 2.2 shows the permeability values that were modified, other parameters remaining unchanged from Table 2.1. Using these values, the first-cycle recovery factor was calculated to be 0.585; calculated production temperature is shown as curve B in Figure 2.1. Apparently the layered structure of the aquifer noticeably lowers the recovery factor. This is significant because layering is difficult to detect through conventional well-test analysis.

2.3.3.3 Second Cycle Prediction

The procedure was similar to the first cycle prediction. Only the injection flow rate, temperature history, storage period, and expected average production flow rate were made known to LBL. The three-layered aquifer model described in the previous section was used for the calculation. The second cycle began 24 days after the conclusion of the first-cycle production period. Water at an average temperature of 82°C was injected over a period of about 4.5 months. The variable, experimental injection flow rates and temperatures were averaged into

TABLE 2.2. Parameters Determined by Comparing Experimental and Calculated Temperature Fields During the First Cycle

Aquifer horizontal permeability:

Upper layer	9.6 m thick	42 darcies
Middle layer	5 m thick	105 darcies
Lower layer	6.6 m thick	42 darcies

Average value 57 darcies

Average aquifer vertical to horizontal permeability ratio: 1:6

five segments for the numerical simulation. The total volume injected, about $58,000 \text{ m}^3$, was considerably larger than the volume injected during the first cycle; hence, the thermal radius extended farther than in the first cycle (to about 38 m). However, this distance is still small enough compared to the distance to the supply well to justify using a radial calculation mesh. After injection, the hot water was stored for 34 days.

The simulation of the original production plan--to produce all the injected water through a fully penetrating well screen--was carried out, using a constant fluid flow rate of 200 gpm. The calculated recovery factor is 0.406 and the production temperature is shown in Figure 2.2.

However, this production plan was changed after two weeks of production. At that time the well was shut down and modified to produce fluid from only the upper half of the aquifer; then production was resumed. This scenario was again simulated using a constant flow rate

FIGURE 2.2. Second Cycle Prediction Results

of 200 gpm. The calculated recovery factor is 0.434; the production temperature is shown in Figure 2.2. After the second-cycle calculation was completed, the experimental results were made known to LBL. The experimental recovery factor was 0.452; the production temperature is shown in Figure 2.2. Some of the discrepancies between the experimental and calculated production temperatures are due to the fact that the average experimental production flow rate was 212 gpm (not the 200 gpm used in the numerical calculation). Comparison between the experimental and calculated temperature fields in the aquifer throughout the second cycle show good agreement.

2.3.3.4 Second Cycle Optimization Studies

The recovery factor improvement of about 3% may have been small because the lower part of the modified well screen intersected the high-permeability layer of the aquifer and water may have been selectively produced from this cooler region rather than from the warmer upper region of the aquifer. To study the effects of different injection/production schemes, a series of numerical simulations based on the second cycle was run employing different well-screen intervals. Each simulation used a simplified injection history consisting of one constant injection flow rate and temperature. Table 2.3 summarizes these optimization simulations. Collectively, these results indicate that although buoyancy flow is strong in the aquifer, an improvement of almost 10% can be achieved by selective injection and production schemes.

2.3.3.5 Conclusions

The successful prediction of the first and second cycle results validates the numerical simulation procedure used. Furthermore, the improvements obtained by subsequent calculations in simulating the experimental data throw light on the geological system at the site and the important physical processes occurring during the experiment. Current LBL work involves assisting Auburn University in its planning for the third-cycle experiment. Alternative injection and production

TABLE 2.3. Second-Cycle Summary

	Well-Screen Interval		ε
	Injection	Production	
Experiment	full	full for 2 weeks upper half thereafter	.452
Prediction	full	full	.406
	full	full for 2 weeks upper half thereafter	.434
Optimizations			
A	full	full	.407
B	full	upper 40%	.466
C	full	upper 20%	.496
D	lower half	upper half	.494
E	upper 20%	upper 20%	.504

schemes are being studied to maximize the recovery factor under given constraints. This work will demonstrate the possibility of using numerical modeling in designing and optimizing field operations.

2.3.4 Task 4. Design and Operation Optimization of ATEs Facilities

The purpose of this task, a joint effort of LBL and PNL staff, is to extend the Steady Flow Model (SFM) concept (Doughty et al. 1981) to nonaxisymmetric analysis, thus affording the engineering community an approximate simulation capability.

The approach being followed uses a computational mesh composed of stream tubes of the fluid flow. This mesh has the advantage of exhibiting no numerical dispersion for the convection problem. However, whenever the flow field changes (e.g., injection-storage-recovery), the mesh changes. This necessitates an interpolation procedure to define the temperature at the new mesh points. Progress to date includes the generation of the initial stream tube mesh composed of equal volume elements. The interpolation procedure is being designed by LBL staff. The convective-conductive code, similar to the SFM in theory, is being developed at PNL.

2.4 TECHNICAL PROBLEMS

The publication of relatively simple evaluation methods for non-axisymmetric ATEs applications poses some technical problems. An essential element of this simplified analysis is the application of interpolation techniques that will allow for mass and energy conservation. While seemingly simple, this is no trivial matter in practice. Second, the use of an implicit time-stepping scheme must be explored due to the projected high cost of continuing to use the SFM's explicit algorithm.

The inability of published solutions to adequately test the buoyancy driven flow component became apparent while conducting the verification and validation tests on various codes. Some small level of effort should be devoted to defining an appropriate boundary value problem. A candidate is the cold water drive problem.

A considerable technical void exists in the area of unconfined aquifers with respect to ATEs. Existing codes will handle (or could handle with minor modification) the moving boundary problem of injecting a thermal resource to (or recovering it from) an unconfined aquifer. The lesser drilling costs implied by shallow unconfined aquifers (relative to confined aquifers) will lead to demands upon a largely untried technology. Energy losses or gains from the vadose zone are not modeled by any of the commonly employed analysis packages. Codes employed to date by the UES Program are devoted to confined aquifers and saturated flow. Experience within the UES Program has been that coupled code use and field experimentation leads to excellence in both areas. It may be appropriate to explore the technical problems posed by an unconfined ATEs facility through a combined field and numerical approach.

2.5 PUBLICATIONS

Four publications document the numerical modeling task in more detail.

- Childs, S. W., and G. Malstaff. 1982. Final Report: Heat and Mass Transfer in Unsaturated Porous Media. PNL-4036, Pacific Northwest Laboratory, Richland, Washington.
- Doughty, C., G. Hellstrom, C. F. Tsang and J. Claesson. 1981. A Study of ATES Thermal Behavior Using a Steady Flow Model. LBL-11029, Lawrence Berkeley Laboratory, University of California, Berkeley, California.
- Ichimura, V. 1982. Final Report for Hydrologic Studies Support: INTERCOMP Code Conversion. College of Engineering Research Report 82/15-1, Department of Civil and Environmental Engineering, Washington State University, Pullman, Washington.
- Mercer, J. W., C. R. Faust, W. J. Miller and F. J. Pearson, Jr. 1981. Review of Simulation Techniques for Aquifer Thermal Energy Storage (ATES). PNL-3769, Pacific Northwest Laboratory, Richland, Washington.

2.6 REFERENCES

- Avdonin, N. A. 1964. "Some Formulas for Calculating the Temperature Field of a Formation During Thermal Injection." Neft i Gas. 7(3):37-41.
- Coats, K. H., and B. D. Smith. 1964. "Dead-End Pore Volume and Dispersion in Porous Media." S.P.E.J. pp. 73-84.
- Gringarten, A. C., and J. P. Sauty. 1975. "A Theoretical Study of Heat Extraction for Aquifers with Uniform Regional Flow." Journal of Geophysical Research. 80(35):4956-4962.
- Hantush, M. S. 1959. "Nonsteady Flow to Flowing Wells in Leaky Aquifer." Journal of Geophysical Research. 64(8):1043-1052.
- Hoopes, J. A. and D. R. Harleman. 1967. "Dispersion in Radial Flow from a Recharge Well." J. Geophys. Res. p. 72.
- INTERCOMP Resource Development and Engineering, Inc. 1976. A Model for Calculating Effects of Liquid Waste Disposal in Deep Saline Aquifers: Part I - Development; Part II - Documentation. PB-256 903, U.S. Geological Survey, Water Resources Division, Reston, Virginia.

Nelson, R. W., and J. A. Schur. 1978. "A Preliminary Evaluation Capability for Some Two-Dimensional Ground-Water Contamination Problems." BCSR-38, Boeing Computer Services, Richland, Washington. (Reissued with minor modifications as PATHS Groundwater Hydrologic Model. PNL-3162, Pacific Northwest Laboratory, Richland, Washington.)

Theis, C. V. 1925. "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of Well Using Groundwater Storage." Transactions, American Geophysical Union. 2:519-524.

3.0 LABORATORY/FIELD ANALYSIS

S. C. Blair

Pacific Northwest Laboratory

Laboratory and field analysis efforts have been performed by Pacific Northwest Laboratory and Terra Tek, Inc.

3.1 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.

3.2 TASKS

The laboratory/field analysis component consists of four tasks.

3.2.1 Task 1. Permeability/Creep Compaction Testing

The effect of increased temperature on the permeability of rocks in a host aquifer is an important consideration in the design and operation of an STES facility. Several laboratory experiments reported in the literature have suggested that the permeability of common aquifer materials decreases with increasing temperatures in the range of 25 to 150°C (Danesh 1978; Muhammadu 1976; Weinbrandt 1972). Over the past two years permeability experiments have been conducted on Massillon sandstone and Ottawa sand, at Terra Tek and PNL, to quantify the effects of temperature on permeability of these materials and to identify mechanisms causing permeability damage. Tests during 1980 indicated that permeability degradation observed in the laboratory was due to contamination derived from the testing apparatus and recommended that future tests be conducted using corrosion-resistant vessels and include filtration of pore fluid upstream of the sample.

This year additional laboratory tests following these recommendations were conducted at Terra Tek to monitor the effect of temperature on permeability and sample strain.

3.2.2 Task 2. Aquifer Properties Test Facility Development

This task involves management and technical overview of the design, construction, installation, and operation of a STES laboratory flow loop. 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.

3.2.3 Task 3. Geochemical Modeling

This task involves the development and application of a geochemical computer code specifically for STES. The model will include mass transfer simulation (mineral precipitation/dissolution), kinetic control for major aquifer minerals, and ground-water speciation compilations at temperatures from 25°C to 150°C. This model can be used for data from field test facilities or from laboratory experiments conducted with the Aquifer Properties Test Facility. Guidelines are being developed for collecting and analyzing geochemical data necessary for input to the geochemical models to determine chemical processes active in a STES aquifer storage system.

3.2.4 Task 4. Injectivity Studies

Significant impairment of injection rates has been experienced at the Stony Brook and Auburn field sites. Mechanisms thought to be responsible for this impairment include chemical precipitation, gas blinding, and particulate plugging. The injectivity studies are designed to provide data on processes of injection impairment through both laboratory experiments and field studies. The laboratory experiments are designed to test the hypothesis that mobilization of internal fines caused permeability impairment at the Stony Brook FTF, while the field studies, conducted at the Minnesota FTF, employ a Field Injectivity Test Stand capable of monitoring fluids during injection and withdrawal operations.

3.3 TECHNICAL PROGRESS

3.3.1 Task 1. Permeability/Creep Compaction Testing

Permeability reduction and material compaction studies have been performed on some generic reservoir materials: Massillon sandstone, Ottawa silica sand, and a simulated sand pack using these two materials. Laboratory testing of core was performed at in situ pressure, with steady-state liquid flow, and at room and elevated temperature. Three major test types were performed: 1) flow with temperature variation to establish baseline permeability data, and to help establish the magnitude and nature of flow- and temperature-induced permeability reduction mechanisms, 2) flow with repeated cycles of heating and cooling to help establish the magnitude and nature of permeability reduction mechanisms induced by thermal fatigue, and 3) simulated injection in sand pack samples to establish the magnitude and nature of permeability reduction mechanisms induced by injection or temperature. Massillon sandstone generally showed a permeability value at 150°C, averaging about 60% of its room temperature value. This is shown in Figure 3.1. Ottawa silica sand generally showed a permeability value, at 150°C, averaging about 65% of its room temperature value (Figure 3.2). Sand pack specimens also generally showed a value, at 150°C, averaging about 50% of the room temperature value (Figure 3.3).

After cooling from 150°C, Massillon sandstone showed a permanent permeability reduction to about 88 to 60% of the starting value (Figure 3.1), while Ottawa silica sand showed essentially complete recovery of permeability (Figure 3.2). Sand pack specimens exhibited greater permanent permeability reduction to about 70% of the starting value (Figure 3.3). Permeability impairment in the sand pack specimens was both time- and temperature-dependent.

Repeated heating and cooling cycles did not induce significant permanent permeability reduction. After four thermal cycles, sandstone permeability was about 80% of its starting value, while silica sand was essentially unaffected.

FIGURE 3.1. Permeability and Compaction Test

FIGURE 3.2. Sand Pack Efficiency Test

FIGURE 3.3. Thermal Fatigue Test

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

3.3.2 Task 2. Aquifer Properties Test Facility Development

Construction of the APTF was completed in June 1981; system operator training acceptance testing took place in July. The system was shipped to PNL in August and permanent installation of the APTF was completed in October. During the period October 1981 to March 1982 an extensive series of shakedown tests and calibration procedures was performed on the system to ensure data quality. These tests included checkout and calibration of various subsystems under conditions of

increased pressure and temperature. Chemical characterization of the flow system was also completed. Core samples from the Minnesota FTF have been received and testing of these samples is in initial stages.

3.3.3 Task 3. Geochemical Modeling

During the past year, work in this task has been directed toward model development, model applications and the establishment of water sampling requirements. The original ion-speciation/solubility WATEQ model was improved by merging it with a model (MINEQL) capable of simulating mass transfer. A copy of the latest version of EQ3/EQ6, which includes both mass transfer and dissolution kinetics subroutines, has been obtained for future modeling use. The WATEQ model has been used to evaluate possible solubility controls on the ground-water composition at the Minnesota Field Test Facility and the data requirements for geochemical modeling studies are being used to produce sampling guidelines for FTFs and the APTF.

The direction for much of the geochemical modeling work performed during the year was guided by information produced early in the year on geochemical modeling for the STES Program. This information included a discussion of: 1) benefits of applying geochemical modeling to STES technologies; 2) status of geochemical models, as well as their codes and thermodynamic data bases at PNL; 3) a list of analytical data requirements for input to these geochemical models; and 4) proposed developments in geochemical models needed for the STES Program. The report concludes that reinjection of thermally-altered water into ground-water aquifers has been plagued with numerous problems related to the chemistry of the injected water, the formation water and the mineralogy of the storage aquifer. Often, these problems might have been avoided if proper attention had been given to geochemical considerations. In general, use of a geochemical model can maximize the awareness of a site manager to potential problems that may be avoided. Geochemical modeling can also provide meaningful input to regulatory agencies and public acceptance of STES technology. Geochemical modeling may also provide valuable insight into potential well pipe and screen

corrosion and an evaluation of techniques for their mitigation. It also serves to prioritize the analysis of dissolved chemical constituents and to provide a scientific basis for decisions on the number of water analyses and the required analyses of solids.

One proposed model developmental need was the capability to simulate dissolution and precipitation reaction kinetics. Toward this goal a subcontract had been established in FY80 with Hydrochem Systems Inc. (Golden, Colorado) to evaluate the published kinetic data. They completed the work in September 1981 and submitted a report that surveys and critiques the published literature on the dissolution and precipitation kinetics of the following phases: calcite (CaCO_3); gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$); amorphous silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$); α and β cristobalite and quartz (all SiO_2 polymorphs); x-ray amorphous ferric oxyhydroxide or hydroferrite ($\text{Fe}(\text{OH})_3 \cdot n\text{H}_2\text{O}$); goethite ($\alpha\text{-FeOOH}$); and hematite ($\alpha\text{-Fe}_2\text{O}_3$). An understanding of the reaction kinetics of these compounds is needed: 1) to rigorously explain and model the evolution of ground-water chemical composition with ground-water flow in aquifer systems; and 2) to predict the clogging of aquifers and of wells and their discharge lines with encrusting precipitates of these minerals during pumping or injection. Such clogging has caused reduced yields and the failure of water wells pumping iron-rich ground waters (clogged by precipitated ferric oxyhydroxides), and of heat exchange systems receiving ground waters supersaturated with respect to amorphous silica.

Model development has been progressing to take advantage of available techniques for simulating mass transfer and to incorporate the data on reaction kinetics as they are published. The mass transfer model being developed for STES use will combine the extensive data base found in WATEQ with the MINEQL mass transfer routines. The major components of the new model have been assembled and are currently being tested. As a backup to the PNL model and to use in verification of certain calculations, the latest version of the EQ3/EQ6 model has been obtained and is being installed on a local computer.

The WATEQ model was used to evaluate two sets of ground-water chemistry data from the Minnesota FTF. The results show that the ground water is at apparent equilibrium with calcite and cristobalite (an SiO_2 polymorph). Neither aluminum nor E^H values were reported; consequently, equilibrium with respect to several important iron oxyhydroxides and aluminosilicates could not be established. Furthermore, this limited data set cannot be used to define the state of the system. As more data are received and additional parameters are measured (e.g., E^H , $\text{Fe}^{2+}/\text{Fe}^{3+}$ aluminum concentration), it should be possible to more clearly determine the equilibrium state of the natural ground-water system.

The geochemical modeling of any system requires adequate input data; guidelines for the collection, preservation, and analysis of chemical data are being developed. During this year, reference material published by EPA, USGS and PNL on sampling ground water and geothermal fluids was obtained and will be used in drafting the guidelines.

A solution sampling system for the APTF has been designed. It will use the existing upstream and downstream sampling ports on the system and will consist of a micrometering valve, collection vessel, and assorted connective hardware. Procedures for preserving and analyzing the samples are being established. The measured physical properties and solution composition will be used as input to an ion-speciation/mineral-solubility model to determine the solid phases in apparent equilibrium with the solution for a particular set of environmental conditions. A time series of samples will be taken under constant temperature/flow conditions to determine if the system is truly at equilibrium with respect to the calculated solid phases. Samples will also be taken for a variety of temperature/flow conditions to adequately represent potential field conditions.

Work has begun on testing the chemical integrity of the APTF. The system was run at 25°C and 50°C , without the sampling vessel in the loop, to determine if the components of the system will influence the fluid composition. The resultant solutions showed significant increases in concentration for calcium, copper, iron, magnesium, and zinc. Sources of these contaminants are being investigated.

3.3.4 Task 4. Injectivity Studies

Construction of the Field Injectivity Test Stand (FITS) was completed in August and was shipped to the Minnesota FTF in November. The FITS has been installed at the Minnesota Site A well and use of the FITS to monitor injection/withdrawal fluids is scheduled to begin in April 1982. Tests to be conducted include: 1) turbidity tests, which

indicate if particulate migration occurs and at what flow rate, and will provide data on the extent of permeability reduction experienced if mobilization of fines does occur.

3.4 REFERENCES

Danesh, A., C. Ehlig-Economides and H. J. Ramey, Jr. 1979. "The Effect of Temperature Level on Absolute Permeability of Unconsolidated Silica and Stainless Steel." Geothermal Resources Council Transaction. Vol. 2, July 1978.

Muhammadu, A. 1976. "The Effects and Pressure on Absolute Permeability of Sandstones." PhD dissertation, Stanford University.

Weinbrandt, R. M., H. J. Ramey, Jr., and F. J. Casse. 1975. "The Effect of Temperature on Relative and Absolute Permeability of Sandstones." Society of Petroleum Engineers 4142.

4.0 FIELD TEST FACILITIES

J. R. Raymond and D. A. Myers

Pacific Northwest Laboratory

4.1 OBJECTIVE

The objective of the field test facility is to obtain engineering design data and to conduct supporting research for solving ATEs technical problems.

Two field test facilities have been selected and are being implemented. Research includes the injection/storage/recovery of thermally enhanced water and the monitoring of thermal plume development during test cycles. The planned research program will provide data to test the validity of numerical analysis methods and a means of developing optimal thermal recovery systems and methods.

Parallel experiments on injectivity are planned for both the Mobile, Alabama and St. Paul, Minnesota sites. The experiments will assess the long-term effects of heat injection on the ground-water systems.

Some work was also performed at the Stony Brook, New York demonstration project site.

4.2 MOBILE FIELD TEST FACILITY (F. J. Molz, Auburn University)

Auburn University's Mobile, Alabama test site has been selected for low-temperature heat storage activities. Mobile FTF activities are centered around injection/storage/recovery of water in the 55 to 90°C range.

4.2.1 Tasks

Work at the Mobile FTF during this reporting period comprised four 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 numerical modeling.
- Task 3 - Inject, store, and recover ground water over three cycles at temperatures of 55°C and 90°C, respectively.
- Task 4 - Monitor the movement of the thermal plume and supply data for computer analysis.

4.2.2 Technical Progress

Tasks 1 and 2 have been completed. The well field was altered to provide for a true doublet test. Observation and monitoring wells were placed so as to allow careful determination of thermal plume migration within the aquifer. In addition, thermal monitoring was made possible by installing thermistors within the upper and lower confining beds. Aquifer characterization was carried out during the previous reporting period. During the 55°C injection test, a tracer (NaBr) was added to the injected water. This tracer was then monitored to ascertain the dispersivity of the storage aquifer. Analysis of the tracer data showed a dispersion coefficient of 0.1 meters. Completion of this calculation marked the fulfillment of aquifer characterization.

Attention at the Mobile site has been directed toward the successful injection, storage and recovery of thermally-enhanced ground water. An initial injection cycle of 58°C water was started in February 1981. The injection rate was held to 45 m³/hr (200 gpm). Difficulties with the boiler system forced early termination of this injection after only 26 x 10³ m³ (6.87 x 10⁶ gallons). Injection occurred over a period of 756 hours. Temperatures were monitored within the aquifer for a corresponding time and then recovery was initiated. Figure 4.1 illustrates the temperature decrease in the recovery well as the experiment retrieved an equal volume of water. Energy recovery on this shortened test amounted to 55.3%.

During this experiment the alteration to the well field, fully penetrating wells within the same aquifer, eliminated clogging problems experienced in earlier experiments. At no time was filtration of the

FIGURE 4.1. Water Recovery Temperature

water, or backflushing of the injection well necessary. Injection pressures maximized at 3 psi as opposed to 21 psi in the previous configuration.

Boiler repairs were carried out during the storage period allowing the second cycle (90°) experiment to proceed on schedule. Initial injection rate of this second cycle was 45 m³/hr (200 gpm) but recurrent overtaxing of the heater system required that the flow rate be reduced to about 23 m³/hr (100 gpm). Injector temperature averaged 82°C. Total injection volume was 58 x 10³ m³ (15 x 10⁶ gallons). Storage was continued for a period of 34 days. Recovery was carried out at 200 gpm for 329 hours. Recovery efficiency during this cycle was less than expected, with initial temperatures of only 56°C. Thermistery data from all monitoring wells showed the influence of convective flow (Figure 4.2). The experiment was stopped and the recovery well modified to reduce its percentage penetration to 50%, and the experiment restarted. Recovery temperature rose 2.5°C but then decreased along the same slope

FIGURE 4.2. Temperature Distribution at End of Storage Period

as before modification (Figure 4.1). Final recovery efficiency after pumping an equal volume was 45.2%. Plots of isotherms within the aquifer following recovery, Figure 4.3, show significant energy remaining in the system.

Efforts to increase the recovery efficiency and quality of energy recovered are underway at this writing. Experience with the latest well modification shows that well penetration percentage, by itself, makes little difference in the final recovery efficiency. At distances greater than about two aquifer thicknesses from a partially penetrating well, flow is essentially radial; as the pumping well is approached, flow lines bend and intersect the pumping well. This radial flow at distance combined with bending near the pumping well results in cool water making up a significant proportion of the total flow. If these effects can be reduced or eliminated, then thermal efficiency will be increased.

The third cycle of the experiment has been altered to take this into account. Injection temperature will be held to approximately 80°C. Another well is being placed close to the current injection/recovery

FIGURE 4.3. Temperature Distribution at End of Recovery Period

well. This additional well will be completed over the lower 50% of the aquifer. The existing well will be further modified to reduce its penetration to about the upper 40% of the aquifer. Pumping rates from both wells will be adjusted to maintain the greatest thermal recovery possible.

4.3 ST. PAUL FIELD TEST FACILITY (W. E. Soderberg and J. C. O'Gara, University of Minnesota)

The University of Minnesota's St. Paul Campus, site of the FY 1980-81 demonstration program, was selected as a high-temperature field test facility (FTF). Following experiments at 100°, 125° and 150°C required for completion of the Aquifer Characterization Report, the site is being converted to an FTF. This site will provide the data necessary to evaluate the feasibility of high-temperature storage.

4.3.1 Tasks

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

- Task 1 - well construction

- Task 2 - surface system construction
- Task 3 - aquifer characterization and modeling
- Task 4 - water chemistry and laboratory studies
- Task 5 - petrological analysis
- Task 6 - environmental assessment.

4.3.2 Technical Progress

4.3.2.1 Task 1. Well Construction

By the end of this reporting period, 10 wells had been completed. Their locations and types (production, monitoring, core boring) are shown in Figure 4.4.

4.3.2.2 Task 2. Surface System Construction

Surface system construction and installation contracts were awarded on January 23, 1981. The above-ground equipment installation (including line-shaft turbine pumps in wells A and B) was completed during November 1981. Initial cold water startup test of the system was made on December 9, 1981 and the system long-term continuous flow test was completed on March 1, 1982.

Site cleanup and restoration was started in November 1981. Site restoration will be completed as weather permits in Spring 1982.

4.3.2.3 Task 3. Aquifer Characterization and Modeling

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

The computer program used for the anisotropy analysis was the three-dimensional finite difference model by Pinder and others (1973), previously used to investigate the study area's isothermal-flow system.

The technique used to examine formation anisotropy was to double the vertical-flow rates for individual formations and compare resulting model-calculated heads to known heads in each formation.

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 4.4. Location of St. Paul FTF Test and Monitor Wells

The Eau Claire, lower Franconia, and St. Lawrence formations were found to be the most sensitive to changes in anisotropy. Of these, the formation most sensitive to changes in anisotropy is the Eau Claire. Changes in this formation affect the computed heads in all other formations from 0.5 to 3.25 ft.

These sensitivities are representative of model results for a system with vertical flow only, and are expected to be less in formations with known horizontal flow. The sensitivities do indicate those formations where errors in anisotropy may affect model results.

The nonisothermal radial-flow model was used to examine the maximum injection rate based on the aquifer's potential for hydrofracturing. The hydrofracture pressure range is calculated to be approximately one-half the lithostatic pressure, or between 400 and 415 psi for the Franconia-Ironton-Galesville aquifer. Using 415 psi as the maximum allowable pressure, a maximum injection rate of 660 gpm was calculated by the model. The maximum pressure was first attained by the Galesville formation. This is because it has an original higher hydrostatic pressure in the wellbore due to its depth.

Laboratory work by Somerton (1976) and Peterson (1981) indicates that increasing temperatures can reduce the permeability of sandstone from 30 to 50%. A decrease in permeability will increase the pressure for a constant rate of injection. This is illustrated in Figure 4.5 for a simulation with two-thirds the base permeability. The maximum pressure increases to approximately 465 psi. For both plots, the maximum pressure increase due to injection is attained within the first minutes of pumping, but as injection continues, the pressure decreases. This is basically because viscosity is a function of temperature. As the temperature increases the fluid viscosity decreases, effectively increasing the hydraulic conductivity of the aquifer, resulting in a pressure drop.

The two plots shown in Figure 4.5 can be used only to examine the range of expected pressure changes. The model used does not treat permeability as a function of temperature. The two-thirds decrease in permeability plot assumes that the decrease in permeability due to

FIGURE 4.5. Pressure Change with Time for Values of Base Permeability and Two-Thirds the Base Permeability and a Constant Injection Rate of 660 gpm

temperature increase is a corresponding event and not a function of time. It is possible that the reported decrease in permeability effect may be offset by the decrease in fluid viscosity and the resulting overall effect on pressure will be less. The plots also show that a variable injection rate may be necessary to obtain a maximum injection rate.

The production well at Site B was developed by the pump and surge method for approximately 10 hours. The maximum rate pumped during well development was 850 gal/min for approximately 4.75 hours; maximum drawdown was measured as approximately 409 ft below land surface. The well recovered for approximately 12 hours and measured water levels were within 0.2 ft of predevelopment levels. This was considered sufficient recovery to conduct a step-drawdown test. Duration of pumping and pumping rate were 220 gpm for 258 minutes, 380 gpm for 217 minutes, and 735 gpm for 190 minutes.

Two methods were used to analyze the drawdown data, a graphical method and an optimization technique. Comparison of the drawdown values formulated from the two methods shows very close agreement except for head loss due to turbulent flow near the well. At low pumping rates, these losses are negligible. The drawdowns computed by the two methods for various pumping rates are shown in Table 4.1.

Rorabaugh (1953) defined "well efficiency" as the ratio of the theoretical drawdown computed by assuming that no turbulence is present to the measured drawdown. Figure 4.6 shows the "well efficiency" curve for production well B at various theoretical pumping rates. The curve indicates well efficiencies of near 90% and greater for pumping rates of 600 gpm and less. The 300-gpm well efficiency is calculated to be 98%; the 600-gpm efficiency is calculated to be 89%. The well efficiency drops off steeply after 600 gpm. Bierscherk (1963) calculated similar effects for 34 wells in Iran and attributes the steep decline to an increase in turbulent flow around the well due to increased pumping rates. For well B, losses due to turbulent flow near the well are expected to be negligible due to the low pumping rates.

Using the methods described by Harrill (1970), an approximation of transmissivity from the recovery of the step-drawdown test on well B was calculated at 1179 ft² per day.

The completed well at Site A was developed for approximately 8 hours using the pump and surge method. The maximum rate pumped during development was approximately 900 gpm for 3.0 hours. The well recovered for approximately 18 hours and was within 0.3 ft of predevelopment water levels. This was considered sufficient recovery to conduct a step-drawdown test. Duration of step-drawdown test pumping and pumping rate were 182 minutes at 267 gpm, 164 minutes at 480 gpm, 104 minutes at 584 gpm, and 133 minutes at approximately 1000 gpm.

The two methods used to analyze the drawdown data are similar to those used for well B, a graphical method described by Rorabaugh (1953) and an optimization technique described by Labadie and Helweg (1975).

TABLE 4.1. Drawdown in St. Paul Well B for Various Discharge Rates

Discharge Rate gpm	Drawdown (feet)	
	Graphical	Optimization
100	24.13	23.92
200	49.50	48.09
300	76.13	73.03
400	104.00	99.44
500	133.13	128.27
600	163.50	160.58

FIGURE 4.6. Well Efficiency for St. Paul Production Well B

Drawdowns computed for various pumping rates are shown in Table 4.2. Comparison of computed drawdowns shows close agreement at low pumping rates and a gradual divergence at higher rates. This same trend was computed for results of well B data and is generally related to the turbulent head loss part of the overall drawdown equations.

Figure 4.7 shows the well efficiency curve for well A as calculated by the same procedure as used for the well B test. The curve indicates an efficiency of approximately 80% for a pumping rate of 300 gpm and 60% for a pumping rate of 600 gpm. These values are less than those computed for the ATEs well B where corresponding efficiencies were calculated to be 90 and 89%, respectively.

The lower efficiencies computed for well A could be due to poor well development, as less time was spent developing well A compared to well B, and may improve with testing. Regardless, total drawdowns computed for both wells A and B are close and well efficiency of 80% is not expected to hinder either withdrawal or injection during testing.

The lack of reliable pumping rate data during the fourth step made calculation of the transmissivity by Harrill's method (1970) similar to well B analysis impossible. Instead, an approximation of the transmissivity was obtained using specific capacity data computed from the first step. A specific capacity of 4.49 gpm/ft was calculated after one hour of pumping. This value was used with curves from Walton (1970) to obtain a transmissivity of 1050 ft²/day. This value is in close agreement with the 1180 ft²/day calculated for well B.

Data from the step-drawdown tests conducted at wells A and B were used for preliminary calibration of the nonisothermal radial-flow model. Although water-level measurements for the step-drawdown tests are available for the monitoring wells near each production well, depth and distance calculations of the wells are not yet complete. This information will be available and used for the long-term continuous rate aquifer test and subsequent model calibration.

Previous estimates of transmissivity within the Franconia-Ironton-Galesville (FIT) aquifer were 300 to 350 ft²/day. Analysis of step-

TABLE 4.2. Drawdown in St. Paul Well A for Various Discharge Rates

Discharge Rate gpm	Drawdown (feet)	
	Graphical	Optimization
100	18.55	19.70
200	41.59	42.47
300	69.14	69.31
400	101.19	100.90
500	137.73	137.79
600	178.77	180.45
800	274.35	284.68
1000	387.92	416.44
1200	519.49	578.17

FIGURE 4.7. Well Efficiency for St. Paul Production Well A

drawdown data indicates a transmissivity approximately three times this value.

The well B simulation indicates very close agreement between actual field data and model-simulated drawdowns for low pumping rates and a greater divergence at higher pumping rates. This is to be expected because the model simulates drawdowns assuming the well is 100% efficient and drawdown is due only to aquifer characteristics while the actual field data is reflecting head loss due to aquifer characteristics and actual well completion.

The difference between model-simulated and field drawdowns can easily be accounted for with head loss due to well completion. Positive head change at low pumping rates indicates that a slightly higher value of transmissivity may be necessary for final model calibration.

The difference between model-computed and field drawdown and head loss due to well completion for well A is similar to that of well B. Head loss due to well completion easily accounts for differences in model-simulated and field drawdowns.

It should be noted that observation wells near wells A and B will be used for final radial flow-model calibration. Problems with using pumping well water-level measurements are obvious from the previous discussion. The pumping well information is extremely helpful in narrowing the range of aquifer transmissivity; from preliminary model calibration transmissivity values between 950 and 1000 ft²/day are very close to those of the FIG aquifer.

A continuous rate aquifer test was performed at Site A. The well was pumped at an average rate of 340 gpm for approximately 4.5 days. Drawdown measurements were taken in all observation wells located at Sites A, B, and C. Figure 4.8 illustrates drawdown in terms of pressure for observation points in the upper Franconia, lower Franconia, and Iron-ton-Galesville formations for observation well AM2.

Drawdown data were analyzed for transmissivity and storage coefficient using the curve matching methods described by Lohman (1972).

FIGURE 4.8. Drawdown for Observation Points in Well AM2

Because the well does not have continuous screen and the lower Franconia acts as a confining layer, the test data were treated similar to a multiaquifer well. Relative hydraulic conductivity values for the upper Franconia and Ironton-Galesville formations were used to proportion the pumping from the screened intervals within the aquifer. A total transmissivity of $1,090 \text{ ft}^2/\text{day}$ and a storage coefficient of 2.55×10^{-5} is calculated of the upper Franconia and Ironton-Galesville aquifer.

4.3.2.4 Task 4. Water Chemistry and Laboratory Studies

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

Ground water from an array of monitor wells is being collected and analyzed. Characterizing the water chemistry before heat injection will help predict the extent of carbonate precipitation and also will establish baseline water quality values for comparison with samples collected after heat injection.

The rates of precipitation and dissolution are crucial to chemical predictions. Experiments using aquifer rocks are being carried out over the temperature range of 25° to 150°C. The experiments also give a rough estimate of precipitation kinetics, which will be used to predict dissolution rates in the aquifer during hot water storage. Dissolution rates are expected to be proportional to surface area.

A reliable method for collecting water samples from deep wells was developed. Samples were taken from ATEs monitoring wells and analyzed. High pH and silica concentrations in certain wells suggest grout contamination. Thorough flushing of these wells is planned.

The rates of dissolution of representative aquifer rocks at temperatures from 45° to 150°C have been measured. Because dissolution rates are proportional to interfacial area, measurement of specific surface areas of ground rocks used in dissolution experiments and natural aquifer rocks permits extrapolation of experimental results to in situ conditions. Dissolution experiments involving glauconite- and dolomite-containing rocks from a relatively impermeable part of the Franconia aquifer are in progress and calculations of silica precipitation rates are planned.

Chemical equilibrium computations suggest that the maximum precipitation of calcium and magnesium carbonates and silicates occurs between 75° and 125°C. Silica and aluminum concentrations approach 10 mM and 0.1 mM, respectively, at high temperatures. Because these concentrations are orders of magnitude greater than saturation at 10°C, precipitation of amorphous silica and aluminum hydroxide can be expected after heat recovery and reinjection of ground water. Computations involving recent analytical results and inclusion of iron and manganese in computations are planned.

Water samples were taken from production wells A and B, and monitoring wells AM1 and AS1, to isolate and enumerate coliform and aerobic and facultative anaerobic heterotrophic bacteria in water.

Coliform organisms were isolated in water samples from wells A and B. While this could indicate contamination of the aquifer, it is more likely due to contamination of the casing and distribution system, which could not be disinfected. Further testing should clarify this situation.

A low concentration of all bacteria was present in AS1, probably due to the high pH of the water ($\text{pH} > 11$). Additional pumping of water from this monitor well has reduced the pH to 8.5.

4.3.2.5 Task 5. Petrological Analysis

Detailed core descriptions were completed. Correlation of lithologic units and natural gamma logs between cores AC1 and BC1 is remarkably consistent (Figure 4.9).

Gamma logs for CM1 and well B indicate the same consistent sequence of beds in the confining beds and the aquifer. Because of equipment problems, no gamma log was obtained for well A prior to pump installation. Observations made during visual inspection of both wells A and B using a downhole television system are consistent with observations made previously in hole AC1.

Seventy-five thin sections were prepared. Nearly all samples had to be impregnated with epoxy prior to sectioning. Slabs of core for use as a megascopic reference for many of the same intervals were cut as these samples were prepared.

Point counts on 19 thin sections, 16 from the FIG aquifer, were made. Each count included between 200 and 800 mineral points equally spaced along parallel paths approximately perpendicular to bedding (that is, parallel to the length of the core). A sodium cobaltinitrite solution was used to stain potassium feldspars, orthoclase and microcline, on the slides counted.

FIGURE 4.9. Summary of Lithologies and Hydrologic Zones of the Franconia-Ironton-Galesville Aquifer and Confining Beds, St. Paul Field Test Facility

St. Lawrence Formation. Lithologies of the St. Lawrence formation in the cores include laminated mudstone, silty and sandy dolomites, dolomitic siltstones and intraclastic conglomerates. Porosity in the samples of mudstone consists of very small intergranular spaces, similar to that of the silty dolomite. Significant portions of the dolomite in the sample are present as pore fillings, replacing quartz and feldspar, and in patchy burrow fillings of dolomitic mud. The porosity of 0.1% for the silty dolomite is probably as high as is present in the St. Lawrence formation, except for the very spectacular intraclastic conglomerate near the top of the AC1 core, which has a high vuggy porosity.

Franconia Formation. The Franconia formation consists of four principal lithologies: 1) fine glauconitic feldspathic sandstone and siltstone; 2) fine dolomitic feldspathic sandstone; 3) alternating thin beds of micaceous feldspathic siltstone and shale; and 4) sandy or silty dolomite and intraclastic conglomerate (Figure 4.9). All four members (Reno, Mazomanie, Tomah and Birkmose) previously recognized in the region are present in the core (Austin 1969). Each of the lithologies has a significant authigenic minerals content, including dolomite and potassium feldspar. Glauconite, which is typical of the unit, is not a far-traveled mineral.

Fine glauconitic feldspathic sandstones and siltstones typical of the Reno and Birkmose members have intergranular porosity. Because of the grain sizes, permeability is expected to be relatively low. The "mustard bed", which would be in this category, has a very low porosity value, probably resulting from the very high glauconite content, the alteration of it, and the material's lack of strength.

Fine dolomitic feldspathic sandstones which are typical of the Mazomanie member have intergranular and vuggy porosity. This lithology makes up much of the relatively permeable portion (hydrologic zone 2, Figure 4.9) of the Franconia formation. Glauconite is relatively sparse (<5%). Relatively little silt-sized material is present in this unit. Cementation is variable; both friable and well-indurated beds are present.

The alternating thin micaceous feldspathic siltstone and shale beds of the Tomah member have cracks and vugs as principal effective porosity. Most cracks are subvertical, most vugs are less than 0.5 cm in diameter, and all cracks and vugs are restricted to the siltstones. Permeability is expected to be low.

The dolomites, which are most common in the Birkmose member but present in all members, exhibit a wide range of porosity whether sandy, silty, and/or intraclastic. Thin sections of dolomites were made from only relatively low porosity beds. Pores are principally vugs, cracks and solution cavities.

Ironton-Galesville Formations. The Ironton and Galesville formations consist of medium-, coarse- and fine-quartzose sandstones, with fine feldspathic sandstone, and thin interbeds of shale. Many of these units are friable. Intergranular porosity as measured in thin sections ranges from about 14 to about 27%. It is certain that porosities of uncemented intervals with no core recovery are even higher. Permeability of the Ironton and Galesville formations is relatively high. An important accessory mineral in the Ironton and Galesville formations, often as a partial cement, is pyrite.

Eau Claire Formation. The Eau Claire formation exhibits a variety of relatively fine-grained lithologies: 1) silty feldspathic sandstone, 2) feldspathic siltstone, 3) silty mudstone, and 4) shale. Any of these lithologies are highly fossiliferous in particular beds. The formation also has highly glauconitic beds. Porosities measured thus far of silty sandstones are 10 to 15%. From megascopic examination of the core, the values are expected to be highly variable. Grain sizes of the units of the Eau Claire make it likely that permeability is very low, especially across the bedding (vertically).

4.3.2.6 Task 6. Environmental Assessment

During the reporting period, work was performed on the following tasks:

- Task 1 - environmental reporting

- Task 2 - environmental quality assurance
- Task 3 - environmental assessment and monitoring.

4.3.2.6.1 Environmental Reporting. Two major reports were published jointly in March 1981. The Phase I - Preliminary Environmental Assessment and the Phase I - Environmental and Institutional Monitoring Plan addressed three major issues: 1) nature and scope of project, 2) environmental assessment and monitoring, and 3) institutional plan.

Typical environmental concerns were investigated in Phase I Preliminary Environmental Assessment. Such concerns include:

- aquifer and ground water impacts
- biological impacts
- well impacts
- air quality impacts
- energy impacts
- solid waste impacts
- noise impacts
- surface water impacts
- employment impacts
- transportation impacts
- community charter impacts
- land use impacts
- historical resources, health services and educational services.

A preliminary assessment of probable impacts was given for each of the above issues. Phase 2 of the project was also assessed briefly for probable environmental impacts.

4.3.2.6.2 Environmental Quality Assurance. The principal objective of environmental quality assurance is to ensure the accuracy and reliability of water chemistry, microbiology and thermal monitoring data for the ATES Project. In this regard, plans and reports were reviewed pertaining to:

- site and record control
- aquifer characterization report

- regulatory assessments (including state agency permits)
- microbiological monitoring
- water quality monitoring (field and laboratory)
- legal assessments
- community relations
- system operation and maintenance
- institutional assessments.

4.3.2.6.3 Environmental Assessment and Monitoring. Environmental information, particularly water quality and microbiological data, were reviewed and evaluated. These data form the basis of the project environmental assessment. They may also have significant environmental implications for future ATES type activities.

Water chemistry data from monitoring wells on the ATES site have been collected and reviewed. Laboratory data pertaining to mineral solubilities were also reviewed. Silicates showed increased solubility at high temperatures while carbonate solubility was reduced by elevated temperature. Those facts will bear upon possible rock dissolution and upon possible aquifer plugging. Further field and laboratory testing will determine the extent of such reactions.

Environmental site monitoring was performed during construction and drilling operations. Continued site monitoring will be undertaken as significant progress is made on the project.

4.4 STONY BROOK DEMONSTRATION PROJECT (W. V. Skinner, Dames & Moore, Inc.)

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

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

4.4.1 Chilled Water Injection Test

The limited nonisothermal chilled water injection test, started in January 1982, was completed in July 1982. The test utilized an existing 12-in. well near, and a 150-ton chiller in, the Engineering Heavy Laboratory. A new 6-in. well was installed 280 ft from the 12-in. well and screened at the same depth range as the existing 12-in. well. Nine specially constructed observation wells were strategically positioned about the doublet wells to provide for temperature and water level measurements. After installation, baseline temperature and water level measurements were obtained. Following this, a 48-hour pumping test was performed to determine the aquifer characteristics. A doublet test was then performed.

The doublet test consisted of three parts. During the first, 51°F ground water was pumped at a rate of 300 gpm from the newly installed 6-in. well and piped to the 150-ton mechanical chiller located in the Heavy Engineering Laboratory. The water temperature was reduced to 41.3°F and the water was then injected into the 12-in. well via the pump column pipe. The injection period continued for 42 days, during which 18.2 million gallons of chilled water were injected. Aquifer response was tracked by means of the observation wells. Pumping rates and pumped water temperature were monitored with flow meters and temperature recorders. After injection, the chilled water was stored for 72 days to determine the effect of the natural hydraulic gradient on chill plume migration and to measure the other thermal losses. During the storage period, the temperature of the center of the chill storage zone increased by less than 0.5°F.

The recovery of chilled water was accomplished by pumping the 12-in. well (into which the chilled water had previously injected) and returning this recovered water to the aquifer through the 6-in. well. The temperature and volume of the recovered chill water were monitored, as they were during the first portion of the test. The chilled water was pumped from the recovery well at 300 gpm, but the reinjection well would not accept the water at this rate due to plugging early in the reinjection cycle from some unknown cause. During the initial part of the recovery period the production water gradually and uniformly increased in temperature. Toward the end of the recovery period the production water temperature began to asymptotically approach the aquifer ambient temperature.

An analysis of energy recovery was made for the chill injection test. The analysis was based on the temperature versus time relationship of the water recovered while pumping a volume of water equal to the volume injected. Temperature measurements in observation wells at the end of the recovery period indicate that, in comparison with baseline measurements, only a relatively small amount of residual chill remained in the aquifer. In evaluating the efficiency of recovery, two approaches were taken: 1) to compare the total chill energy recovered with the total chill energy injected and 2) to compare the usable chill energy recovered with the total chill energy injected. The first value is a measure of general aquifer efficiency of storage and recovery. The second value is germane to applications in air conditioning where there is an upper temperature limit (the cutoff temperature) for the cooling water that can be used in air conditioning systems. Consequently, the efficiency of recovery is based upon the percentage of chill recovered at or below the cutoff temperature.

At the doublet test site, the chill energy recovery in terms of total injected chill energy was approximately 60%. Using a 3°F cutoff temperature rise, the chill energy recovery was approximately 30%. These figures are based upon a 3°F "round trip" heat gain in transmission through the chill injection/recovery system that was apparent from temperatures observed at the surface and in the monitoring

wells. Numerical simulation of recovery, in which the ground water flow was normalized (by the addition of wells and pumps designed to extract ground water upgradient and inject water downgradient) indicates that the total efficiency could be increased to more than 80%.

4.4.2 Aquifer Characterization

On March 24, 1981, because of the funding rescission, PNL directed Dames & Moore to suspend all work on the Stony Brook ATEs Demonstration Project that was not directly associated with aquifer characterization. The suspension caused deferral of all milestones except completion of aquifer characterization. This milestone was completed in September 1981 with issuance of the Comprehensive Aquifer Characterization Report.

All geohydrologic data collected during the last reporting period from drilling, sampling and testing of the nine monitoring/test wells and injection/production wells were evaluated for the report.

Three aquifers occur in the area: the Lloyd sand member of the Raritan formation; the Magothy aquifer, and the Upper Glacial aquifer (in ascending order), consisting of the saturated portion of the undifferentiated glacially derived sediments.

The occurrence and movement of ground water within the geological regime is the result of a hydrologic balance between rainfall on the island and discharge through the sediments to the surrounding bodies of water. The natural temperature of ground water at any specific point within this system is generally near the mean annual air temperature in the area but increases slightly in the direction of flow as a result of the normal geothermal gradient. Consequently, variations in ground-water temperature from the mean value generally result from variations in ground-water flow rate and distances from the recharge zones.

Stony Brook lies approximately 1.5 miles north of the ground-water divide. Because the deeper aquifer sediments do not surface (outcrop) on the island, and the island is surrounded by seawater, the only fresh water source in the deeper aquifers is recharge from overlying aquifers.

Ground-water flow is downward in the central portion of the island, becomes horizontal between the island center and perimeters, and is upward in discharge zones near the shore and under adjacent bodies of water. An analysis of water levels in piezometers screened in different depths at the Stony Brook campus indicates ground-water flow in this area has a downward component. Consequently, ground water is flowing from the Upper Glacial aquifer to the underlying upper Magothy aquifer. The sedimentary environment in which the Upper Magothy aquifer was formed resulted in discontinuous, variable thickness, thinly bedded sediments. Consequently, although a specific bed may be found at one location, it may not be present a few hundred feet distant.

An idealized condition for aquifer storage requires confining layers or beds above and below the storage zone. Although Stony Brook does not have well defined confining layers, the results of the doublet test indicate that the injected chilled water was probably confined, not by continuous individual confining layers, but rather by thinly bedded, less permeable horizontal laminae, which occur throughout the formation, and which may be more prevalent and/or continuous in specific zones. Generally, the zones of more prevalent interbedded less permeable clayey silts/laminae are less than 3 ft thick, with many zones less than 1 ft thick. At the test site no correlation could be made between zone thickness and lateral continuity. Individual zones are composed of an alternating thinly bedded (often less than 1/4 in.) sequence of fine to coarse sand with relatively minor silt, and silt to silty clay with relatively minor sand. These individual layers of silt or sand can vary laterally. Vertical permeability or hydraulic conductivity was therefore simply a function of the abundance of clayey fractions and the areal extent of the zone of increased clay content.

Because there are no well defined confining zones in the aquifer flow system beneath Stony Brook, the hydraulic conductivity (a measure of the ease with which water can flow through a porous medium) through the individual laminae is less significant than is the cumulative effect of zones of laminae in confining injected chilled water. The nature of the sedimentation results in the aquifer being highly anisotropic; that

is, the aquifer is less permeable perpendicular to structure than along bedding. At the Stony Brook test site the average horizontal hydraulic conductivity appears to be on the order of 100 times the vertical hydraulic conductivity. Low vertical hydraulic conductivity was detected (on the basis of a limited number of laboratory tests) both within the aquifer chill storage zone and within the zones above and below the chill storage zone, which were nominally designated as "confining layers". Because of the stratified nature of the sediments within the chill storage zone and within the "confining zones" of the Magothy formation, the vertical hydraulic conductivity of small test samples (6-in. long cores) are expected to vary from location to location and with depth within a particular boring. Although there are insufficient data to define the average vertical hydraulic conductivity in the chill storage zone and in the "confining zones", it is speculated that, on the average, they are similar.

The hydraulic characteristics for the portion of the aquifer used in the test area were defined early in the investigation. Baseline conditions were established for both hydraulic and thermal conditions. A 48-hour pumping test was performed during which the aquifer hydraulic characteristics were determined from data obtained in the nine observation wells. The thermal and hydraulic data were consistent and reasonable in consideration of the geological environment. The rate at which ground water would flow through the aquifer per foot of vertical section with a gradient of one foot of differential head per foot of length (transmissivity) was found to range from 4700 to 9900 ft^2 per day. The variation in transmissivity occurred laterally from well to well and with the type of analytical method used. The Hantush-Jacob method for steady-state flow, which considered artesian leakage, gave the base computer simulation match to the field data. Modeling of the doublet test used the transmissivity value of 4700 rounded off to 5000 ft^2/day for the entire test site. Other data, water levels, and the temperature at 325 ft suggest a narrow zone of relatively high transmissivity within the test area. These results are not inconsistent with the depositional environment in which the aquifer developed, i.e.,

stream channels, over-bank sediments, swampy conditions, all of which suggest that variable hydraulic conductivity, both vertically and horizontally, is to be expected.

Natural ground-water flow rates and directions are very important in an ATEs system, because a relatively high velocity will cause stored chilled water to drift excessively. The aquifer permeability, based upon a uniform aquifer thickness of 55 ft used in the numerical simulation and a transmissivity of 5000 ft²/day, was about 91 ft/day. With an average hydraulic gradient of 0.00334, the average Darcy velocity was estimated to be 0.30 ft/day. With an effective porosity of 0.25, the approach velocity (also called average pore velocity) was estimated to be 1.2 ft/day. The velocity of the chill plume movement during the chill storage period was estimated to be about 0.6 ft/day.

Several relatively undisturbed core samples were obtained for laboratory study to measure porosity, permeability (vertical), heat capacity and thermal conductivity of the sediments. A laboratory porosity of approximately 35% was found to be consistent in all samples tested, including the more and less clayey portions of the aquifer. The heat capacity was found to be approximately 0.65 cal/cc/°C. This was in the expected range because the heat capacity of saturated sediments does not usually vary appreciably. The average thermal conductivity, as determined in both the laboratory and in the field, was found to be 7×10^{-3} cal./°C/cm. This parameter also does not vary appreciably for various saturated sediments.

Baseline temperature measurements revealed an unusual reverse thermal gradient in the upper 400 ft of sediments at Stony Brook. This may have been caused by the injection of warm water discharged from air conditioning systems previously used on campus. It is suspected that some of the extraneous heat may have been contributed by unknown leaks in the high temperature (350°F) hot water main. In a natural environment, ground water generally becomes warmer with depth because of the upward heat flow from the interior of the earth. At Stony Brook the

temperature was found to decrease with depth, at least to about 400 ft, which was the maximum depth of the observation wells at the Stony Brook test site.

A computer numerical model (GREASE-2) of the Upper Magothy at Stony Brook was prepared to permit simulation of aquifer response to thermal energy storage. The model was first checked by comparisons with available analytical solutions. Initial simulations of the doublet test were performed using regional data to predict aquifer response. Generally, these results were consistent with the observed aquifer response. The numerical model was then calibrated with isothermal pumping test data and verified with nonisothermal doublet test data such that simulations more closely matched the observed performance. This model could then be used to predict aquifer performance and recovery efficiency in the Magothy aquifer at the Stony Brook site for various conceptual designs with some reasonable level of confidence.

Based upon the result of the field test, the model studies, and other available information, most portions of the Magothy aquifer under the Stony Brook campus can be considered for an ATEs storage zone. Final selection of storage zone limits would have to be established on the basis of results from pilot borings, however. For the feasibility test, the storage zone was selected on the basis of the screen interval in an existing well. Subsequent drilling of ten test borings (converted to nine monitoring wells and one pumping/injection well) at the test site indicated that, although this portion of the Magothy aquifer does contain relatively few clayey zones, the overall gross character of this portion does not differ appreciably from other portions of the Magothy formation.

4.4.3 Cost Estimate for Aquifer Thermal Energy Storage Alternatives

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

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

- A small-scale demonstration on one or a few buildings (Heavy Laboratory and Computer Science building), which would use a small cooling tower, such as the Earth and Space Science Building Cooling Tower, and the existing aquifer doublet field (installed as part of the completed aquifer characterization studies).
- A full-scale demonstration using the original concept with the Marley cooling tower and the complete campus distribution system.

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

Application of ATES for air conditioning of the Stony Brook West Campus is technically feasible. Although some difficulty was experienced with injection, it does not appear to be outside the scope of an engineering solution. Studies are tentatively planned to investigate and define better those factors that affect the performance of injection wells.

Results of the doublet test performed during the feasibility study indicate the most significant parameter affecting storage efficiency is drift of the stored chilled water caused by natural ground-water flow.

Because of energy transfer from pore-fluid (ground water) to formation media (sand), thermal drift is approximately one-half the ground-water drift. Final design of the well field based upon the computer simulation of "best performance" well position would also provide for normalization of hydraulic gradient to prevent thermal drift and thereby maximize efficiency. Generally, it appears reasonable to expect recovery efficiencies of over 80% for the Central Plant Option, and 50% for the Heavy Engineering Laboratory Option, where there would be an upper temperature limit of recovered chilled water.

4.4.3.1 Heavy Laboratory and Computer Science Buildings Option

Air conditioning needs (60 tons) for the Computer Science Building are currently met by chillers (now approaching the need for replacement) located within the building. Heat rejection is accomplished with well water discharging to recharge wells. This building is not connected to the Central Plant chilled water system. Air conditioning needs (100 tons) for the Engineering Heavy Laboratory are met by the Central Plant system.

The proposed design is an expansion and conversion of the chill energy storage experiment to a permanent 250-ton air conditioning facility. The design for this system is based on the results of the ATES experiment (aquifer doublet test) at the site. The 250 tons of cooling for the proposed ATES system incorporates, as major components, the unused Engineering Heavy Laboratory well and the cooling tower located near the Earth and Space Science Building. An additional well, heat exchanger piping mechanical equipment and controls would be added. Chilled water would be produced during winter months near the Earth and Space Science Building cooling tower. The proposed ATES system is designed for storage of 90 million gallons of chilled water using two wells approximately 450 ft apart and capable of transferring ground water at a rate of 600 gpm. This would provide for the required recovery of 56 million gallons of water at 43°F or lower.

A preliminary economic analysis for this option indicates a simple payback period of 7.7 years, based upon construction costs of \$656,000,

a \$40,000 credit for the existing chillers in Computer Science, and an annual energy savings of \$80,000.

4.4.3.2 Central Plant Option

Development of a conceptual design for a Central Plant ATES system on the Stony Brook campus was the original objective of the chill energy storage demonstration project. The preliminary conceptual design is based upon analyses of results of the ATES experiment at the site and the results of the evaluation of the existing facilities.

Current design needs for the 21 buildings now served by the central chilled water plant total 15,888 tons. Current capacity of the central plant chillers is 9000 tons. Thermal transport capacity is restricted by the approximately 11,000 gpm maximum flow rate through the chiller evaporator with a 20°F entering and leaving differential temperature. Buildings were designed to operate at various differentials from 10° to 20°F during maximum load. The restriction through the evaporator results in insufficient flow through in the transport system on days of maximum demand upon the system.

The chilled water distribution network currently in use at SUNY would be utilized in the ATES system. Additional piping and appurtenances will be required, however, to connect the new well field with the existing chilled water in the winter distribution pipelines. The existing Marley cooling tower would be utilized in the winter to provide chilled water. A heat exchanger would separate the cooling tower circulating water from the ground water to protect the aquifer from possible sources of airborne contaminants. Although the peak ground-water transfer (from one set of wells to another) rate would be rather high (11,000 gpm), the system is "balanced" and no net withdrawal of water would occur. Because of this, well interference would be limited to the near vicinity of the ATES well field.

The existing mechanical chillers would be used in conjunction with cold water derived from the proposed ATES system. During periods of low demand for chilled water, the air conditioning system would operate solely on chill derived from the ATES system. During periods of peak chill demand (in excess of 10,000 tons) the air conditioning system will operate with the mechanical chillers and the ATES system producing chilled water in parallel. Because of this mode of operation, there is no effective cutoff temperature as there would be for the operation of the proposed ATES option for the Heavy Engineering Laboratory. The air conditioning system could, therefore, utilize any ATES chilled water that is available as long as it is cooler than the input to the mechanical chillers. Because of this freedom, which is not available in the ATES option for the Heavy Engineering Lab, the well field for this large-scale system can be designed on the basis of chilled water available from the cooling tower and not solely on the peak chill demand of the air conditioning system.

This ATES system is designed for storage of approximately one billion gallons of 41°F water. Final well field design would be based upon the results of computer simulations of well field alternatives using the GREASE-2 numerical model developed as part of the feasibility study. In the preliminary conceptual design used for this cost estimate, the well field comprises two rows, 2000 ft apart, of 12 large diameter wells spaced 60 ft apart. This would result in an area approximately 2000 x 1200 ft, or 55 acres. Estimated construction costs are \$9 million and annual energy savings are \$800,000.

Preliminary economic analysis of the Central Plant ATES system indicates that the estimated payback of 11 to 12 years is outside the generally acceptable range for consideration by SUNY. However, the operating advantages and indirect benefits should be considered in review of the economic analysis, as well as potential change in any cost comparison based upon current fuel price. Also, the capital and operating cost of an additional 450-ton chiller, which would be necessary to provide for current West Campus needs, should be considered in the cost-benefit evaluation.

4.4.4 Injection Well Plugging Study

Plans were made to investigate the reduction in production/reinjection well PI-2 injection capacity when stored, chilled water (from storage well PI-1) was reinjected during the nonisothermal chill storage test. This study was programmed to begin early in FY 1982, but funding and contractual problems have deferred start of the work until May 1982.

The investigation will involve remedial work on well PI-2 to attempt recovery of original injectivity capacity through well surging, overpumping and, if necessary, chemical treatments. During this work, produced water will be analyzed to attempt identification of the factors causing the problem. If injectivity capacity is improved, the short-term reinjection test (isothermal or chill) will be run for proof of principle.

4.5 REFERENCES

- Austin, G. S. 1969. Paleozoic Lithostratigraphic Nomenclature for Southeastern Minnesota. Minnesota Geological Survey Information Circular 6.
- Bierschenk, W. H. 1963. "Determining Well Efficiency by Multiple Step-Drawdown Tests." Inter. Assoc. Sci. Hydrol, No. 64, pp. 493-507. Berkeley, California.
- Harrill, J. R. 1970. Determining Transmissivity from Water Level Recovery of Step-Drawdown Tests. pp. c212-c213. U.S. Geol. Survey Prof. Paper 700-C.
- Hellstrom, G., C-F Tsang, and J. Claesson. 1979. Heat Storage in Aquifers. Buoyancy Flow and Thermal Stratification Problems. p. 70. Lund University, Sweden.
- Labadie, J. W., and O. J. Helweg. 1975. "Step-Drawdown Test Analysis by Computer." Ground Water. 13(5):438-444.
- Rorabaugh, M. I. 1953. "Graphical and Theoretical Analysis of Step-Drawdown Test of Artesian Well." In ASCE Proceedings. Hyd. Div. 79:362-1/362-23.

PART II.
SEASONAL THERMAL ENERGY STORAGE
Nonaquifer Thermal Energy Storage

This part describes the technical and economic assessments of nonaquifer thermal energy storage concepts. Findings regarding seven potential concepts are presented in Section 5.0. The economic assessment effort is documented in Section 6.0.

5.0 NONAQUIFER SEASONAL THERMAL ENERGY STORAGE

D. E. Blahník

Pacific Northwest Laboratory

5.1 OBJECTIVE

The objective of the nonaquifer STES task is to survey, evaluate, select, and develop potential nonaquifer thermal energy storage concepts for seasonal use.

5.2 TECHNICAL PROGRESS

The initial survey and evaluation of thermal energy storage concepts indicated that, in general, promising STES concepts are characterized by temperatures less than 95°C, low-cost storage media (water and rock), construction with earth, good insulation, imperviousness to leaks, and economies of large scale. The initially recommended concepts falling into that category included pond, lake, cavern, tank, earth, rock and ice thermal storage. Those seven concepts have received the most evaluation emphasis during the past year.

A formal assessment of the seven concepts was presented in papers at the Mechanical, Magnetic and Underground Energy Storage 1981 Annual Contractors' Review in August 1981, and at the Seasonal Thermal Energy Storage and Compressed Air Energy Storage International Conference in October 1981.

Except for ice storage, these concepts are all based upon use of sensible heat. Other latent heat concepts and thermochemical concepts were found to be relatively undeveloped and high in cost for seasonal storage. Currently the only thermochemical concept that might be considered is the sulphuric acid/water chemical heat pump. The other latent heat concept that might be considered uses low-cost salt hydrates such as Glauber's salt.

5.2.1 Technology Assessment

Table 5.1 summarizes the relative state of the seven concept technologies. Tank is excellent and pond and ice are good. Cavern and

TABLE 5.1. Nonaquifer STES Concept Technology Assessment

<u>Concept</u>	<u>Relative State of Technology</u>	<u>Development Needs</u>
Pond	Good	Liner and insulation
Lake	Poor	Insulation/liner system and environmental effects
Cavern	Fair	Lining and insulation methods, chemical and thermal cycling effects
Tank	Excellent	Tank and insulation cost reduction
Earth	Fair/Good	In situ heat exchange and insulation methods
Rock BH	Fair	Drilling cost reduction and lining methods
Ice	Good	Improve production and harvesting methods, low cost insulation and heat exchange

rock borehole (BH) are fair, and earth is fair-to-good. Although lake technology is poor, it could be accelerated and implemented very rapidly.

Most of the concepts need development improvements in lining and insulation systems above 65°C. For chill storage, such as ice, existing materials are probably adequate if they can be made leak-tight. Lake storage needs more study of environmental effects. Cavern chemical and thermal cycling effects must be examined closer. Improved detail design and construction methods would be helpful to make all of these concepts more attractive to use.

5.2.2 Store Sizing

Figure 5.1 indicates the approximate store capacity size ranges (in home equivalents) required for achieving cost- and thermal-effectiveness. The sizing is crude and was based generally upon costs of less than \$15,000/home, storage efficiencies greater than 70%, and

FIGURE 5.1. Home Equivalent Capacity Required

size ranges discussed in the literature. Generally the home equivalent capacity for a STES system requires at least 50 or more homes to be justified. Ice and earth storage can likely be used down to one home capacity at some sites, especially if heat pumps are used. Tank and pond storage may also have some potential for less than 50 homes at some sites where solar heating and cooling and multiple annual turnover of inventories are used. The larger capacity for tanks is possible if gravity dam tanks are used. Gravity dam tanks and lakes must have very large capacities. Comparatively, aquifer storage would probably be sized between 75 and 2,000 homes. In Figure 5.1 the capital costs are high at the low end of the capacity range and vice-versa at the high end.

5.2.3 Capital Cost

The capital costs can vary substantially and probably extend beyond the ranges shown in Figure 5.2. These capital costs are for the stores alone and do not include source, use and thermal transport system costs. Ice, existing cavern and lake have the potential for being lowest in

- (a) CAN EXCEED ONE INVENTORY PER YEAR
 (b) NATURAL CAVERN OR ABANDONED MINE
 (c) WITH GRAVITY DAM TANK

FIGURE 5.2. Approximate Capital Cost (Single Inventory Turnover)

cost. Lake and existing cavern require very large capacities, however. Moderate costs can be expected for pond, constructed cavern, gravity dam tank, rock borehole and earth storage. Conventional tanks are the most costly. Aquifer storage capital costs, by comparison, would range from \$20 to \$200/10⁶ Btu and would generally be lower than nonaquifer costs.

The capital costs shown in Figure 5.2 are based upon a single annual thermal inventory turnover. The first four concepts listed have capability of multiple inventory turnovers on an annual basis. The effect of multiple inventory turnovers is important to costs. For example, for a common design and site the pond cost range could be reduced to a \$25 to \$100 per million Btu range if two turnovers of inventory occur in a year. For five turnovers the cost range would be \$10 to \$40. The effect of inventory turnover rates will be expanded in the next section.

5.2.4 Inventory Turnover Effect

Figure 5.3 indicates how thermal energy operating cost rates (\$/MBtu and ¢/kWh) can vary as a function of water storage capital cost (\$50 to \$400/10⁶ Btu capacity) and the annual storage inventory turnover rate

FIGURE 5.3. Approximate Costs Versus Inventory Turnover (Storage Only)

(1 to 20 times/year). Annual levelized costs (operations, maintenance and capital recovery) were assumed to be about one-third the capital cost of a storage system. The cost of fuel oil heat at 65% boiler efficiency is used as a line of reference.

Figure 5.3 shows how increased storage costs can be justified by more frequent inventory turnovers. A \$50/10⁶ Btu capital cost system is needed to be competitive at one turnover and at least 10 turnovers are needed at \$400/10⁶ Btu.

Concepts such as tank, cavern, pond, and lake storage have the capability of having a large number of inventory turnovers because they can be efficiently charged and discharged at the same time. Therefore, even the more expensive concepts such as tank storage can have STES applications.

5.2.5 Thermal Effectiveness

Table 5.2 indicates the heat recovery potential for all of the concepts is good, especially when supplementary heat pumps are used.

Tanks are excellent because the control of the thermocline is good. Ice is excellent because the heat of fusion assures a constant withdrawal temperature during cooling. Earth and rock borehole are likely to require temperature boosting by heat pumps or fossil fuel burning to be feasible.

5.2.6 Advantages

Pond technology is well advanced, but not with temperatures above 65°C. Lake stores can be made very large and they have the potential of being low in cost because modular construction can be performed quickly. Cavern construction is underground and usually leaves the surface area free for other uses.

Tank technology is the most advanced. Almost all sites can be used for tanks. High storage temperatures are no problem, and with adequate insulation, excellent recoveries are obtained. Multiple tanks can be used to improve efficiencies and barriers can be installed to provide flexibility in operations. Tanks provide a high degree of reliability and reduce the need for site characterization and environmental assessment.

TABLE 5.2. Heat Recovery Potential^(a) and Quality

<u>Concept</u>	<u>Rating</u>
Pond	Good
Lake	Good
Cavern	Fair to Good ^(b)
Tank	Excellent
Earth	Fair to Poor
Rock BH	Fair to Poor
Ice	Excellent

^(a) >80% potential for all concepts

^(b) with insulation

Earth storage can be used at a large number of sites. It has the potential of being used for small size systems, such as individual homes or farms if site characteristics are right and it is used in conjunction with heat pumps. Rock borehole, based upon Swedish studies, has a very low cost potential because of low insulation costs and utilization of in situ rock storage and insulation.

Ice storage also has low cost potential and it can be used for systems down to single home size. Technology for ice production is established and should be adaptable to STES systems. Ice has good thermal effectiveness and its high heat of fusion allows for dense thermal storage and a cooling supply at a steady 32°F temperature.

Table 5.3 presents the advantages of each of the seven concepts.

TABLE 5.3. Nonaquifer STES Concept Main Advantages and Disadvantages

<u>Concept</u>	<u>Advantages</u>	<u>Disadvantages</u>
Pond	Technology good, many sites	Pond dam safety
Lake	Large size, low cost potential	Undeveloped, environmental and regulatory hurdles, alternative uses
Cavern	Underground storage	Some uninsulated caverns require heat booster, high excavation costs
Tank	Technology excellent, good site availability, thermally effective, flexibility, low cost	Higher cost
Earth	Site availability, potential small capacity usage	Site variations, low temperature discharge heat
Rock Borehole	Low cost potential	Variation and limited sites, low temperature discharge heat
Ice	Low cost, small capacity usage, good technology, good thermal effectiveness, compact storage	Site limitations for naturally generated ice

5.2.7 Disadvantages

Table 5.3 also lists some of the main disadvantages of the various concepts.

The disadvantages of cut-and-fill ponds are the safety aspects due to potential flooding. Lake storage is surprisingly not a well developed concept. Perhaps this is due to the fact that large capacities (>2000 homes) are required to provide favorable economics. Environmental and regulatory obstacles will have to be overcome. Natural lakes may have competing uses such as recreation, shipping, and others which reduce the sites available.

Small or natural caverns may require booster heat due to the slow heat transfer in the rock. Caverns requiring excavation will be much more costly than existing caverns. Tank costs are relatively high; tanks will usually require more than one annual inventory turnover to be competitive.

Earth storage site materials can vary substantially (e.g., sand, clay, soil). Earth storage concepts that require substantial excavation are costly. Earth materials with low specific heat and thermal conductivities will discharge their heat at lower temperatures and will likely require heat pumps or booster heat (or chill) to be usable. Rock borehole storage must cope with site variations. Available sites with unfractured and nonporous rock bodies are probably limited in the U.S. As with earth storage, the heat will likely be discharged at lower temperatures. Ice storage is limited to sites where climatic conditions are right and the required space is available.

5.2.8 Heat Pump

The heat pump can be valuable in improving the performance of STES systems. The effective capacity of TES systems can be nearly doubled by the use of heat pumps. The heat pumps can take advantage of heat from the earth source as well. One study in Britain used a heat pump to provide a STES pond with the source heat from a river and another heat pump to upgrade the temperature of pond heat distributed to the user. Heat pumps can also increase the flexibility of STES systems.

5.3 CONCLUSIONS

It is apparent that additional research is needed for all of the concepts. Tank storage requires the least amount of research and lake storage the most. Development of lining and insulation systems are requirements common to all concepts.

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

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

The best site availability occurs for tank, earth and pond stores. Usually at least a 50-home capacity is needed to make a store cost- and thermal-effective. A one- to 50-home capacity may be possible for ice storage. It may also be possible for less than 50 homes to use tank and pond storage where multiple annual inventory turnovers are possible due to use of solar or steady waste heat sources and perhaps when used with heat pumps. Earth storage may be used for one or more homes when it is used with heat pumps.

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

No single concept is best for all sites. All concepts, except tanks, are very site-specific. They are also capital-intensive and must be designed to take advantage of site characteristics and the local thermal source and use requirements.

5.4 RECOMMENDATIONS

Currently, the most attractive areas for performing research appear to be in the least costly methods. The less economic concepts will receive increasing attention when power and fuel costs increase more rapidly than general inflation and when pressures for energy resource conservation increase.

Ice storage in certain parts of the country will be economic the earliest and so should receive the highest priority for research funds. Existing caverns (abandoned mines and natural caverns) are also close to being economic and should be second in priority. This task in FY 1982 is aimed primarily at the assessment of ice and existing cavern thermal energy storage. The approximate rank of priority order for remaining concepts would be ponds, lakes, tanks, earth, rock borehole, and constructed caverns.

More research is needed for lining and insulation materials, and construction design and methods. The concepts also require more accurate thermal, structural, cost, site, and market assessment. Heat pump technology needs to be exploited further.

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

6.0 SEASONAL THERMAL ENERGY STORAGE ECONOMIC ASSESSMENT

D. R. Brown

Pacific Northwest Laboratory

6.1 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 UES Program Office.

6.2 TASKS

The economic assessment work has three tasks:

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

6.3 TECHNICAL PROGRESS

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

Development and documentation of the computer model AQUASTOR was completed in the past year with the publication of User Manual for AQUASTOR: A Computer Model for Cost Analysis of Aquifer Thermal Energy Storage Coupled with District Heating or Cooling (Huber, Brown, and Reilly 1982). The model optimizes system design and calculates the life-cycle cost of district heating (cooling) using thermal energy supplied by an ATES system coupled to a seasonal energy source.

AQUASTOR has the flexibility to simulate a wide range of system configurations, with a large number of technical and economic parameters available for defining the energy storage and distribution systems. Either ATES district heating systems using stored hot water or ATES

cooling systems using stored water can be simulated. The model combines the technical characteristics of supply and distribution systems with financial and tax conditions for the entities operating the two systems into one techno-economic model. This provides the flexibility to individually or collectively evaluate the impact of different economic and technical parameters, assumptions, and uncertainties on the cost of providing district heating (cooling) with an ATEs system.

6.3.1.1 Program Overview

AQUASTOR is designed in modular fashion with 85 technical and economic subroutines. In addition to the standard FORTRAN library functions, 63 subroutines comprising the 1967 ASME Steam Tables are used to calculate thermodynamic and physical properties of pure water, including pressure, temperature, enthalpy, specific volume, density, viscosity and fluid quality. AQUASTOR and the steam tables contain approximately 16,000 and 4,000 FORTRAN statements, respectively. The main program controls the sequence of processing by the major submodels to simulate the design and calculate the costs of the ATEs district heating (cooling) system. The major submodels called directly or indirectly by the main program are shown in their organizational structure in Figure 6.1.

FIGURE 6.1. Major Submodels and Order of Execution in AQUASTOR

6.3.1.2 Executive Routine for Supply and Distribution Submodels

The executive routine is a key subroutine in the AQUASTOR code. It initiates and controls the iterations between the subroutines comprising the components of the ATES supply and distribution submodels. The executive routine iterates between the supply and distribution submodels in an attempt to match up the annual energy (fluid) supply with annual energy (fluid) demand in designing the supply and distribution systems. This involves a triple set of nested iterations to design heat exchangers, pipelines, and wellfields, and balance mass and thermal flows between the supply and distribution (demand) portions of the system. These iterations take into account water and thermal losses in the aquifer and system piping.

6.3.1.3 Supply System Submodel

The supply system submodel simulates the design and calculates the capital and operating costs of the ATES supply system. This includes the heat exchanger interfacing with the external energy source, the fluid transmission systems to and from the storage and supply wellfields, and the aquifer.

AQUASTOR assumes that thermal energy is available from a seasonal energy source in a liquid medium (water) and is extracted through a liquid-to-liquid heat exchanger located at the energy source. The extraction of thermal energy from a gaseous medium, such as steam, air or industrial waste gases is not an option of AQUASTOR. An option for a heat exchanger is also provided at the end of the transmission line from the storage aquifer (inlet to the distribution system). This heat exchanger can be used both to protect the aquifer from environmental damage and to protect the expensive distribution system from corrosion.

AQUASTOR does not have a geohydrologic model to simulate fluid and thermal flow within the aquifer. Instead, the characteristics of the aquifer are represented by three input parameters: fluid recovery fraction, thermal storage efficiency, and discovery (natural) aquifer temperature. The fluid recovery fraction is simply the ratio of the

water volume recovered from storage wellfield to previously injected volume. The thermal storage efficiency is similarly the ratio of the energy recovered to energy injected, both defined with respect to the discovery (natural) water temperature of the aquifer.

The model uses a simple enthalpy balance to determine the average temperature of water recovered from the aquifer through the storage and supply wellfields based upon the values for the natural aquifer temperature, fluid recovery fraction, thermal storage efficiency, and computed injection temperature into the aquifer. AQUASTOR treats only the steady-state condition, and aquifer thermal efficiency is assumed constant over time. The model determines the average temperature of water recovered from the aquifer through storage and supply wellfields and designs ATEs components based upon this average temperature.

6.3.1.4 Distribution System Submodel

The distribution system submodel simulates the design and calculates the capital and operating costs of the district heating (cooling) distribution system. The distribution system can serve a single point demand (e.g., a large commercial building or factory), residential districts, or a multi-district city. The distribution system submodel is briefly described below in its form for a multi-district city.

The city is defined by its distance from the storage and supply wellfields, climatic conditions, and the number and type of districts within the city. The distance from the storage wellfield to the city is used in designing the fluid transmission line to the city and calculating the fluid temperature and enthalpy entering the distribution system. The climatic parameters are used in determining the annual heat (chill) demand, peak heat (chill) demand, average heat (chill) demand, the load factor, and supplemental heat requirements. The details needed for design of the distribution piping systems are derived from the definitions of the districts (see district input parameter listing that follows).

6.3.1.5 Input Data Description

AQUASTOR has over 150 input variables available for definition by the user via the FORTRAN NAMELIST feature. Most of these would commonly be left set to their default values, with a select group of variables chosen for parametric cost investigating purposes. Parametric analyses requiring several consecutive simulation cases are easily handled by the model. Input data are broken into supply system and distribution system groups. The major data subgroups and their more important input parameters are listed below.

- Supply Energy Source: flow rate and temperature data
- Supply Heat Exchanger: temperature and performance data
- Distribution Heat Exchanger: temperature and performance data
- Wellfield: well dimensions, flow capacity, completion characteristics, number and drilling difficulty
- Aquifer: fluid and energy recovery fractions and discovery temperature
- Supply Transmission Piping and Pumps: distances, manifolding, well spacing, aging factors, and pump/motor efficiency
- Climatic Parameters: annual, peak, and design heating and cooling degree days, and indoor and outdoor design temperatures
- Districts: dimensions, length of mains, elevation, heat and chill demand, building density, population, retrofit costs
- Distribution System Piping Design: pipe and insulation materials and configuration
- Financial and Economic Parameters: debt-equity ratio, taxation, insurance, depreciation, inflation, escalation, energy costs, system life and interim capital replacement rates.

6.3.1.6 Output Description

Several output options are available to select various levels of detail in the printout from the AQUASTOR code. The standard printout

shows the input data, the final techno-economic iterations between the supply and distribution systems, annual cash flows for the supply and distribution systems, and a technical and financial summary of the simulation results.

The output from the final iteration between the ATES supply system and distribution system describes the fluid flow rates, pipe diameters, pipe schedules, insulation thickness, thermal losses, pressure drops, pumping requirements, capital costs, and operating costs of the major ATES elements. The technical summary provides a succinct expression of the pertinent source, user, and aquifer characteristics plus design and flow data for the ATES piping and distribution systems. Financial summary information includes economic data for both supply and distribution entities, purchased energy costs, component cost escalation rates, as well as the levelized cost of energy to the end-user, both totaled and by capital, O&M, purchased thermal energy, and pumping electrical energy components.

6.3.2 Task 2. Detailed Economic Evaluation of ATES Heat Storage

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

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

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

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

The source temperature deliverable to an ATES system plays an important role in system economics. Higher storage temperatures are expected to yield poorer thermal efficiencies due to tilting of the thermocline within the aquifer and conductive losses at the "bubble" interface. Despite the poorer thermal efficiency, a higher source temperature ultimately allows a higher deliverable temperature to the user, with more usable energy per pound of water. This higher energy density allows lower system fluid flow and directly reduces the amount of piping, pumping, well drilling, etc. required. Of course, higher temperature sources will probably command a higher purchase price. In this analysis, no attempt is made to differentiate between the cost of energy at various temperatures. Rather, the ATES costs estimated are based on examining a range of possible costs on a "what if" basis.

Significant economies of scale are available for ATES systems. In fact, fairly large systems are required to achieve cost-effectiveness. For point demand systems, costs are fairly constant for peak demands (at 25% load factor) 8 to 10 MW and larger. Costs rise quickly for systems with peak demands less than 3 to 5 MW. Residential developments achieve the available economies of scale at larger system sizes due to the addition of extensive distribution piping networks.

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

The availability of a suitable aquifer is obviously of prime concern when considering an ATEs installation. Potential site-specific availability of aquifers is not addressed here. This analysis assumes a (more or less) suitable aquifer exists and examines the cost effect of a range of possible thermal efficiencies. As expected, aquifer thermal efficiency is an important ATEs cost parameter, especially with high purchased thermal energy costs.

ATEs-delivered energy costs are compared with the costs of hot water generated from more conventional fuel sources in Figure 6.2. Levelized costs for electrically heated water (at 5¢/kWh and 7% annual escalation) and oil heated water (at \$1.00/gallon and 8% annual escalation) are compared to costs for an ATEs point demand configuration with a 10-MW peak demand and 25% load factor. ATEs costs are shown as a function of purchased thermal energy. Figure 6.3 shows both the potentially low delivered energy costs available from an ATEs system and its strong cost dependence on the cost of purchased thermal energy.

Cost components are shown in Figure 6.3 for point demand and multi-district city ATEs systems. Capital and thermal energy costs dominate. Capital costs, as a percentage of total costs, increase for the multi-district city due to the addition of a large distribution system. The proportion of total cost attributable to thermal energy would change dramatically if the cost of purchased thermal energy were varied.

This investigation considered only the storage of energy from a seasonal heat source. Cost estimates were based upon the assumption that all of the energy is stored in the aquifer before delivery to the end user. Systems with near-continuous heat sources would be able to supply some energy directly, and so only a portion of the energy would need to be stored underground. Delivery costs from such systems would be less, because these systems would require less pumping energy, probably a reduction in pipe size and number of wells required, and potentially less heat loss within the aquifer.

FIGURE 6.2. A Comparison of the Cost of Ates Against Conventional Technology

FIGURE 6.3. Aquifer Thermal Energy Storage Component Cost Breakdown

6.3.3 Task 3. Nonaquifer Chill Storage Analysis

Several nonaquifer chill storage concepts are being technically and economically evaluated at the conceptual design level. The technologies under consideration include frozen (saturated) earth, ice-releasing heat pipe, ice tank and two versions of an ice pond. The concepts represent innovative approaches and techniques of the old idea of gathering and storing winter chill for use during the summer.

Each concept is being designed to deliver an annual load of 10^9 Btu, with a peak load of 1.2×10^6 Btu (100 tons). This size of load is intended to represent a commercial building of median size. The analysis is considering several design-cost tradeoffs described below for each of the concepts.

Insulation in one form or another must be employed to avoid excessive thermal losses during the storage season. The primary choice here is between using earth or manmade products as the thermal barrier. Earth is, of course, the much cheaper material, but a thicker layer is required to achieve the same performance. Earthen insulation can also impose large excavation costs on a system. Manmade insulators, although much better thermal barriers, are relatively expensive to purchase. The chosen designs generally employ some combination of earthen and manmade insulation in an attempt to minimize costs.

Different types of plastic and metal piping have been considered for the heat transfer apparatus of each concept. Generally, plastic pipe is cheaper, but metal pipe has a much higher thermal conductivity, which allows for better thermal transfer performance. Piping material is also quite important in structural consideration. The expansion of water into ice as it freezes can create excessive structural loads on certain configurations. The stresses applied affect the choice of piping diameter and wall thickness as well as piping material. Piping dimensions also affect the thermal transfer process; thus, the selection of piping material and size specifications represents an iterative procedure where both structural and thermal transfer requirements must be met at a minimum cost.

Each concept requires some sort of chill-capturing device which transfers winter chill in the form of air to a liquid medium. The liquid medium, in turn, transfers the collected chill to the storage medium through a second chill-transferring device. Several design parameters, in addition to those mentioned above, must be considered in order to minimize the cost of these two heat exchangers. Approach temperatures at both sides of both heat exchangers, and the heat transfer area of both heat exchangers can be varied to minimize cost while delivering the required store of chill. A choice must also be made between laminar and turbulent flow. Turbulent offers much better heat transfer at the inside surfaces of the storage heat exchanger. However, the overall heat transfer is largely controlled by the ice log that forms around the piping and the pipe wall itself (if the pipe is plastic). With plastic pipe and laminar flow, the additional heat transfer resistance and subsequent storage heat exchanger size increase is offset by reduction in the size of the overall piping system.

6.4 REFERENCES

- Huber, H. D., D. R. Brown and R. W. Reilly. 1982. User Manual for AQUASTOR: A Computer Model for Cost Analysis of Aquifer Thermal Energy Storage Coupled with District Heating or Cooling. PNL-4236, Pacific Northwest Laboratory, Richland, Washington.
- Reilly, R. W., D. R. Brown and H. D. Huber. 1981. Aquifer Thermal Energy Storage Costs with a Seasonal Heat Source. PNL-4135, Pacific Northwest Laboratory, Richland, Washington.

PART III.
COMPRESSED AIR ENERGY STORAGE
Reservoir Stability Studies

This part contains summaries of the tasks and projects conducted in support of Reservoir Stability Studies. Efforts to formulate stability criteria for the three potential CAES reservoir types are documented in Section 7.0. Section 8.0 reports on work undertaken to model the thermohydraulic performance of porous media (aquifer) reservoirs. Section 9.0 discusses laboratory experiments in the CAES Porous Media Flow Facility. Field studies of the Pittsfield, Illinois aquifer are described in Section 10.0. Laboratory tests of salt typical of formations likely to be used with CAES are discussed in Section 11.0.

7.0 STABILITY CRITERIA FORMULATION

R. D. Allen

Pacific Northwest Laboratory

7.1 OBJECTIVE

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

7.2 TASKS

The program comprises formulations of stability criteria according to the three types of geologic compressed air storage reservoir: 1) hard rock cavern, 2) salt cavity, and 3) aquifer. The three tasks are:

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

7.3 TECHNICAL PROGRESS

Tasks 1 and 2 have involved assemblage of data from the literature, from laboratory and numerical modeling studies funded by the CAES program, and from limited field studies partially funded by the CAES program. Three drafts each of the hard rock and salt cavity documents have evolved consecutively. The changes reflect successive critical reviews by PNL geotechnical personnel and recognized external specialists.

The hard rock document has been thoroughly reviewed by David C. Willett of Acres American, Inc., and Leif G. Eriksson of ERTEC Western, Inc. Both have offered substantial constructive changes relating to geologic exploration and cavern design. Arlo F. Fossum of RE/SPEC, Inc. has examined the document for accuracy of interpretation. Robert L. Thoms of Louisiana State University has scrutinized the salt document

for accuracy of expression, particularly in matters not fully resolved at this time. Tasks 1 and 2 are scheduled for completion by the third quarter of this fiscal year.

Task 3 completion will depend on future findings from the Pittsfield, Illinois, field study. Copious information from the natural gas storage literature, laboratory studies of typical reservoir and caprock specimens and numerical modeling results on aquifer reservoirs have been compiled. Modeling specific to the Pittsfield geology and comprehensive mineralogical, physical and rock mechanical examinations are being conducted for this reservoir. Operating behavior and CAES interactions with the reservoir and hydrologic system are subjects to be addressed in the testing.

7.4 PUBLICATIONS

Two major publications were produced during this reporting period.

Allen, R. D., A. F. Fossum and T. J. Doherty. 1982. Geotechnical Factors and Guidelines for Storage of Compressed Air in Excavated Hard Rock Caverns. PNL-4180, Pacific Northwest Laboratory, Richland, Washington.

Allen, R. D., T. J. Doherty and R. L. Thoms. 1982. Geotechnical Factors and Guidelines for Storage of Compressed Air in Solution Mined Salt Cavities. PNL-4242, Pacific Northwest Laboratory, Richland, Washington.

8.0 PREDICTION OF THE THERMOHYDRAULIC PERFORMANCE OF POROUS
MEDIA RESERVOIRS FOR CAES IN SUPPORT OF THE
FIELD TEST AT PITTSFIELD, ILLINOIS

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

8.1 OBJECTIVE

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

The prediction of reservoir performance was based on application of a series of numerical computer models developed within the CAES program at PNL. These models were applied to four basic reservoir problems at the Pittsfield site: bubble development, water coning, thermal development, and near-wellbore dehydration.

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

Water coning is illustrated in Figure 8.1. During an air discharge cycle the depressurization around the wellbore causes mobile water in the vicinity of the wellbore to move toward the wellbore. The intrusion of water into the near-wellbore region could adversely affect reservoir operation. The water will reduce the relative permeability. During the thermal cycling tests, the presence of water in the near-wellbore could enhance geochemical reactions that reduce permeability. This could generally occur in an oxidizing environment when the temperature exceeds about 75°C (Stottlemire and Erikson 1980).

FIGURE 8.1. Water Coning During Reservoir Extraction Cycle

Because most of the reservoir pressure loss occurs in the convergent region near the wellbore, decreasing the permeability in that area will require greater pressure losses to maintain a given air mass flow rate. In the most severe case, total communication with the reservoir could be lost due to pore plugging.

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

The thermal analysis was performed using the single-phase two-dimensional model described by Wiles (1979a). Modifications were made to approximately account for the porosity and effective permeability due to the presence of liquid phase predicted by the two-phase model.

The dehydration of the near-wellbore region was evaluated because of the potential adverse effects, described above, associated with the presence of water in the near-wellbore region. This analysis was performed with the two-phase, one-dimensional model described by Wiles (1979b).

8.2 FIELD TEST ANALYSIS

The field test will be operated in two distinct phases. The first is the bubble development phase. This will be followed by the air cycling studies. The analysis was performed in consideration of this schedule. The air cycling studies were based on the prediction of bubble development.

8.2.1 Reservoir Description

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

The conditions applied to the analysis are defined in Table 8.1. The relative permeability and capillary pressure functions are shown in Figures 8.2 and 8.3, respectively.

8.2.2 Bubble Development

Bubble development was initiated computationally using a bottom-hole pressure ramp that increased the pressure linearly with time during the first 24 hours. The pressure was increased from 10 to 18.7 atm. Thereafter, the bottom-hole pressure was held constant. This ramp simulates the step-wise pressure increases that will be applied in the field test as a precaution against potential fracturing of the reservoir caprock (Katz et al. 1963).

The bubble development simulation was terminated after 60 days of continuous air injection. The predicted air injection rate over this period is shown in Figure 8.4. An anomaly occurred after 24 hours when the pressure ramp terminated. There was an immediate reduction in pressure-limited flow rate. This may have been due to an equilibration between the imposed pressure and gravitational and capillary forces. This would effect a decline in the downward thrust of the bubble, leaving only the radial component to accommodate further bubble growth.

TABLE 8.1. Reservoir Description

Geometry	
Depth to top of structure	215 m
Caprock slope	1/80
Vertical thickness of storage zone	68 m
Well diameter	20 cm
Producing length	3 m
Outer radius of modeled region	800 m
Assumed radius to hydrostatic pressure	10^4 m
Properties	
Permeability (horizontal)	700 md
(vertical)	700 md
Porosity	20%
Rock thermal conductivity	2.16 W/m°C
Rock thermal capacity	2.62 MJ/m ³ °C
Saturation functions	
Relative permeability	
(air) $k_r^g = (S_{c,g} - S)^2$	$2.34 - 1.37(S_{c,g} - S)^2$
(water) $k_r^l = (S - S_{c,l})^3$	$4.93 - 3.72(S - S_{c,l})$
Critical saturation for gas mobility, $S_{c,g}$	0.90
Critical saturation for liquid mobility, $S_{c,l}$	0.20
Capillary pressure	
$P^C = \left(\frac{0.05525}{S - 0.15} \right) - 0.065$ atm	
Operating conditions	
Discovery pressure	10 atm
Maximum injection pressure	18.7 atm
Maximum injection air flow rate	1250 scfm
Discovery temperature	14°C
Maximum injection temperature	200°C
Injection humidity	0

FIGURE 8.2. Reference Relative Permeability Functions

FIGURE 8.3. Reference Capillary Pressure Function

FIGURE 8.4. Volume Flow Rate Versus Time for 275 psi Constant Pressure Air Injection

The advance of the 50% saturation front is shown in Figure 8.5. This value of saturation was chosen because it represents significant displacement of water and significant mobilities of both air and water. The bubble growth is initially both downward and horizontal. The downward growth slows appreciably as gravitational and capillary forces approach an equilibrium with the bubble pressure. Further bubble growth is primarily horizontal.

After 60 days of air injection, a period of closure was computed for 30 days. During this closure the air-water interface approached the horizontal. Also the bubble continued to expand to approach a hydrostatic equilibrium. The average bubble pressure decreased from about 16 atm to about 12 atm during this time. The rate of equilibration depends on the applied capillary pressure function and the

FIGURE 8.5. Lines of Constant Saturation (50%) Versus Radius for Different Time Periods During Bubble Development.

assumed radius- to a hydrostatic sink. According to the capillary pressure function used in the analysis, the entire vertical thickness of the resultant bubble is within the transition zone. As a result, gravity drainage is incomplete and the entire air storage zone will contain mobile water. This is a unique feature of the demonstration reservoir and would not be expected for a commercial facility. A smaller radius to a hydrostatic sink would effect more rapid bubble growth. Field tests should allow a better prediction of this radius.

Analyses performed using permeabilities other than 700 md showed that bubble growth is primarily dependent on the horizontal permeability. This results because bubble growth is primarily a horizontal phenomenon, as observed by consideration of the scales used in Figure 8.5. A vertical permeability of 350 md made almost no difference in the bubble growth rate while a horizontal permeability of 3500 md increased the potential growth rate by more than four times.

8.2.3 Air Cycling

The demonstration site testing will continue with several months of air cycling after bubble development. The analysis of this cyclic

injection and withdrawal of air to the reservoir encompasses three primary topics: water coning, thermal development, and near-wellbore dehydration. In the analysis water coning is treated separately from thermal development and dehydration. In nonisothermal reservoirs these phenomena are likely to be strongly coupled, as is suggested by the analysis results.

Air cycling begins with the bubble development solution after 30 days of reservoir closure. The injection/withdrawal cycles that were evaluated were designed to preserve the bubble air mass, although some overinjection may be practiced in the field to depress the air-water interface and make up any leakage. For the conditions of the demonstration reservoir the cyclic air injection is flow limited.

8.2.4 Water Coning

The purpose of the water coning analysis was to define an injection/withdrawal cycle for which water coning would not be a problem. This cycle would serve as a guideline for designing the thermal development tests.

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

The first cycle analyzed was defined as having equal injection and withdrawal periods of 12 hours. The 50% saturation front after 12 days of cycling is shown in Figure 8.6 at the conclusion of both the final injection and withdrawal cycles. The initial position of the front is the bubble development solution after 30 days of closure. The results suggest a strong potential for significant water coning to occur in the field test. A subsequent analysis using only 4 hours of air injection and 20 hours of withdrawal still showed some water build-up occurring. To maintain the bubble air mass with this cycle, the extraction air flow rate was only 20% of the injection flow rate. This result was at least

FIGURE 8.6. Water Coning: 50% Saturation Front

partially due to the continuing equilibration of the bubble. These results suggest that operational controls may not be sufficient to control water production in the field test. A geologic barrier of low permeability below the wellbore may exist in such bedded materials, although such a barrier has not yet been identified in the experimental work.

Water coning was simulated for a case of a vertical permeability of 350 md, thereby simulating a barrier to vertical water migration. The rate of increase of water build-up was only slightly affected. Thus, a barrier to oppose water coning will need to be significant to be effective.

In an earlier study, Wiles and McCann (1981) concluded that water coning should not be a significant problem for a commercial CAES facility. However, the demonstration site reservoir has two unique

features that contribute to a greater possibility that water coning will occur. First, and perhaps most important, is the relatively low pressure of the reservoir. The air density at the bottom-hole pressure during withdrawal may be less than half of that during injection. As a result, to achieve equal mass flow rates for a 12-hour injection/12-hour withdrawal cycle, an unbalanced pressure gradient exists with the net effect of drawing water toward the wellbore. However, even when the pressure gradient is unbalanced in the other direction as is the case for the 4-hour injection/20-hour withdrawal cycle, continuous water build-up still occurs. This results because water flowing upward is supplied from a region of high liquid mobility while downward flow of water is dominated by a lower mobility. Thus, when water moves up it is essentially trapped. The second unique feature of the reservoir is that the entire air storage zone is within the capillary transition zone. This fact reduces the potential for gravity drainage, thus contributing to water entrainment. Because of the capillary behavior, mobile water remains in the vicinity of the wellbore even after 30 days of reservoir closure. Consideration is currently being given to extending bubble development time to mitigate these effects.

Additional conclusions pertaining to water coning are:

- Additional bubble development to further depress the air-water interface is probably not an effective means to reduce water coning.
- The injection/withdrawal interval of the wellbore must be at the top of structure to minimize water coning.

Although these results suggest that water coning is very possible at the Pittsfield site, this is not necessarily true. Much depends on the actual conditions in the air storage zone. In particular, low permeability layers would inhibit vertical water migration.

8.2.5 Thermal Development

Drilling technology limits the distance from the injection/withdrawal well to the surrounding observation wells. This distance may

be on the order of 3 m. The initial thermal development calculations were intended to indicate whether or not a heated region could be established beyond this radius within the time frame of the field test.

A cycle of 4 hours of injection and 4 hours of withdrawal was used. An injection temperature of 200°C was defined to exist at the bottom-hole. Four weeks of cycling were simulated. Radial temperature profiles are shown in Figure 8.7. These profiles were taken along the top of the reservoir at the conclusion of the final extraction cycle for each week. If thermal recovery from the reservoir were complete, then no thermal build-up would occur. Therefore, these curves represent the thermal energy lost to the reservoir. Because peak recovery temperatures increased, then the rate of thermal loss to the reservoir decreased, as one might expect. The temperature dip near the wellbore was due to the effects of cooler air being drawn from below.

The results of this analysis indicated the need for computational coupling of the two-phase flow and thermal models. As thermal development proceeds, withdrawal air temperatures increase, thereby reducing the density. To achieve a prescribed air mass flow rate, the velocity must increase. Such behavior would contribute to water coning.

The results of the preliminary thermal development analysis suggest that some thermal data should be obtainable at the observation wells. However, the following factors could contribute to a less favorable result:

- Heat losses between the aboveground equipment and the reservoir have not been accounted for.
- Dehydration in the near-wellbore region will inhibit thermal growth.
- The advance and retreat of underlying water will smear the thermal front.

FIGURE 8.7. Thermal Development: Radial Temperature Profiles After Final Weekly Extraction Cycle

- To avoid water coning, long withdrawal cycles at low flow rates may be necessary. In the time frame of the field tests this would reduce the total thermal energy to which the reservoir is subjected.

These items will be the subject of more detailed analysis in the future.

8.2.6 Dehydration

The dehydration of the near-wellbore region proceeds as follows. During injection of undersaturated air at elevated temperature, the air gains moisture as it moves radially outward. The air finally reaches a radial position where it is saturated at the local pressure and temperature. As the air moves beyond this point, condensation occurs. By this mechanism a dehydrated zone is established around the wellbore.

Beyond this so-called "dry front" there is a transition region characterized by some saturation build-up. Water is eventually removed from the reservoir during a withdrawal cycle. Air moving toward the wellbore gains moisture as it enters the region of increasing temperature. However, it gains moisture only until it reaches the dry front. The air is then withdrawn from the reservoir at a saturated state determined by the pressure and temperature of the dry front.

The analysis of dehydration for the field site reservoir was based on a cycle of 4 hours of injection and 4 hours of withdrawal. Radial saturation profiles are shown in Figure 8.8. These results can be compared against data from the field test where extraction humidity will be monitored. Such a comparison will likely show differences in predicted and actual data for the following reasons:

- If the injection air during bubble development is undersaturated, then a dehydrated zone may already be established around the wellbore when cyclic operation begins.
- The model predicts that, in the presence of liquid water, the air will be saturated at the local thermodynamic conditions. A proper accounting of the rate process would probably reduce the predicted outlet humidity.

DEHYDRATION- RADIAL SATURATION PROFILES

FIGURE 8.8. Radial Saturation Profiles at Various Times during the Simulation

- Water coning may introduce water to the heated zone around the wellbore, thereby increasing outlet humidities.
- An injection humidity of zero, as used in this analysis, is not likely achievable in the field test. A nonzero value would reduce the dehydration rate.

8.3 SUMMARY

The analysis described in this paper demonstrates the capability of the computer models developed at PNL to analyze the thermohydraulic performance of CAES porous media reservoirs. Emphasis has been directed at analysis in support of the field test program. It was found that unique features of the site may require special attention. These include the pressure of the reservoir and the fact that the entire air storage zone may be influenced by capillary behavior. These features would not be typical of a commercial CAES site. The analysis also revealed that water coning in nonisothermal reservoirs is strongly coupled to thermal development and dehydration.

8.4 REFERENCES

- Katz, D. L., M. R. Tele, K. H. Coats, M. L. Katz, S. C. Jones, and M. C. Miller. 1963. Movement of Underground Water in Contact with Natural Gas. The American Gas Association, New York, p. 129.
- Stottlemire, J. A. and R. L. Erikson. 1980. An Experimental Study of the Response of the Galesville Sandstone to Simulated CAES Conditions. PNL-3399, Pacific Northwest Laboratory, Richland, Washington.
- Wiles, L. E. 1979a. Numerical Analysis of Temperature and Flow Effects in a Dry, Two-Dimensional Porous Media Reservoir Used for Compressed Air Energy Storage. PNL-3047, Pacific Northwest Laboratory, Richland, Washington.
- Wiles, L. E. 1979b. The Effects of Water on Compressed Air Energy Storage in Porous Rock Reservoirs. PNL-2869, Pacific Northwest Laboratory, Richland, Washington.

Wiles, L. E. and R. A. McCann. 1981. Water Coning in Porous Media Reservoirs for Compressed Air Energy Storage. PNL-3470, Pacific Northwest Laboratory, Richland, Washington.

9.0 POROUS MEDIA EXPERIMENTAL TASKS

R. L. Erikson

Pacific Northwest Laboratory

This paper summarizes the results of laboratory experiments conducted between March 1981 and March 1982 in the CAES Porous Media Flow Loop (PMFL) and other ancillary laboratory data relevant to the CAES field project. The experiments were designed to investigate in situ physical property alterations of sandstone reservoir rock.

9.1 OBJECTIVE

Experimental evaluation of the Pittsfield reservoir materials has been the specific objective of all experimental work during this reporting period.

9.2 SUBTASK DESCRIPTIONS

Subtasks described herein discuss the acceptance testing of the CAES PMFL; experiments conducted in the PMFL on the permeability stability of St. Peter sandstone; and other ancillary permeability measurements relevant to the CAES field project.

9.2.1 Subtask 1. Equipment Development and Acceptance Testing

The major thrust of this subtask in the last 2 years has been the development of the CAES PMFL and the successful test acceptance of this system. A major weakness in the experimental efforts of past years has been the inability to accurately simulate anticipated CAES field conditions in the laboratory. The advantage of the new flow system is that physical properties of reservoir rock can be measured at the temperature and pressure of interest under dynamic air-flow conditions, thereby accurately simulating CAES conditions. Samples of reservoir material can therefore be tested in the laboratory under simulated field conditions. The results can be used for lab-field data correlations and long-term reservoir stability projections.

9.2.2 Subtask 2. Porous Media Experimentation

The experimental results presented in this report consist of experiments conducted in the PMFL and other ancillary data pertinent to the CAES field project. The experiments were designed to determine the response of Pittsfield field study samples to CAES conditions imposed by the field tests. Experiments conducted in the PMFL were designed to investigate: 1) temperature-stress/strain effects of the permeability of sandstone; 2) dynamic fatigue of reservoir rock under temperature and stress cycling; and 3) measurement of the rate of desaturation of reservoir sandstone. Samples of St. Peter sandstone obtained from wells on the field site were used in all experiments.

9.3 TECHNICAL PROGRESS

9.3.1 Subtask 1. Equipment Development and Acceptance Testing

The acceptance testing of the PMFL, initiated in September 1980, was completed in May 1981. The various acceptance tests completed were: 1) system leak and pressure tests; 2) air-flow control; 3) steam system; 4) electric valve control system; 5) auxiliary trace heater system; and 6) hydraulic system. During the stages of acceptance testing and preliminary experiments with sandstone samples, modifications and techniques were developed to expand the capabilities of and help reduce the downtime of the instrument.

Various pressure vessel seal materials were tested for high temperature durability before Viton was selected as a suitable O-ring material. Several servo-controlled valves were replaced with manual valves that maintained a superior seal at high temperatures. Moreover, the capability to measure the pressure drop and flow rate through a rock sample was increased to 0 to 100 psi and 6 to 60 cm³/sec, respectively. This modification expands the capability to accurately measure in situ sandstone permeabilities to values ranging from a few millidarcies to greater than 5 darcies.

Perhaps the most difficult task was the development of a leak-proof sample jacket capable of withstanding high temperature and pressure. The jacket is necessary to isolate the pore fluid (air/steam) from the confining pressure hydraulic fluid (oil). After numerous jacket failures, a technique using a combination of teflon tubing and high-temperature RTV was perfected and the number of failures significantly reduced.

9.3.2 Subtask 2. Porous Media Experimentation

9.3.2.1 Ancillary Measurements

The permeability of St. Peter sandstone to nitrogen gas was measured at room temperature and pressure on core samples taken from borehole Yakley No. 1. Samples were prepared to allow gas flow both parallel and perpendicular to bedding planes. The data for permeability as a function of depth are illustrated in Figure 9.1. Average permeabilities parallel and perpendicular to the bedding were 576 and 695 md, respectively. The considerable scatter in the data is attributed to the variable degree of cementation and friability of the sandstone. The quantity of data is not sufficient to demonstrate anisotropy of permeability with respect to bedding orientation. The measured porosities of samples recovered from 216 to 224 m (707 to 735 ft) in this borehole varied from 12 to 18%.

9.3.2.2 Porous Media Flow Loop Experiments

Experiments in past years have incompletely simulated such CAES aquifer field conditions as air flow, confining pressure, and dynamic stress. The flow loop allows experimental design to incorporate physical property measurements at realistic temperatures and pressures under dynamic conditions of air flow. For example, reservoir rock will be characterized with respect to: 1) permeability under a confining pressure, 2) stress-strain behavior, 3) rates of desaturation, and 4) cyclic thermal fatigue.

FIGURE 9.1. Gas Permeability Versus Depth, Yakley #1

The majority of experiments completed in this reporting period have concentrated on permeability measurement as a function of the independent variables of temperature, confining pressure, strain, and air humidity. The values of the independent variables were chosen to be consistent with values anticipated at the field site. Permeability of sandstone samples was measured perpendicular to the bedding by adjusting values of the air flow rate and pressure drop across the core. One experiment of short duration involved the measurement of the desaturation rate of a St. Peter sandstone sample.

In initial experiments, the permeability of a triaxially loaded St. Peter sandstone sample from a depth of 210 m (689 ft) in borehole Yakley No. 1 was measured. The experimental parameters controlled were: 1) temperatures of 22°C (72°F) and 93°C (200°F), 2) confining pressure (hydrostatic) of 8.3 MPa (1200 psi) and 17.3 MPa (2500 psi), and 3) a pore air pressure of 1.9 MPa (275 psi). Permeabilities measured at these temperatures were less than 100 md. Moreover, the permeability decreased by approximately 40% in heating the sandstone to 200°F. Increasing the confining pressure to 17.3 MPa (2500 psi) had no effect on the measured permeabilities. Although the data indicate air permeability decreasing with temperature, more experimentation is needed to quantify the significance of this response.

A dehydration curve for the same St. Peter sandstone sample from Yakley No. 1 is shown in Figure 9.2. The data were obtained as the sample was isolated at steady-state values of temperature (200°F), confining pressure (1200 psi), and pore pressure (275 psi). Dry air at a specific humidity of 0.01% and a flow rate of 3 to 4 cm³/sec was injected into the sample. Moisture removal from the rock was monitored by measuring the effluent air humidity. The high initial rate of moisture removal gradually decreased as the outlet air humidity approached the inlet air humidity. A portion of the residual water content may not be removable under these conditions because of isolation in occluded pores and high capillary forces.

A second set of permeability experiments was conducted on a St. Peter sandstone sample from 657 feet in the Pittsfield injection/withdrawal borehole. The sample permeability was measured using dry air as the sample was cycled between 70° and 350°F at a constant confining pressure of 1200 psi. The data for this temperature cycle are shown in Figure 9.3. Air permeability for this sample is considerably greater than for the previously tested samples from borehole Yakley No. 1. The permeability decreased from initial values of approximately 3 darcies at 70°F to 2.1 darcies at 350°F. Upon cooling back to room temperature, the sample permeability measured at ambient temperature was

FIGURE 9.2. Drying Curve for St. Peter Sandstone

FIGURE 9.3. Permeability Versus Temperature

approximately 2.6 darcies. Therefore, this sample exhibits a small hysteresis in that the permeability did not return to the initial values.

The strain data for this temperature cycle indicated a small compression of the sample, approximately -0.3%. Moreover, the sample strain was caused predominantly by the pressurization of the sample to 1200 psi. Increasing the temperature to 350°F after the initial pressurization had little effect on sample strain. Because the sample strain did not change appreciably between 70° and 350°F, it is probably not the major cause of the permeability decrease at higher temperatures. Second, the permeability hysteresis exhibited by this sample after one temperature cycle can also not be explained simply by sample deformation. An alternate explanation involves the liberation of small particles in the rock as it is heated under dynamic air flow. Loose particles lodging in pore throats could effectively decrease air flow through the rock and decrease permeability. Moreover, once particles become lodged in the pore throats, it may be difficult to dislodge them. This is a plausible explanation for the permeability hysteresis noted in these experiments. In future experiments, sandstone samples will be subjected to multiple strain/temperature cycles designed to investigate the hysteresis effect in more detail. It must be determined if the hysteresis effect continues over numerous temperature cycles. Second, the effects of air humidity on permeability must be fully evaluated.

10.0 AQUIFER FIELD STUDY AT PITTSFIELD, ILLINOIS

R. D. Allen and T. J. Doherty
Pacific Northwest Laboratory

J. A. Istvan
PB-KBB, Inc.

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

10.1 OBJECTIVES

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

- Demonstrate the feasibility of storage and cyclic injection/retrieval of warm compressed air in using an aquifer reservoir.
- Investigate physical, chemical and mineralogical effects of CAES on reservoir rock, caprock, and wellbore, and compare with laboratory results.
- Verify and evaluate numerical modeling of bubble formation, dehydration and water displacement, thermal growth, and cyclic thermal performance.
- Evaluate system performance with respect to bubble growth rate, mass transfer rates, thermal development and recovery, water production, and entrainment of mineral particulates.

10.2 TASKS

The aquifer field study is divided into three broad phases: exploration, design and construction, and operations. The Pacific Northwest Laboratory as project manager, and PB-KBB of Houston, Texas, as design, construction and operations contractor, have worked closely to implement these phases. The exploration phase was completed during June 1981 with acquisition of the construction permit under direct PNL supervision with various minor subcontractors. Design and construction began with drilling of the injection/withdrawal well in late June; this activity has been the major field study effort during this reporting period. Throughout this time, PNL has provided project management, technical assistance to the contractor, and design and procurement approval. PB-KBB has had the responsibility to drill and complete the injection well and instrumentation well field; to design, procure, and construct the surface facility and subsurface instrumentation system; and to plan preliminary tests in conjunction with PNL. The operations phase of the project is scheduled to begin in September 1982 with development of the air storage bubble. Field study work for this reporting period is described below on a task-by-task basis; the descriptions document both PNL and PB-KBB efforts.

10.2.1 Project Management and Technical Support (PNL)

The purpose of this task is to provide overall project direction and to integrate the numerical and experimental work described elsewhere in this Annual Report with the field study activity. During the exploration phase, PNL provided detail direction of subcontracts for leasing, drilling and geophysical and geological assistance. During the design, construction, and operations phases, this task includes contract negotiation with PB-KBB, project administration and review approval, and technical support of contractor activities.

10.2.2 Permitting (PNL)

The permitting task primarily involves acquiring the Form A construction permit and the Form B operations permit from the Illinois Environmental Protection Agency under interim Underground Injection Code

rules for the field test activities. This task is integrated with the activity of the CAES Environmental Concerns Project, funded by DOE-EV (ECT), which has been investigating the environmental aspects of all CAES technologies. Other minor permit activities are handled directly by PB-KBB, or reviewed and approved by PNL if delegated to subcontractors.

10.2.3 Exploration (PNL)

This task involved identifying the field study plan, defining required site characteristics, screening and selecting sites, and qualifying the site according to a set of technical and legal criteria prior to initiation of construction. Qualification includes drilling for core and structure, geologic evaluation, seismic prospecting, ground water sampling and analysis, and providing input to the permitting process.

10.2.4 Surface Facility Development (PB-KBB)

The objective of this task is to design, procure, and construct a facility capable of injecting, withdrawing, and monitoring air at a suitable air storage site. It includes the civil, mechanical, and electrical equipment and a structure sufficient to allow continuous all-weather testing. The facility is to provide an air compression plant; heating and filtering equipment; instrumentation for monitoring flow, pressure, temperature and humidity; and semiautomatic control equipment allowing flexibility of operation. The facility is also to provide operator services and data acquisition system housing and services for both surface and subsurface instrumentation.

10.2.5 Well Field Development (PB-KBB)

This task initiates site construction activities. Upon completion of exploration and permitting, a drilling rig mobilized to the site will drill the injection/withdrawal well into the storage formation. This well, located at the highest point in the structural trap, will then be cased and cemented using steam injection geothermal completion methods to ensure wellbore integrity through pressure and temperature cycling.

Final preparation of the well for air injection will include installation of tubing string, packer, and well screen immediately prior to air injection.

A radial array of instrumentation and monitoring wells will then be drilled. Two wells, sufficiently sized for multiple temperature, pressure, and saturation instrumentation, will be placed as close as vertical control in drilling will allow. These wells are to be cased and cemented. Sealing and gravel packing details will be integrated with subsurface instrumentation. Four monitoring wells are to be drilled at various radial distances from 25 to 200 m away from the injection wells. These wells, designed primarily for neutron logging and air pressure and water level monitoring, will be drilled, cased and cemented into the storage formation.

All wells are to be cored over some interval including caprock and storage formation. This core will provide data for final operations permitting.

10.2.6 Water Sampling (PB-KBB)

This task includes downhole pump testing of the formation prior to air injection. The primary purpose is to acquire water samples for IEPA permitting and geochemical studies, but sufficient data are to be acquired to allow characterization of formation hydraulic conductivity to water.

10.2.7 Subsurface Instrumentation (PB-KBB)

Downhole measurement of the air storage system response to bubble development, cyclic air injection, and thermal response is critical to understanding aquifer reservoirs. This task requires design, calibration, and installation of sensors capable of reliable, accurate, and continuous measurement of temperature, pressure, water content, and humidity. The task also includes creation of an integrated data acquisition system to provide instantaneous and permanent records of near wellbore response.

10.2.8 Air Injection to Develop Storage Bubble

This task is the first stage of actual testing on the site. A 3-month period will be required to develop a storage bubble of adequate volume for further testing. Bubble development data from surface and subsurface systems are to be compared with numerical predictions of response; agreement or problems will be discussed in the report. Procedures and plans to control bubble development will be developed and approved prior to test initiation.

10.2.9 Cyclic Air Injection and Withdrawal

This task covers the central and most important function of the field test--prototypic injection and recovery of air in an actual aquifer storage system over time periods and cycles that are typical of CAES operations. The basic test plan for cycling calls for four isothermal cycling periods of 3 months each. The isothermal temperatures are specified as 50°, 100°, 150°, and 200°C with pressure-balanced and mass-balanced cycles. Cycling options will be developed prior to testing and approved by PNL.

10.2.10 Post-Test Coring, Core Analysis, and Disposition

This task covers maintenance, handling, and disposition of pre- and post-test cores prior to and during testing. It also controls the post-test coring work, which consists of drilling a single well for coring purposes as close as feasible to the injection point.

10.2.11 Decommissioning and Site Restoration

All items of equipment, structures, foundations, pipelines, and utility lines and connections will be removed when testing is complete. All wells will be grouted in accordance with Illinois state regulations relating to the abandonment of oil and gas wells. All damages caused by construction, operation, ingress, and egress will be repaired or compensated. The land will be restored, as nearly as practicable, to its original condition. Current budget conditions may preclude performance of this activity, so this responsibility may be transferred to others.

10.2.12 Technical Reporting, Interpretation and Data Transmittal

This activity covers preparation of technical reports related to field test activities, interpretation of field study results in light of prior experimental and numerical studies and applicable storage experience, and the recording, storage and transmittal of raw and processed data from field study instrumentation.

Formal and informal reports are to be prepared as follows:

- annual report and annual contractors' review
- monthly management and UCRS reports
- well field development report
- surface facility design
- test planning report
- instrumentation system report
- test facility description report
- operations and maintenance manual
- bubble development report
- 50° cycling report
- 100° cycling report
- 150° cycling report
- 200° cycling report
- final report.

Interpretation of data from the field test shall be the joint responsibility of all parties in the field study, with specific control of direction resting with PNL. Data storage and transmittal shall be open and relatively continuous, with both hard copy and recorded version maintained according to approved QA procedures.

10.3 TECHNICAL PROGRESS

The exploration phase of the field study project was completed early in this reporting period and will be reported here only briefly. Design and construction tasks (described in Sections 10.2.4 to 10.2.7) constituted the major activity after the construction permit was

acquired in June 1981. Currently, fabrication and construction activities are well underway, all major procurements have been placed, and operations startup is scheduled for September 1982. Progress on a task-by-task basis is described below.

10.3.1 Project Management and Technical Support

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

The project management aspects of this task changed as the project made the transition from the exploration to the design and construction phase. Exploration required PNL to administer many small subcontracts for activities such as geologic assistance, site leasing, legal assistance, drilling, coring, seismic exploration, and core evaluation in addition to integrating this work with PNL technical administration and reporting to the sponsor. The design and construction phase began when PB-KBB was selected as the main contractor on a single, much larger subcontract. The management role with respect to integration with other technical contributors and reporting to the sponsor remained relatively unchanged. However, PNL's administration and technical support role with respect to the PB-KBB subcontract during the well field development phase became more of a review and approval function under the defined work scope rather than direct management. Facility design, construction, and instrumentation work has required more direct management, more control of subcontractor activity and careful review of second-tier subcontractor procurements because of budget considerations. The project has been hindered by budget uncertainty and some contracting difficulties, but is currently on a firm construction schedule aimed at initiation of operations in September 1982.

10.3.2 Permitting

Two critical achievements occurred during this reporting period. First, when the exploration activity was completed, a Form A

construction permit request and technical and environmental feasibility report were filed with the Illinois Environmental Protection Agency. This permit request was one of the first received by the IEPA under their interim Underground Injection Code rules and therefore received careful scrutiny. A series of meetings and comment responses ensued to clarify the CAES field test details to the IEPA staff. The permit allowing construction activities to begin was issued in June 1981. PB-KBB then initiated site drilling activities.

Second, during the construction phase, a work plan of technical requirements to fulfill IEPA requirements for the Form B operations permit and its associated well completion report was defined and implemented. Both PB-KBB and PNL were involved in the Form B preparation and submittal. Initial responses from the IEPA have been positive. Followup commentary is currently underway and final receipt of the operations permit is expected before the end of August 1982.

10.3.3 Exploration

The exploration task was completed during the first quarter of this reporting period. The primary activity was analysis of data and materials from exploration activities during the preceding year. Core and water samples from exploratory drilling were analyzed and reported on by subcontractors to PNL or PB-KBB. An extensive submittal was prepared by Dames & Moore, site geologic consultant, for inclusion in the Form A permit process. Dames & Moore also synthesized the exploration phase of the project in an extensive two-volume report. Topics covered included regional environmental and geologic data, drilling and coring records for the 11 structural test wells sunk during this activity, lithologic and geophysical logs from the holes, and a summary of the seismic exploration and interpretation work performed on the Pittsfield structure.

The results of this task provided a solid data base defining the site, structure, and materials available at the Pittsfield site and allowed the design and construction contractor to proceed confidently with development of the field test facility.

10.3.4 Surface Facility Design, Procurement, and Construction

Design of the surface facility was initiated midway through this reporting period based on the general requirements of the PB-KBB scope of work, and the more specific requirements resulting from the PB-KBB proposal and technical interactions between PB-KBB and PNL. The surface facility consists of the air compression plant, the process and surface instrumentation equipment, and the civil work and structure necessary to site and house this equipment, as well as the surface equipment and data acquisition system associated with the downhole instrumentation.

The air compression plant was originally planned to be an electric powered 1250-scfm, 300-psi package system purchased for the field test. Investigation of prime mover power sources indicated that natural gas was an economic choice with respect to high local rates for electricity. Further cost analysis indicated that the compression equipment, if provided with an oil cleanup system to provide oil-free air, could be leased, resulting in capital and cash flow benefits, and minimize maintenance and demobilization concerns. Compressor package lessors were consulted and a lease/maintenance agreement and technical specification for this equipment were formulated.

BCC Engineering of Midland, Texas was selected by PB-KBB to provide the air compression plant. The plant consists of a complete skid-mounted compressor system. The prime mover is a naturally aspirated natural gas fired 400-hp diesel engine driving a four-stage intercooled and aftercooled reciprocating compressor. The compressor is of the balanced force design, minimizing foundation problems, and has adjustable clearance pockets to allow significant variations in pressure ratios. This, along with throttle control, will allow the operational flexibility necessary to match the compressor system to the reservoir response. The skid contains a radiator type air cooling system that provides for engine cooling, interstage cooling, and aftercooling, so that it is fully self-contained; natural gas comes on the skid, compressed air comes off. The lease agreement also provides for inclusion of a full-time operator/maintenance man who is local to the

Pittsfield area. The lessor is thus fully responsible for compressor operation and maintenance. The compressor skid is due on site during August 1982.

The process and instrumentation equipment has been designed and procurements placed. BCC Engineering of Midland, Texas is the fabricator and installer. The equipment is primarily skid-mounted to allow the maximum advantages of shop fabrication. Process equipment, as provided along the flowpath, begins with an oil and particulate filtering system and associated valving at the point where compressor air is delivered. Downstream of this is an air dryer; at this point inlet air is at instrument air quality standards. Air then flows either to a gas-fired package heater for temperature control or then bypasses to the backpressure control system and to the instrumentation station. It then goes through a shutoff valve prior to delivery to the wellhead. Return air is routed through a scrubber in case liquid water is withdrawn, then passes through instrumentation stations again. A backpressure control valve is provided to set withdrawal pressure that correlates to the withdrawal flow rate, and air exits through a muffler.

Instrumentation provided on this equipment includes pressure, temperature, flow rate, and humidity measurement on the process air. This information is routed to a data logging system that processes data and provides operational and test data to both the operator and to diskette storage. Other instrumentation information is routed to power-operated valves or to self-contained packages such as the heater and dryer to control their operation. The control system is designed to operate at constant pressure for either injection or withdrawal with flow rate then measured to determine reservoir response. The system is flexible and pressure can be quickly adjusted to alter flow rates.

Civil aspects of the surface facility include the access roads, foundations, drainage, and sewage systems. These are currently complete or near completion. A package building is being provided to shelter the operators, most process equipment, and the injection and close-in

monitoring wells, and to provide a controlled environment for both the surface instrumentation, and the data acquisition and processing systems described in Section 10.3.7. Utilities for the facility include 200-amp electrical service from the Illinois Rural Electric Cooperative and water routed from the adjacent Pike County water district. Natural gas, the primary power source, is provided by the City of Pittsfield through a new gas line laid for this project from the western end of Pittsfield.

10.3.5 Well Field Development

Well field development began in mid-June 1981, and represented the first phase of construction. The first well, the injection/withdrawal well, was drilled at the peak of a small second-order dome on the highest point of the Pittsfield anticline. The well was drilled into the St. Peter, cased with 7-in. casing and cemented back to the surface by the beginning of July. The casing was carefully torqued and steam injection well techniques and materials were utilized for cementing. Figure 10.1 illustrates the final well design; the tubing, packer, and screen will not be installed until just prior to air injection, scheduled for July 1982. The screen will be gravel-packed in place to control sand production from the loosely cemented "green" sandstone at the top of the St. Peter formation. Caprock core and approximately 15 ft of St. Peter core were also taken from this well.

Six monitoring wells of two types (designated A, B, C, D, F and G in Figure 10.2) were then drilled to complete the preinjection well field. Well E, a post-injection well, will be drilled at test completion to acquire core for comparative evaluation. Wells A, B, C, and D are sampling and logging wells, drilled at 90 to 210 m north, east and south of the injection well. Their purpose during the test is to monitor bubble thickness but, because of their locations, they also provided valuable additional data to confirm the structure. These wells were cored to various depths in the St. Peter and 2-7/8-in. tubing was cemented in place to bottom hole. Wells F and G (see Figure 10.2) are close-in monitoring wells to provide instrumentation locations quite close to the injection/withdrawal well. They were drilled after the

FIGURE 10.1. Injection/Withdrawal Well Design

FIGURE 10.2. Locations, Elevations, and Bottomhole Deviations of Pittsfield Wells

other wells to permit use of deviation allowances and trends from previous drilling that could be used to precisely locate them with respect to the injection/withdrawal well bottomhole location. Bottom-hole separation after the controlled drilling was maintained with 1% of the surface separation, with well F at 3 m from the injection/withdrawal well and well G at roughly 8 m away. These wells were drilled to the top of the St. Peter formation, cased with 7-in. casing and fully cemented in place. Then these wells were cored into the St. Peter, 20 ft taken in F and 50 ft taken in G. These wells will be instrumented, gravel-packed and cemented closed prior to testing.

The well field development, consisting of seven wells, was completed in October 1981.

10.3.6 Water Sampling

Limited pump testing was performed on the injection/withdrawal well in February 1982 to provide water samples for the Illinois Environmental Protection Agency Form B permitting. This testing was to characterize the hydraulic conductivity of the formation, but the injection/withdrawal well did not expose sufficient surface to the formation in its current condition. Another small pump test is scheduled for May 1982 to acquire extra formation water for experimental purposes.

Water samples from these tests were analyzed by the State Water Survey of the Illinois Institute of Natural Resources. Results were compared with those previously reported Dames & Moore and were quite similar; the more carefully acquired recent samples were slightly higher in alkalinity and total dissolved solids. Future work will consist of minor cleanout pumping of the injection and instrument wells at the time of final equipment installation.

10.3.7 Subsurface Instrumentation

The subsurface instrumentation design was based on the initial PB-KBB proposal, but the design has undergone extensive evolution during this period to emphasize reliability and reasonableness of cost through use of proven state-of-the-art sensors. Energy Resource Management of Tucson, Arizona is assisting PB-KBB with this effort.

Design of the instrumentation system consisted of sensor selection and calibration, lead routing, and installation method determination and integration of sensors with the data acquisition system. Permanent downhole instrumentation is provided only in the near wellbore region where continuous recording is necessary. More distant monitoring wells will have surface pressure sensors and will also be used for neutron logging to determine air/water interface location. The close-in wells F and G will have multilevel measurement stations at different distances and azimuths from the injection well to gain a three-dimensional appreciation of reservoir response. The instruments are capable of measurement in three different environments: relatively dry rock with warm to hot air flow; partially saturated cool rock with both air and water flow; and fully saturated rock at ambient or flow induced pressure levels. Installation will be embedment in an Ottawa sand pack within the open boreholes to simulate actual in situ conditions. Sensors to be used in wells F and G (see Figure 10.3) include:

- temperature - platinum resistance elements - T
 - thermocouple psychrometers - TCP
- pressure - diaphragm, strain gauge - P
- humidity - thermocouple psychrometers - TCP
 - cellulose crystal strain gauge - SGS
- water content - thermocouple psychrometer - TCP
 - nylon resistance block - PAD.

Well G will have four monitoring levels; Well F will have two levels. The stations will each be capable of the full range of measurements. All leads will be bound into a single cable and will be prechecked and calibrated as a unit. These instrumented cables will be run in the hole and carefully gravel-packed in place. The wells will be sealed, cemented back to the surface to preclude leakage, and will require only removal of the wellhead and cutoff for demobilization. In addition, logging tools may be used in a closed tube in the near wellbore region as a backup. This would be done in a separate logging well if sufficient funds are available.

INSTRUMENT WELLS 'F', 'G'

FIGURE 10.3. Cross Section of Closed-Instrument Wells

Wells A, B, C, and D are the sampling/logging wells configured as shown in Figure 10.4. They will be provided with a surface pressure monitor as the only continuously recorded output. These wells are well outside the thermal region, and pressure response and air storage bubble thickness are the measurable quantities of interest. The surface pressure reading will provide bubble development information and will imply local bubble thickness. Bubble thickness will be determined directly by neutron thermalization logging tools intermittently run in the holes through a wellhead lubricator. This is the standard bubble measuring tool used by the natural gas storage industry. These wells will also be perforated to allow for air and water sampling.

The injection/withdrawal well will also be instrumented for downhole pressure, temperature, and relative humidity. These instruments will be installed in the well screen area with leads run up through the injection tube. This instrumentation station will be recoverable.

FIGURE 10.4. Sampling/Logging Well Design

The instrumentation system consists of over 30 channels of data requiring recording, digitization, processing, and storage. The data stream will require varying sampling rates depending on the process being monitored (e.g., bubble development, cycling). Therefore, a minicomputer data acquisition system has been selected to control reading intervals, to file raw data, to perform some processing for monitoring reservoir response, and to output to both hard copy and diskette storage.

The design of the subsurface instrumentation system is complete, most procurements have been made, and calibration and assembly are well underway. A formal design report is due during June 1982 and field installation is scheduled for two weeks during August 1982.

10.3.8 Bubble Development

Work on this task is scheduled to begin in September 1982. The air bubble will be injected using dry air with relative humidity of less than 5% at a temperature close to that of the natural reservoir. Air is

to be injected near the top of the St. Peter sandstone over an approximately 2.5-m interval. The air injection pressure is to be less than 2070 kPa (300 psi) with a flow rate limit of approximately 35.4 scmm (1250 scfm). This will enable displacement of ground water within the aquifer, which has a discovery pressure of 1035 to 1104 kPa (150 to 160 psia).

The injected air will be monitored for relative humidity, temperature, pressure, and mass flow rate at the surface. Temperature will also be measured near the bottom of the well in the wellscreen section.

Calculations of bubble growth, based upon numerical methods similar to those used to compute natural gas storage volumes, have yielded approximate values of bubble volume versus time. After 60 days of injection, the "50% saturation front" had a computed radius of more than 350 m and computed thickness of 14 m. The total volume of air injected will be approximately 110×10^6 scf. The projected bubble dimensions at equilibrium are radius 500 m and center thickness 20 m. These calculations have been used as a guide in monitoring well layout and scheduling injection. The final bubble dimensions are sufficiently large to enable short-term cyclic withdrawal and injection without causing large variations in the bubble's areal extent or thickness.

10.3.9 Air Cycling

This task is scheduled for initiation in the Fall of 1982.

Air cycling is prescribed to simulate the operation of the unit length of a producing section of one well of a full-scale CAES aquifer installation. Definition of exact cycle period, injection temperature, injection pressures, mass flow rates, air humidity, and number of cycles at each temperature depends on numerical modeling using the specific characteristics of the reservoir. This work is currently underway based on a series of numerical models developed at PNL during previous research. The frequency will be one cycle per day with approximately 7 hr injection followed by 11 hr withdrawal, a 6-hr rest period, and equal

air masses injected and withdrawn. The injection pressure will not exceed 50% of the minimum laboratory-measured threshold pressure integrated for the total caprock thickness.

The baseline test matrix consists of injection at four temperatures varying from 50°C (122°F) to 200°C (392°F) in steps of 50°C (122°F). On the basis of 3 months of cycling per step, this cyclic testing matrix requires 12 months.

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

Work in the air cycling task and all subsequent effort is currently planned to be partially or wholly supported by the Electric Power Research Institute.

10.3.10. Post-Test Coring and Core Disposition

Core from the well field development was distributed to Davies, Almon and Associates, a PB-KBB subcontractor, and to PNL aquifer experimental tasks. After analysis, all core will be given to the Illinois Geological Survey for final disposition.

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

10.3.11 Decommissioning

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

10.3.12 Technical Reporting, Interpretation and Data Transmittal

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

QA Plan	February 1982	Received
Well Field Development Report	March 1982	Received
Surface Facility Design	April 1982	Received
Test Plan Report	May 1982	Received
Instrumentation System Report	June 1982	Scheduled
Test Facility Description Report	August 1982	Scheduled
Operations and Maintenance Report	August 1982	Scheduled
Bubble Development Report	November 1982	Scheduled
50°C Cycling Report	February 1983	Scheduled
100°C Cycling Report	May 1983	Scheduled
150°C Cycling Report	August 1983	Scheduled
200°C Cycling Report	November 1983	Scheduled
Final Report	January 1984	Scheduled

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

10.4 CONCLUSIONS

The Pittsfield, Illinois CAES aquifer field test involves simulation of full-scale air storage with a shallow confined and

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

10.5 PUBLICATIONS

Major publications describing aspects of the field study include:

Allen, R. D., "Basis for CAES Field Test at Pittsfield, IL," Proceedings of International Conference on Seasonal Thermal Storage and Compressed Air Energy Storage, CONF-811066, Vol. 2, Seattle, Washington, October 19-21, 1981.

Allen, R. D. and T. J. Doherty, "Aquifer Stability Investigations," CAES Seminar and Project Report sponsored by Electric Power Research Institute, Department of Energy and Public Service Indiana, Chicago, Illinois, September 17-18, 1981.

Dames & Moore, Inc., Geologic and Hydrologic Input to Feasibility Study for Battelle Pacific Northwest Laboratories, Park Ridge, Illinois, 1981.

Istvan, J. A., "CAES Aquifer Experiment at Pittsfield, IL," Proceedings of International Conference on Seasonal Thermal Storage and Compressed Air Energy Storage, CONF-811066, Vol. 2, Seattle, Washington, October 19-21, 1981.

Wiles, L. E., R. L. Erikson, R. D. Allen and T. J. Doherty, "Numerical and Experimental Analyses of the Porous Medium Reservoir at Pittsfield, Illinois," Proceedings of Mechanical, Magnetic and Underground Energy Storage 1981 Annual Contractors' Review Meeting, Washington, D.C., August 24-26, 1981.

11.0 LABORATORY TESTS OF SALT SPECIMENS SUBJECTED TO LOADINGS
AND ENVIRONMENTAL CONDITIONS APPROPRIATE TO A
COMPRESSED AIR ENERGY STORAGE RESERVOIR

R. L. Thoms and R. M. Gehle
Louisiana State University

11.1 GENERAL OBJECTIVES

Program objectives were to perform laboratory tests and to formulate long-term stability criteria for compressed air energy storage (CAES) reservoirs in rock salt. Criteria will be based on data obtained from laboratory tests at Louisiana State University (LSU) and also from in situ tests performed in southern Louisiana salt mines. The resulting criteria should optimize long-term utilization of CAES reservoirs in rock salt.

11.2 TASKS UNDERTAKEN

The required work effort was divided generally into conventional laboratory tests and in situ tests in salt mines.

11.2.1 Task 1. Laboratory Cyclic Thermal and Mechanical Testing of Salt

The objective of this task was to determine deformation and property alteration of rock salt subjected to steady-state and cyclic mechanical and thermal loads associated with CAES reservoirs. Effects to be monitored included changes in permeability and acoustic emissions. Salt specimens from at least four different sources were tested to check for possible variations in salt response.

11.2.2 Task 2. In Situ Slant Borehole Pressure Cycling Testing

Boreholes were slant-drilled beneath pillars in salt mines and subjected to cyclic pressure and thermal loads such that hole diameter changes (diametric displacements), acoustic emissions, and possible salt degradation were monitored. Correlation between values obtained with this in situ test program and laboratory tests was to be analyzed.

11.2.3 Task 3. In Situ Permeability Measurements

Permeability was to be investigated in situ at several locations in the Cote Blanche salt mine to determine effects of amounts of impurities in salt and loading history.

11.2.4 Task 4. Development of Stability Criteria

The objective of this task was to develop quantitative criteria for long-term stability of CAES reservoirs such that plant operators may utilize these criteria for planning operations to be as cost-effective as practical.

11.2.5 Task 5. Reporting

Monthly reports and a final report included data and findings of the test program along with stability criteria development for CAES salt reservoirs.

11.3 TECHNICAL PROGRESS

11.3.1 Task 1. Cyclic Thermal and Mechanical Testing of Salt

Table 11.1 illustrates the matrix of laboratory tests selected for performance on cylindrical specimens from a typical salt source. Axial and lateral stress conditions are given, along with elevated temperature conditions. Each column represents the test schedule, from top to bottom, for two cylindrical salt specimens. The specimens typically had length and diameter respectively of 8 in. (200 mm) and 4 in. (100 mm). Not shown are Brazillian tests, which were performed on three specimens from each source of salt tested.

Specimens of salt were obtained from a relatively large number of domes; however, an adequate amount to perform a major number of tests shown in Table 11.1 was obtained from a smaller number of the same domes. Brazillian tests were performed on all of the salt sources selected for study.

TABLE 11.1. Stress Conditions for Tests, psi (6.9 kPa)

	<u>Uniaxial Compression</u>	<u>Triaxial Compression</u>	<u>Triaxial Compression</u>
Creep (A)	1000 Axial 0 Lateral	1500 500	750 2500
	2000 0	3500 1500	1000 3500
Cyclic (B)	500-1000 0	1000-5000 0-500	450-750 2250-2500
	1000-2000 0	3000-3500 1000-1500	750-1000 3000-3500
Cyclic/Thermal (C)	Maintain cyclic stress conditions. Elevate temperatures to 180°F.		

For laboratory tests salt was studied from the following sources: Avery Island, Jefferson Island, West Hackberry, Bayou Choctaw, Bryan Mound, Vacherie, and Rayburn's salt domes. In addition, salt was obtained from the Huntorf dome in West Germany and the Red Lake deposit of north-western Arizona. Time and cost limitations did not permit obtaining and testing specimens from the bedded salt deposits of the U.S., although the opportunity existed to core specimens from at least one mine in Kansas.

Table 11.2 indicates tests completed on cylindrical specimens as of late March 1982. The final column of relatively high pressure triaxial extension tests represents tests most difficult to perform, and subsequently left until last to execute. Some modifications of these conditions are likely, for specimens tested to date failed very soon after testing was initiated.

TABLE 11.2. Tests Performed According to Table 11.1

	<u>Uniaxial Compression</u>	<u>Triaxial Compression</u>	<u>Triaxial Compression</u>
Bryan Mound	2, 4(A,B)	4, 1(A,B)	2, 1(A,B), 3(A)
Bayou Choctaw	1, 1(A,B)	4(A,B)	
West Hackberry	2	2, 1(A,B)	2(A,B), 3(A)
Rayburn's	1	1, 1(A,B)	In progress
Vacherie		In progress	

*Numbers = Number of specimens tested, Letters = Phases completed according to Table 11.1. Numbers only indicate all phases completed.

Figure 11.1 represents data from a test that was carried through the typical three phases of testing, i.e., static loads, cyclic loads (both at room temperature), and cyclic loads at elevated temperatures. These data indicate elevated temperature affected salt deformation more than cyclic loading under at least one load environment typical of a CAES reservoir.

Permeability tests were performed on Jefferson Island salt in a modified triaxial cell to obtain the results indicated in Figure 11.2. Data indicated salt was strongly dependent on its history; i.e., if subjected to extensional strains or lack of confinement, it exhibited measurable values of "induced" permeability. The combination of increased confining pressures and a relatively few cycles of load caused salt specimens to exhibit permeability that decreased to immeasurably small values (Figure 11.2).

FIGURE 11.1. Long-Term Triaxial Extension Test with Cycling Loads

FIGURE 11.2. Permeability of Jefferson Island Rock Salt

11.3.2 Task 2. In Situ Borehole Pressure Cycling Testing

In situ borehole testing was moved to the Cote Blanche salt mine in early 1981, following flooding of the original in situ test site in the Jefferson Island mine on November 20, 1980.

Twelve test holes were slant-drilled beneath a mine pillar by Domtar, Ltd., with typical configuration indicated in Figure 11.3. Four test holes were prepared by reaming and "epoxying" nominal 2-in. aluminum pipe to depths of 8 ft (2.44 m). Of the remaining holes, two were used for "flatjacks" for monitoring stress, and four others were used for monitoring acoustic emissions and for performing cross-borehole permeability tests.

FIGURE 11.3. Typical Borehole for In Situ Tests

Figure 11.4 depicts data obtained by pressurizing a hole with air and monitoring diametric displacements, acoustic emissions, and corresponding applied pressures. The test was started with a static phase and then continued with a cyclic phase. Short-term response of the salt to applied pressure was approximately linear, with a long-term creep closure effect due to the overburden.

The air pressure test apparently caused no significant damage to the salt as indicated by acoustic emissions (AE). The hole was later pressurized to a relatively low value of 550 psi (3.8 MPa) with air and no significant AE was recorded. Safety considerations thereafter required the use of oil (or other essentially incompressible liquid) as a pressurizing medium for larger values of applied pressure.

High pressure tests next were carried out to progressively load salt until fracture occurred. These hydraulic fracturing tests yielded valuable in situ test data for "threshold" performance of CAES reservoirs in salt.

Figure 11.5 illustrates the test set-up for the high pressure testing, and Figure 11.6 depicts data corresponding to the initial fracture of the borehole. The AE data clearly defined the fracture of the salt around the hole.

Following initial fracture of the hole at approximately 2500 psi (17.2 MPa), the hole was repressurized to slightly less than this value [approximately 2300 psi (16 MPa)] repeatedly (seven times). This illustrated the characteristic of the salt to reseal under overburden effects even after being previously "hydro-fractured".

Follow-up testing on the fractured hole included additional loadings to apparent fracture (or loss of fluid-holding capacity) and repeated cyclic loadings at less than short-term, post-fracture pressure capacity. The final test series indicated that, under repeated cyclic loads, the hole tended to lose fluid (oil) through the surrounding salt, with some retained in a neighboring hole. Thus, the fluid-holding capacity of the previously fractured hole progressively deteriorated under cyclic loads.

(a) Initial Pressurization

(b) Cyclic Pressurization

FIGURE 11.4. Air Pressurization of Borehole in Salt Mine

FIGURE 11.5. Instrumentation and Apparatus for High-Pressure Oil Tests

FIGURE 11.6. Hydraulic Fracturing for Boreholes in Salt.

From the borehole pressurization tests estimates also were obtained of short-term, in situ deformation moduli for rock salt. An estimate also was obtained for the in situ state of stress around the borehole based on the hydraulic fracturing of the salt. However, this estimate was treated with reservation due to the proximity of neighboring boreholes that could have affected the salt fracturing behavior.

Two trips were made to the Cote Blanche mine to obtain cores from laboratory testing. Experienced personnel used techniques that had been successful in the Jefferson Island mine. However, the primary objective of obtaining cores was not accomplished, because the salt at the in situ site was a fine grained, "weakly cemented" type. The cores could not be retrieved in adequate lengths [8 in. (200 mm)] for triaxial tests, and repeatedly broke apart. Further, "fist-sized" pieces of salt picked off the pillar wall at the site could be broken up by hand. The presence of "weak" salt at the Cote Blanche in situ test site implies that conclusions based on data collected there generally would be conservative in character.

11.3.3 Task 3. In Situ Permeability Measurements

Cross-borehole in situ gas (freon) permeability testing was performed in the Cote Blanche mine at the CAES test site. The test was set up to collect quantitative data; however, no flow through salt between the two holes could be detected over a period of 2 hours. Thus, the in situ permeability of the salt was essentially insignificant.

Laboratory measurements of rock salt, as expressed previously in this report, depend upon state of confining stress and extent of specimen disturbance. For in situ measurements in boreholes it appears reasonable that the character of the overburden stress, location in the mine, and type of drilling used for the boreholes affects results. However, if borehole pressures approach values of overburden stress, apparent permeability is induced.

Significant effort was spent on developing a quick, portable permeability measuring "packer" tool for use in boreholes in the Cote Blanche mine. Plans and a complementary analysis for such a device were

completed, along with an initial model that was field-tested. The packers did not seal adequately against the rough surfaces (helical texture) of holes drilled for blasting in the mine. Time remaining for the project did not permit completion of a second-design model that incorporated a more compliant packer material.

11.3.4 Task 4. Development of Stability Criteria

Dr. Thoms participated in a report on stability criteria with personnel from the Pacific Northwest Laboratory.

11.3.5 Task 5. Reporting

Monthly reports have been presented regularly. A summary report currently is in preparation.

11.4 PUBLICATIONS AND PRESENTATIONS IN TECHNICAL MEETINGS

Gehle, R. M., and R. L. Thoms. In press. "Monitoring Cyclic Load Effects on Rock Salt in In Situ." In Proc. Third Conf. on Acoustic Emissions in Geol. Struc. and Matls, eds. R. Hardy and F. Leighton. The Pennsylvania State University.

Gipson, G. S., and R. L. Thoms. 1981. "On the Transport of Gaseous Matter Through Permeable Media Between Cylindrical Cavities." Int. J. Engr. Sci. 10(8):1095-1100.

Thoms, R. L., and R. M. Gehle. 1981. "Experimental Study of Rock Salt for Compressed Air Energy Storage." In Proc. Int. Conf. on Energy Storage. CONF-811066, National Technical Information Service, Springfield, Virginia.

Thoms, R. L., and R. M. Gehle. In press. "In Situ Response of Rock Salt to Cyclic Loads." In Proc. First Conf. Mech. Behavior of Salt, eds. R. Hardy and M. Langer. The Pennsylvania State University.

PENDING PRESENTATIONS

Thoms, R. L., and R. M. Gehle. 1982. "Test on Rock Salt for Compressed Air Energy Storage." Paper presented at the Spring Meeting of Solution Mining Research Institute (SMRI), April 19, 1982, Albuquerque, New Mexico.

Thoms, R. L., and R. M. Gehle. 1982. "Experimental Study of Rock Salt for Compressed Air Energy Storage." Paper presented at the Symposium on Rock Mechanics Related to Cavern and Pressure Shafts, May 1982, Aachen- West Germany.

PART IV.
COMPRESSED AIR ENERGY STORAGE
Second-Generation Concepts Studies

Individual efforts in support of the Second-Generation Concepts Studies are reported on in this part. Section 12.0 summarizes work toward documenting the CYCLOPS-MOD1 thermodynamic analysis code. The materials screening tests conducted by Fluidyne Engineering Corporation are described in Section 13.0. Finally, thermal/chemical examinations of candidate thermal energy storage bed materials are documented in Section 14.0.

12.0 DESIGN STUDY FOR SECOND-GENERATION CAES CONCEPTS

J. A. Fort

Pacific Northwest Laboratory

12.1 OBJECTIVE

The objective of this task is to prepare a user's manual for the CAES thermodynamic analysis code CYCLOPS-MOD1, complete with simulations of second-generation CAES designs.

12.2 TASK DESCRIPTION

The computer code CYCLOPS-MOD1 has been used to determine the thermodynamic performance of CAES cycles. As noted in the objective statement, the task is to write a user's manual for this code. This manual will include an overall description of the code, a description of each component model, and an input guide describing the input parameters. Simulations of several second-generation CAES designs will also be included in an appendix, to provide sample simulations for the user.

12.3 PROGRESS

The code documentation effort is in progress. A rough draft has been prepared; however, additional information and revisions are still needed.

Inputs have been prepared for the first of five planned design simulations. Conceptual designs are being reviewed for the application design parameters. When needed parameters are unavailable, uniform assumptions will be made for all design simulations.

13.0 COMPRESSED AIR ENERGY STORAGE THERMAL ENERGY STORAGE

MATERIALS SCREENING TEST

FluidDyne Engineering Corporation

13.1 OBJECTIVE

The objective of this program was to perform thermomechanical materials screening tests on candidate thermal energy storage (TES) media for compressed air energy storage (CAES) applications.

13.2 TASK DESCRIPTION

Design studies of adiabatic and hybrid compressed air energy storage systems have indicated technical and economic advantages of storing and reusing the heat of compression developed during the charging phase of the storage cycle. This heat would be stored in sensible heat storage units and returned to the compressed air during the power generation phase. Based on economic and performance considerations, 1.27-cm (1/2-in.) Denstone balls, a fireclay product of the Norton Company, and 0.95-cm (3/8-in.) iron oxide pellets were recommended as the TES media. Other suggested TES media included 2.54-cm (1-in.) cast iron balls and crushed rock.

Compressed air energy storage operating conditions expose the media to thermomechanical and thermochemical effects that could degrade bed performance and create dust that could damage the expansion turbine's blades. Mechanical loads come from the dead weight of the pebble column [heights of 19.8 m (65 ft) are being considered], and from the alternating differential expansion and contraction of the bed relative to the containing vessel during each daily thermal cycle. Pebbles are especially prone to dusting and breakage under such conditions because of the point-to-point contact between the pebbles within the bed. If dust particles are elutriated in sufficient quantity and are sufficiently large, they may cause erosion within the turbines. Large particles from pebble fracture may tend to plug regions within the bed

and thereby reduce its performance as a heat exchanger. Thermal ratcheting outward of the vessel wall each thermal cycle was also considered to be a potential design problem.

Media cost over the typical 30-year life of a plant is also an important economic consideration. The candidate materials ranged in cost from \$10/ton to \$1000/ton at current prices.

Thermal, hydraulic, and mechanical performance of the candidate materials were to be determined, and media comminution and particulate elutriation were to be measured and characterized. The test data would be primarily applicable for media screening and secondarily applicable for design of full-scale TES beds.

13.3 TECHNICAL PROGRESS

Task numbers were assigned for the various operations including design, construction, and shakedown of the test facility as were for the testing of the various materials. As of March 1, 1982, three materials had been successfully tested, and preparations were near completion for the test of the fourth material. The remaining tasks include completion of the fourth test, further work on scaling data to large units, and preparation of a combined FluidDyne-PNL final report.

13.3.1 Test Facility

The thermal cycling test facility was designed to simulate the most critical thermomechanical features of full-scale operation. Budgetary restrictions imposed three limits: operation at atmospheric pressure, reduced bed size, and use of dry gases. Pressure level does not affect the thermomechanical conditions in the bed, so this restriction was not significant. Pressure level can affect particle elutriation. The test was run at nominal full-scale mass velocity so that the gas velocity is much higher than at full-scale as is, therefore, the inertial force to promote elutriation. In this sense the elutriation data are

conservative. Condensation in the bed occurs in the high pressure TES of the adiabatic CAES cycle, but for thermomechanical screening it is sufficient to run a dry test. The dead weight in the static bed is a function of both the bed height and the bed aspect ratio per the Janssen equation, the relationship that accounts for dead weight load dissipation to containment walls by friction. Because load is an important thermomechanical effect a method of loading the bed is used.

The test vessel schematic is shown in Figure 13.1 and a process schematic is shown in Figure 13.2. The externally insulated steel vessel is 0.91 m (3 ft) in diameter and is 6.1 m (20 ft) high. It will accommodate a 4.9-m (16-ft) high bed and flanged sections can be rearranged to accommodate shorter beds. An upper and lower stainless steel grate-and-screen assembly encloses the matrix, and the 445-KN (100,000-lbf) capacity hydraulically driven load simulator transfers its load to the upper grate by means of push rods. The load simulator is pictured in Figure 13.3. The U.S. Department of Energy provided funding for the design and construction of the test facility and for testing of two materials. Funding for testing of two additional materials was provided by the Electric Power Research Institute.

Thermal and hydraulic performance data are obtained from vessel and media temperature sensors and from gas pressure sensors at approximately 30-cm (1-ft) intervals along the bed. A pebble temperature rake also extends across the diameter of the top of the bed. Strain gages and temperature sensors are located on the vessel circumference at approximately the axial midpoint of the vessel. This instrumentation at the point of maximum bed temperature change is to detect any manifestation of vessel ratcheting. Isothermal bed pressure drop and top of the bed velocity distribution measurements are made before and after thermal cycling as well as are strain gage calibration checks by heating the empty vessel walls. Filter samplers are used to measure particulate rate on both the upper and lower air outlet lines. An additional particulate measuring station in the upper, hot air outlet

FIGURE 13.1. Test Vessel Schematic

FIGURE 13.2. Test Loop Process Schematic

FIGURE 13.3. Load Simulator

provides size distribution by classifying the particulate into eight size ranges. Relative bed motion is obtained by a position indicator on the hydraulic rams.

Each batch of pebbles is inspected before and after thermal cycling and photographs are taken during bed removal at approximately 30-cm (1-ft) increments. Bulk density is measured and elutriated particulate is chemically analyzed to determine the amount of iron oxide scale, if any, that came from the piping.

Two tests used for quality control in the production of iron ore pellets are used to give a relative ranking of the different materials and of the relative effects of thermal cycling. These are the ASTM E-279 Tumble Test and ASTM E-382 Compression Strength Test. Post-test samples are taken from three bed locations: 1) the bottom of the bed, which is the region of maximum thermal shock; 2) the middle of the bed, which is the region of maximum temperature change; and 3) the top of the bed, which is the region of maximum exposure to high temperature and to maximum mechanical load.

All of the above measurements will reveal changes caused by thermal cycling and some will provide fundamental data that can be used for design. The principal concern, however, is to contribute to the relative ranking of the materials rather than to provide a definitive design data base. The latter will likely require a longer duration test of a selected material to reduce the time scale factor.

13.3.2 Test Conditions

Air filtered by a baghouse is drawn into the test apparatus by a fan. Air either goes to the bottom of the vessel and is heated as it flows upward through the bed, or it passes through a burner fired by propane at high excess air and then to the top of the vessel where it heats the bed as it flows downward through the bed. An automatic controller switches the flow direction according to temperature set points. The bottom of the bed setpoint is used to limit the thermal shock to a representative level, and the top of the bed setpoint is

selected to give equal hot and cold phases. A 4- to 5-hour cycle will usually produce a full temperature change in the middle of the bed at a mass velocity typical of full-scale CAES/TES design concepts. Operator attention is required only for test facility maintenance and to service such instrumentation as the particulate samplers. The majority of the data is automatically logged and monitoring plots of reduced data are periodically issued. The range of test conditions is shown in Table 13.1, and typical bed axial temperature profiles are shown in Figure 13.4.

13.3.3 Bed Materials

The fireclay pebbles, Denstone, were production grade material purchased from the Norton Company at the small lot price of \$650/ton. Annual U.S. production is comparable to the requirements of a single 1000-MW adiabatic CAES plant. Construction of multiple CAES plants will likely require construction of new plant capacity, but may benefit from

TABLE 13.1. Test Conditions

<u>Parameters</u>	<u>Medium</u>			
	<u>Denstone</u>	<u>Iron Oxide</u>	<u>Dresser Basalt</u>	<u>Cast Iron</u>
Bed height, ft	16.3	15	15.5	10
Gas inlet temperature, °F	840	900	900	860
Air inlet temperature, °F	100	105	105	105
Gas flow, lbm/hr	3300	3800	4000	5100
Air flow, lbm/hr	3300	3350	3950	4600
Pressure level	Atmos.	Atmos.	Atmos.	Atmos.
Duration, cycles	116	103	104	--
Duration, hours	420	480	530	--

FIGURE 13.4. Typical Bed Axial Temperature Profile

significant unit price reduction because of the large amount required. No special handling or preparation was done; the material was tested in the as-received condition.

The iron oxide pellets, donated by the Cleveland-Cliffs Iron Company, were production grade material from stockpile and were produced from magnetite ore. Annual production of the U.S. taconite industry is an order of magnitude greater than required by a full-scale CAES plant, and the product is widely distributed throughout the country. Cost is closely tied to iron content and there is little prospect of product improvement or reduction in cost from the current price of approximately \$45/ton. The material was quite dusty and efforts at washing the iron oxide pellets were unsuccessful.

The cast iron balls were purchased from American Magotteaux Corporation at the small lot price of \$1050/ton. High chrome balls, 27%, were selected to maximize corrosion resistance. They were not heat-treated and were tumbled longer than normal in the "knock-out"

drum. Alloys of sufficient hardness can be mass-produced from scrap raw material in automatic machines. Depending upon chrome content and other manufacturing considerations, the large volume price for a CAES plant could be in the vicinity of \$750/ton. No special handling was done prior to filling the bed, and a small number of marked balls ranging from 8% to 32% chrome were placed on top of the bed. Sample balls processed in the sand drum were also placed on top of the bed.

With the assistance of the U.S. Geological Survey and the University of Minnesota Mineral Resources Research Center, candidate rock types were selected, local suppliers were identified and a means of processing the rock was made available. Free quartz is one of the most frequently encountered rock-forming minerals. Unfortunately, its thermal expansion behavior renders it questionable for CAES/TES. In the upper temperature part of the CAES/TES, the thermal expansion coefficient of quartz increases significantly. Because this may cause undesirable thermal stress levels in the host rock, the candidates for the fired rock test were limited to those rocks in which little or no free quartz is incorporated. If the initial rock test yielded encouraging results, the quartz question could be more properly addressed in tests designed specifically for that purpose. Rocks (gabbro, anthracite, and basalt) that do not contain free quartz are common in this region, and are characteristically "tough" and "strong" rock. Railroad ballast grade Dresser basalt rock was purchased from TCI Trap Rock Company for \$6.75/ton, FOB the quarry. In this form it is sharp-edged and ranged in size from 1.27 cm to 5.08 cm (1/2 in. to 2 in.) with irregular shapes. Further processing (autogeneous grinding) was done to yield 1.27+ cm (1/2+ in) material with a round "stream pebble" appearance. Additional washing would likely have further reduced the amount of fine particulate.

13.3.4 Test Results

Testing of Denstone, iron oxide, and Dresser basalt was completed, and testing of the iron balls was in progress at the time of drafting this paper (March 1982). Comparative isothermal pressure results are shown in Figure 13.5. First note that the frictional characteristics of

FIGURE 13.5. Isothermal Pressure Loss Comparison

the rounded but irregular rock are approximately equal to the spherical Denstone and iron oxide. Although fundamental heat transfer data could not be readily obtained in the high thermal conductance bed, the implication by analogy is that the thermal performance of rock will also approximate that of 1.27-cm (1/2-in.) spheres. The iron ball data are lower because of its nominal 2.54-cm (1-in.) diameter. There is little difference between pre- and post-test which is evidence that there was no significant difference in hydraulic performance over the test interval. The axial bed pressure loss profiles at each of these test points as well as the pressure loss data taken during the thermal cycle test were smooth and repetitive giving further evidence that there was no deterioration in hydraulic performance during the test. Typical axial pressure loss data (beginning and end of hot and cold phases during the Denstone test) are shown in Figure 13.6.

Particulate rate measurements as measured by the filter samplers are compared in Figure 13.7. Multiple filter samples from both the upper and the lower gas discharge lines were combined to give an envelope of data. The rates are not excessive with respect to either

FIGURE 13.6. Typical Axial Pressure Loss Data, Thermocycling Test

FIGURE 13.7. Elutriated Particle Emission Comparison

turbine wear or bed wastage over a 30-year design life. There are discernable downward trends over time, and a longer test would be required to determine the limiting rates. Both sampler locations yielded approximately the same results, indicating that the rate may not be sensitive to gravity. The Dresser basalt results are not quite as favorable as those for the Denstone, but the performance difference is apt to be offset by the cost difference between the two materials.

Comparative size distribution data are given in Figure 13.8, which is an interpretation of multiple samples for the test media. The iron oxide particle sizes are significantly higher than the other two materials, and may not be acceptable for fired turbine applications. The other materials, Denstone and Dresser basalt, are apt to be acceptable at the measured elutriation rates (Figure 13.7).

Results from the ASTM tests are presented in Tables 13.2 and 13.3. The crush strength data given for the Dresser basalt are questionable because the strength of many of the samples exceeded the capacity of the test equipment and the rock's irregular shape made the testing procedure difficult. The strength of the cast iron balls also exceeded the capacity of the test equipment. From a crushing strength point of view the iron oxide seemed to improve.^(a) The Denstone seemed to lose strength from the top of the bed downward to the bottom of the bed. The tumbler test (ASTM E-279) results in Table 13.2 do not show a similar decrease in mechanical integrity for Denstone so the loss of strength may not be related to mechanical damage due to thermal shock (at the bottom of the bed) or temperature change (in the middle of the bed). The tumbler test results are a measure of media resistance to handling, and therefore an indication of wear resistance within the bed to thermally induced motion. The results for Dresser basalt are in a different form, because of its wider size variation. These data do not reveal any significant loss with thermal cycling.

^(a) The PNL autoclave tests documented in Section 14.0 showed a decrease in iron oxide test crush strength in the presence of moisture; therefore, the increase in strength in the thermomechanical test may be a direct result of drying the porous media during the test.

FIGURE 13.8. Approximate Comparison of Size Distribution

TABLE 13.2. Compressive Strength Test (ASTM E-382) Results

	Pre-Test	Post-Test		
	Random Sample	Top of Bed	Center of Bed	Bottom of Bed
Denstone (3 lots of 20 specimens each)				
Average, lbf	523	566	415	352
Std. deviation	218	204	109	84
Iron oxide (3 lots of 20 specimens each)				
Average, lbf	360	481	478	449
Std. deviation, lbf	157	126	163	142
Dresser basalt (many specimens exceeded 1000 lbf limit of apparatus)				
Average, lbf	829			
Cast iron exceeded limit of test device				

TABLE 13.3. Tumble Test (ASTM E-279) Results

	<u>Pre-Test</u>	<u>Post-Test</u>		
		<u>Top of Bed</u>	<u>Center of Bed</u>	<u>Bottom of Bed</u>
Denstone (2 post-test samples)				
Before tumble weight fraction, 1/4+	0.9999	1.0000	0.9998	0.9997
Before tumble weight fraction, 1/4-	0.0001	0.0	0.0002	0.0003
After tumble weight fraction, 1/4+	0.9990	0.9992	0.9990	1.0000
After tumble weight fraction, 1/4-	0.0010	0.0008	0.0010	0.0
Iron oxide (2 post-test samples)				
Before tumble weight fraction, 1/4+	0.9995	0.9998	0.9998	0.9995
Before tumble weight fraction, 1/4-	0.0005	0.0002	0.0002	0.0005
After tumble weight fraction, 1/4+	0.9925	0.9760	0.9787	0.9735
After tumble weight fraction, 1/4-	0.0075	0.0240	0.0213	0.0265
Dresser basalt (1 post-test sample)				
Before tumble weight fraction, 3/8+	100	100	100	100
Before tumble weight fraction, 3/8-	0	0	0	0
After tumble weight fraction, 3/8+	0.993	0.985	0.983	0.986
After tumble weight fraction, 3/8-	0.007	0.015	0.017	0.014

Strain gage data were taken throughout the tests, and both recalibration procedures and redundant instrumentation were used. Although cyclic variations in strain were measured, there was no measurable strain accumulation during material tests or between tests. Therefore, to an accuracy of approximately 50 microstrains there was no manifestation of vessel ratcheting. This is a very important result that is applicable for both spherical pebbles and for the rounded but irregularly shaped rock. It is unknown whether these results will also extend to irregular sharp-edged media such as crushed rock.

The results from the chemical analysis of elutriated particulate were inconclusive. The principal objective of the analysis was to quantify the amount of iron oxide that may have come from scale on the piping, and therefore only Denstone and the rock samples were tested. The presence of rust should have been indicated by an increase in iron oxides and a proportional decrease in other species. Instead, there was an increase in iron oxide with an offsetting decrease in alumina.

By observation and by photographic log the only visible damage occurred during the Denstone and iron oxide tests. During bed removal, approximately 5 to 10 broken pebbles could be seen at a given level adjacent to the 0.91-m (3-ft) diameter wall from about 30 cm to 122 cm (1 to 4 ft) below the upper grate. After the iron oxide test, a few broken pebbles were also found in the same region of the bed. Note that this would be the location of maximum normal and radial static pressure as caused by the load simulator. Post-test photographs of Denstone, iron oxide, and Dresser basalt are presented in Figures 13.9, 13.10, and 13.11, respectively. Free floating dust was readily observable throughout the bed before and after the thermal cycling test, indicating that even fine particulates may not freely move through the pebble bed matrix. Further support for this is given by the apparently small influence of gravity on elutriation rate and by noting that the measured elutriated particle size was much smaller than would be predicted. It should also be noted that the iron oxide had the appearance of having more fine dust within the bed after the test. A likely explanation of

FIGURE 13.11. Post-Test Dresser Basalt

FIGURE 13.10. Post-Test Iron Oxide

FIGURE 13.9. Post-Test Denstone

this qualitative observation is that dust adhering to the pellets with the presence of surface moisture was subsequently freed after exposure to the hot, dry gases during thermal cycling.

A typical time-wise axial temperature profile (cast iron test) is shown in Figure 13.12. The thermocouples were located approximately 15 cm (6 in.) radially inward from the containment vessel, and were influenced by a time-dependent, diametrical temperature profile. This profile is caused by 1) the differences between the time constants of the vessel wall and the media, 2) a radial flow distribution profile, and 3) heat losses through the vessel wall. The thermocouple rake was placed approximately 15 cm (6 in.) below the upper grate, and provided the typical results shown in Figure 13.13 (bed cooled or air phase during the iron oxide test). Radial flow distribution data were determined by a pre- and post-test velocity survey of isothermal flow at the top of the bed using the "egg crate" assembly shown in Figure 13.14. Although the data were scattered, the outer 7.6 cm (3 in.) of bed diameter had approximately 10% more flow per unit area than did the interior. There was no discernable differences in performance as measured in the horizontal plane of the bed (from the beginning to the end of the test).

Bed bulk density measurements (in a small container) and net bed height change during thermal cycling are given in Table 13.4. Small cyclic bed height variations were observed during the test, and 100+ cycles were insufficient to clearly determine the asymptote of accumulated bed height change. Iron oxide pellets [because the pebble diameters ranged from 1.59 cm to 0.95 cm (5/8 in to 3/8 in)] and the rock with its irregular shapes and size variation probably are more affected by settling to a maximum packing density. Thus, their net height change is greater than that of the more uniform Denstone. Most of the height change occurred over the initial thermal cycles for all materials.

FIGURE 13.12. Typical Time-Wise Bed Temperature Profile

FIGURE 13.13. Temperature Across Top of Bed

FIGURE 13.14. Egg Crate Assembly for Radial Flow Distribution

TABLE 13.4. Miscellaneous Physical Data

<u>Measured Characteristics</u>	<u>Media</u>			
	<u>Denstone</u>	<u>Iron Oxide</u>	<u>Dresser Basalt</u>	<u>Cast Iron</u>
Maximum dimension, in.	0.5	0.625	2.0	1.0
Minimum dimension, in.	0.5	0.375	0.5	1.0
Shape	Spherical	Spherical	Rounded irregular	Spherical
Bulk density, lbm/ft ³	92	113	130	281
Height change, in.	0.59	2.1	1.8	--

13.4 CONCLUSIONS

The three nonmetallic materials can be ranked solely on the basis of the thermomechanical data. Dresser basalt should be chosen over iron oxide pellets. It is cheaper, stronger, has a lower elutriation rate and smaller elutriated particles, and was not significantly affected by thermal cycling. The thermochemical tests (Section 14.0) will reinforce this with data showing iron oxide's vulnerability to water, and the rock's chemical inertness. Denstone has a lower elutriation rate and smaller particulates than the rock, but both materials' performance may be acceptable to turbomachinery manufacturers. Dresser basalt particulate data may be improved with a better washing procedure. The rock was stronger in the as-received condition than was Denstone; further, Denstone lost crush strength after thermal cycling (see Table 13.2, middle and bottom samples). Comparable crush strength measurements on the rock are not available from the thermomechanical tests. Finally, Dresser basalt is produced in large quantity and is cheaper than Denstone by a factor of 50 to 100. Therefore, Dresser basalt is a very good first choice candidate for any CAES cycle using thermal energy storage.

It cannot be predicted whether free quartz-bearing rock such as granite or even as-crushed (sharp-edged) Dresser basalt would perform adequately. It is anticipated that the closely related rocks such as

gabbro and anorthosite will be good candidates for the CAES application. Additional longer-term testing of 1000 to 2000 cycles will be needed to provide the data base to support construction of a commercial CAES TES. There is, however, sufficient data to prepare and evaluate a design using Dresser basalt or any other of the tested materials.

Because Dresser basalt is so inexpensive and performed so well, it should be considered for general use as a low-cost thermal energy storage material. Its melting point is approximately 1478 K (2200°F), and it is reasonable to expect that it could be used for applications up to 1089 K (1500°F). This is the approximate operating temperature that has been considered for residential, commercial, and industrial thermal energy storage application.

14.0 ADIABATIC CAES DEVELOPMENT, THERMAL/CHEMICAL SCREENING TESTS

K. R. Wheeler

Pacific Northwest Laboratory

14.1 OBJECTIVE

The objective of this subtask is to examine the integrity of candidate thermal energy storage (TES) materials under conditions of temperature, pressure, stress, and industrial contaminated air. Of specific interest is the effect on bed materials of acid producing contaminants in the presence of condensed water. High temperature oxidation is a potential corrosion problem.

14.2 TECHNICAL PROGRESS

14.2.1 Material Selection

For the near term, the direct contact system for absorption of heat of compression is preferred for TES in the adiabatic CAES. In selecting candidate materials for the storage bed, the primary criteria were material cost, energy storage density, true minimum volume, and matrix weight. Based on these criteria, iron ore, granite rock, Denstone, basalt, and several species of cast iron were subjected to a limited thermal/chemical screening study in a simulated TES bed environment.

14.2.2 Thermal/Chemical Test Systems

A conceptual design study by Acres American detailed the low pressure (TES 1) and the high pressure (TES 2) storage bed operating conditions. Analysis showed that special attention should be given to chemically aggressive TES 2 bed operating conditions:

- high temperature
 - pressure = 1215 psia
 - temperature = 896°F
 - environment = dry compressed air

- dew point temperature
 - pressure = 1215 psia
 - temperature = 280°F
 - environment = industrial quality air.

The return air temperature of TES 2 is low enough to experience condensation under almost all conditions. Water condensation combined with certain industrial air impurities creates a potentially highly corrosive acidic environment for TES materials at the lower temperatures. Rapid oxidation and stress at higher bed temperatures may promote serious surface deterioration.

Two test systems were utilized to simulate the low and high temperature conditions. A dry autoclave pressurized to 1215 psia with industrial grade compressed air and heated to 896°F determined materials resistance to this accelerated oxidation condition. Samples of all materials were simultaneously exposed in the unstressed condition. A second system subjected a 0.1 ft³ volume of each material, stacked in a cylindrical column, to 280°F moist air at the dewpoint. Autoclave pressure was again 1215 psia with material column toploaded to simulate stresses created by overburden. The air in this series was intentionally contaminated with 0.5 ppm SO₂ to simulate typical industrial pollution. The water-SO₂ reaction produces the potential for acidic corrosion of materials at these low bed temperatures. Figure 14.1 is a schematic of the autoclave system flowing moist, contaminated gas through the stressed test column. Exposure time for all materials was 30 days.

14.2.3 Material Evaluation

All materials were characterized before exposure by structural examination, weight, mechanical resistance to crushing, failure mode under compressive load, and chemical composition as reported by material supplier.

Structurally, iron ore exhibits substantial porosity. Denstone also shows some void structure, but not nearly as much as the iron ore.

FIGURE 14.1. Simulated TES Material Environment Reaction Column

The various species of cast iron spheres showed the expected shrinkage cracks and voids resulting from their fabrication processes.

Effects of stress, temperature and corrosive environment on candidate materials' ability to perform in a TES application were measured primarily by change in weight and mechanical strength. Changes in surface characteristics and evidence of spallation were also performance indicators.

14.2.4 High (896°F) Temperature Exposure

Small samples of all TES candidate materials were exposed 30 days to dry, 896°F commercial grade compressed air. System pressure was 1215 psia. After discharge, all materials were evaluated by criteria

previously outlined. Table 14.1 presents results of these observations. Several observations can be offered as a useful interpretation of the data shown in Table 14.1. No significant deterioration of materials surface (including internal structure) occurred as a result of high temperature oxidation. Loosely adherent oxides that did form on cast iron below 27% chrome content were small enough in particle size to probably present no serious turbine problem. This observation might not be valid for large volumes of material over long time periods.

Exposure to 896°F temperature for 30 days did, however, produce a statistically significant change in resistance to crushing force for some materials evaluated for strength changes. Denstone was the notable exception, probably due to its high temperature fabrication as a refractory material. The exact mechanism causing strength changes has not been determined.

14.2.5 Dew Point (290°F) Temperature Exposure

Three nonmetals and one cast iron, representing the range of properties and economic factors for TES materials, were exposed for 30 days to 280°F moisture-saturated air, contaminated with 1/2 to 1 ppm SO₂. This contamination level approximated the air at the Potomac Electric Power Company (PEPCO) site. Water (30 cc) was introduced under autoclave pressure (1250 psia) to maintain a dew point atmosphere. Stresses from overburden in a 65-ft high materials column were simulated by mechanically loading the materials test column with a pressurized bellows.

After a 30-day exposure, each material was first visually examined, as the test autoclave was opened, for evidence of mechanical or chemical change (spallation, surface reaction). Weight and strength changes were then documented. Table 14.2 gives results of the exposures on selected TES candidate materials. Weight loss or gain in these nonmetals, particularly those with substantial internal porosity such as the iron ore, might be due to the hygroscopic tendencies of the particular material. This explanation for weight change was tested by subjecting samples of the nonmetals to 138°C deionized water in an autoclave for 66

TABLE 14.1. Changes in Candidate TES Materials After Exposure to Dry 896°F Air

Material	Weight Loss (Gain), %	Crush Strength (lbs)				Visual Observation	Comments
		Pre-Test		Post-Test			
		x	s	x	s		
Taconite (Hanna Mining)	0.04-0.27	521	183	384	182	No change	Mean crush force significantly changed
Taconite (Cleveland Cliffs)	<0.2	462	150	575	202	No change	Mean crush force significantly changed
Granite (Spokane)	0.04-0.27	584	391	-	-	Slight discoloration	
Basalt (Dresser)	<0.2	1794	808	2390	1194	No change	Mean crush force significantly changed
Denstone	No change	503	117	461	77	No change	Mean crush force not significantly changed
Gray Cast Iron	(0.08-0.15)	20880	1877	-	-	Adherent oxide coating	Oxide particles 3-1.5µm (typical)
White Cast Iron	(0.08-0.15)	28800	-	-	-	Adherent oxide coating	Same as Gray
25% Chrome Cast	No change	52655	3366	-	-	Adherent oxide coating	No oxide below iron rich surfaces
27% Chrome Cast	No change	86360	17266	62440	11903	No change	Mean crush force significantly changed

x = mean load

s = standard deviation

TABLE 14.2. Changes in Candidate TES Materials After Exposure to Moist
280°F Contaminated Air

Material	Weight Loss (Gain), %	Crush Force (lbs)				Visual Observation	Comments
		Pre-Test		Post-Test			
		x	s	x	s		
Taconite (Hanna Mining)	0.03	521	183	384	182	Fine powder on test vessel surface. Limited fracture in top pebbles.	No evidence of surface reaction. Significant reduction in crush load.
Denstone	0.006	503	117	462	85	No evidence of pebble breakage or spallation.	No significant change in crush load. Some brown surface staining.
176 Dresser Basalt	<0.2	1794	808	1492	649	No evidence of pebble breakage or surface reaction.	No significant change in crush load.
25% Chrome Cast Iron	No change	52655	3366	-	-	Slight brown discoloration on surface.	Very resistant with chrome rich surface.

x = mean load

s = standard deviation

hours. The materials were then air-dried followed by oven drying. The results of this comparison are shown in Table 14.3.

Taconite 78-81 (Hanna Mining) showed the expected absorption of water subsequently lost at temperature. The Cleveland Cliffs Taconite appears to have absorbed maximum water before autoclaving with subsequent loss at dry oven temperature. Denstone and Dresser basalt do not appear to be hygroscopic. This was also evident in the negligible weight change during the 30-day dewpoint test.

14.3 CONCLUSIONS

All materials tested in this evaluation appear to be acceptably inert chemically to the simulated TES environment. The iron ore materials both experienced statistically significant strength changes when exposed to the autoclaving tests.

High chrome cast iron balls are strong, corrosion resistant, with high heat capacity, but they are extremely expensive and difficult to obtain in large quantities.

Denstone and Dresser basalt are both chemically inert and spallation resistant. The strength change observed in the basalt during high temperature exposure improved its crush resistance. Denstone remained relatively unchanged by any conditions imposed on test samples during these studies. Although both materials demonstrated acceptable properties during these limited thermochemical screening evaluations, basalt gains an additional advantage in cost and availability.

TABLE 14.3. Hygroscopic Tendencies of Nonmetals

Material	A Pre-Exposure (Air-Cleaned)	B Post-Exposure (Air-Dried)	C Oven Dried (200°C, 3 hr)	Δ_1 Exposure B-A	Δ_2 (B-C)	Δ_3 (A-C)
Taconite 78-81	208.82	216.18	208.02	+7.36	- 8.1	- 0.80
Cleveland Cliffs Taconite	235.32	235.44	223.27	+0.12	-12.12	-12.05
Denstone	412.89	412.63	412.59	-0.26	- 0.04	- 0.30
Dresser Basalt	535.37	535.23	534.76	-0.14	- 0.47	- 0.61
Washington Granite	456.53	456.77	451.94	+0.24	- 4.83	- 4.59

NOTES

Exposure: 138°C, 1250 psi, 66 hours
Parameter: Weight Change

DISTRIBUTION

<u>No of Copies</u>		<u>No of Copies</u>
	<u>OFFSITE</u>	
	US Department of Energy Attn: J. Brogan Office of Energy Systems Res. Forrestal Building 1000 Independence Ave., S.W. Washington, DC 20585	Acres American, Inc. Attn: M. J. Hobson The Clark Building Suite 329 Columbia, MD 21044
	US Department of Energy Attn: R. A. Dunlop Div. of Electric Energy Sys. 12 & Pennsylvania Washington, DC 20585	Acres American, Inc. Attn: D. Willett Liberty Bank Building Main at Court Buffalo, NY 14202
	US Department of Energy Attn: I. Gyuk Office of Energy Systems Res. Forrestal Building 1000 Independence Ave., S.W. Washington, DC 20585	Argonne National Laboratory Solar Thermal Storage Program Attn: A. Michaels Building 362 9700 S. Cass Avenue Argonne, IL 60439
	US Department of Energy Attn: R. Shivers Office of Energy Systems Res. Forrestal Building 1000 Independence Ave., S.W. Washington, DC 20585	Auburn University Attn: F. J. Molz School of Engineering Auburn, AL 36830
	US Department of Energy Attn: J. H. Swisher Office of Energy Systems Res. Forrestal Building 1000 Independence Ave., S.W. Washington, DC 20585	Central Illinois Public Service Co. Attn: A. H. Warnke Vice President Power Supply 607 East Adams Street Springfield, IL 62701
	US Department of Energy Attn: Director, Policy and Planning Office of Conservation and Solar Applications Washington, DC 20545	Commonwealth Edison Co. Attn: T. J. Maiman Sta. Mech. Engr. Dept. Mgr. 36 FN West PO Box 767 Chicago, IL 60690
27	DOE Technical Information Center	Electric Power Research Inst. Attn: R. B. Schainker 3412 Hillview Avenue PO Box 10412 Palo Alto, CA 94303

No of
Copies

Fluidyne Engineering Corp.
Attn: L. Marksberry
5900 Olson Memorial Highway
Minneapolis, MN 55422

GeoTrans Inc.
Attn: J. W. Mercer
PO Box 2550
Reston, VA 22090

Harza Engineering Co.
Attn: A. H. Barber
Director of Marketing
150 S. Wacker Drive
Chicago, IL 60606

Illinois Power Company
Attn: G. E. Huck
Manager of Planning
500 South 27th St.
Decatur, IL 62525

Lawrence Berkeley Laboratory
Attn: C. F. Tsang
University of California
Bldg. 90, Room 1012-H
1 Cyclotron Road
Berkeley, CA 94720

Lawrence Livermore Laboratory
Attn: V. E. Hampel
Integrated Information
Systems
Computation Dept, L-275
University of California
PO Box 808
Livermore, CA 94550

Lawrence Livermore Laboratory
Attn: Jesse Yow
PO Box 808
Mail Stop L-202
Livermore, CA 94550

Lawrence Livermore Laboratory
Attn: Tech. Info. Dept, L-3
University of California
PO Box 808
Livermore, CA 94550

No of
Copies

Louisiana State University
Attn: R. L. Thoms
Institute for Environmental
Studies
Room 42, Atkinson Hall
Baton Rouge, LA 70803

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

Middle South Services
Attn: L. A. Wilson
Advanced Energy Program
Section
Box 6100
New Orleans, LA 70161

Minnesota Geological Survey
Attn: M. Walton
319 15th Avenue S.E.
Minneapolis, MN 55455

National Aeronautic and
Space Administration
Asst. Adm. for Energy
Programs
Washington, DC 20546

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

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

Northern Research & Eng. Corp
Attn: Jerry O. Melconian
39 Olympia Avenue
Woburn, MA 01801

No of
Copies

Oak Ridge National Laboratory
Attn: J. F. Martin
PO Box Y
Oak Ridge, TN 37830

Office of Congressman
Sid Morrison
Attn: Kevin Billings,
Legislative Asst.
1330 Longworth Bldg.
Washington, DC 20515

Oregon State University
Attn: Stuart W. Childs
Dept. of Soil Science
Corvallis, OR 97331

PB-KBB, Inc.
Attn: J. Istvan
PO Box 19672
Houston, TX 77024

Potomac Electric Power Co.
Attn: P. E. Schaub
1900 Pennsylvania Ave
Washington, DC 20006

Public Service of Indiana
Attn: T. W. McCafferty
1000 E. Main Street
Plainfield, IN 46168

RE/SPEC Inc.
Attn: A. F. Fossum
PO Box 725
Rapid City, SD 57701

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

Sandia Laboratories
Attn: L. Radosevich
PO Box 969
Livermore, CA 94550

No of
Copies

Sandia Laboratories
Technical Library Div. 3141
Albuquerque, NM 87185

Sandia Laboratories
Attn: William G. Wilson
PO Box 969
Organization 8453
Livermore, CA 94550

Sandia Laboratories
Attn: R. O. Woods
Organization 4715
Albuquerque, NM 87115

Sargent and Lundy Engineers
Attn: W. C. Walke
Project Manager
55 East Monroe Street
Chicago, IL 60603

Solar Energy Research Inst.
Attn: Director
1536 Cole Blvd.
Golden, CO 80401

Soyland Power Cooperative,
Inc.
Attn: R. Ruzich
PO Box A1606
Decatur, IL 62525

Tennessee Valley Authority
Attn: A. Betbeze
1150 Chustnut, Tower 2
Chattanooga, TN 37401

Tennessee Valley Authority
Energy Research Section
1360 Commerce Union Bank
Bldg.
Chattanooga, TN 37401

No of
Copies

Tennessee Valley Authority
Attn: William Waldrop
Asst. Branch Chief
Water Systems Develop. Branch
Division of Water Management
PO Drawer E
Norris, TN 37828

Terra Tek, Inc.
Attn: C. Cooley
University Research Park
400 Wakara Way
Salt Lake City, UT 84108

TRW Energy Systems Group
Attn: E. Berman
Technical Library
7600 Colshire Drive
McLean, VA 22101

Union Carbide Corporation
Nuclear Division
Attn: Library
Y-12 Plant
PO Box Y
Oak Ridge, TN 37830

Union Electric Co.
Attn: E. M. Mabuice
Manager - Applied Research
Corporate Planning Dept.
PO Box 149
St. Louis, MO 63166

University of Massachusetts
Attn: O. C. Farquhar
Dept. of Geology & Geography
Morrill Science Center
Amherst, MA 01003

University of Michigan
Attn: D. L. Katz
Dept. of Chemical Engineering
2042 E. Engr. Bldg.
Ann Arbor, MI 48109

No of
Copies

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

US Army Corps of Engineers
Attn: Library
PO Box 59
Louisville, KY 40202

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

ONSITE

DOE Richland Operations Off.

H. E. Ransom/D. R. Segna

Pacific Northwest Laboratory

R. D. Allen
D. E. Blahnik
S. C. Blair
D. R. Brown
T. J. Doherty
R. L. Erikson
L. D. Kannberg
C. T. Kincaid
D. A. Myers
J. R. Raymond
K. Wheeler
L. E. Wiles
F. R. Zaloudek
Technical Information (5)
Publishing Coordination (2)