Factors Affecting Storage of Compressed Air in Porous Rock Reservoirs

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May 1983

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Richland, Washington 99352

FOREWORD

The Compressed Air Energy Storage (CAES) Technology Program is funded by the Division of Energy Storage Technology (EST) of the U.S. Department of Energy (DOE). The program is charged with developing the advanced technology base necessary for electric utilities to cyclically store compressed air in geologic reservoirs. Low cost baseload electricity, available during off-peak periods, is used to compress air and deliver it to the underground reservoir. The potential mechanical energy is utilized to generate electricity during peak-load periods. This storage technique reduces the burning of fluid fossil fuels to meet peak load demand, which can favorably affect utility revenues and rates. The introduction of this technology requires effective liaison among the government and private research entities and the electric utilities, and the architect-engineers, machinery manufacturers and environmental specialists who serve them.

This document provides these organizations with stability information and guidelines for siting and operating CAES porous media reservoirs (aquifers). A field experiment to examine compressed air energy storage within an aquifer is underway west of Pittsfield, Pike County, Illinois. Cycling experiments are planned for 1983. This document is interim, conditional on completion of that work. The geologic and operational results of this testing will expand and modify the current state of knowledge about porous rock reservoirs.

T. J. Doherty
Compressed Air Energy Storage Project
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SUMMARY

The natural accumulation of liquid and gaseous hydrocarbons in confined anticlinal or domal porous strata makes possible the economic recovery of these resources. The reverse process of storing natural gas within similar stratigraphic traps is widely accepted and well understood. The storage of compressed air in porous medium reservoirs is being investigated as a technique to convert low cost off-peak baseload electricity into mechanical energy for subsequent reconversion during high demand periods. Dissolved salt and mined hard rock caverns are also being examined for this potential application. In the porous medium concept, an air bubble would be generated within an aquifer by delivery of air at a pressure higher than the hydrostatic discovery head. A volume of water equal to the volume of compressed air would be displaced from the near-well region. Subsequent expansion of the stored air mass through a conventional combustion turbine-generator would provide an increment of electrical energy above baseload output to meet peak loads on demand.

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

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

Issues related to the stability of porous rock reservoirs include:

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

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

- A doubly plunging anticlinal or domed sandstone aquifer conformably overlain by impervious shale, dolomite or limestone caprock represents the most desirable geology for a porous rock CAES reservoir.
- The range of parameters that should be considered includes injection temperature (from formation temperature to 200°C), thickness and closure (10 m or more each), permeability (300 md minimum), porosity (10% minimum), depth (200 to 1500 m), storage pressure (2.0 to 15.0 MPa), primary caprock thickness (6 to 10 m or more), a maximum charging pressure of 18.1 kPa/m of depth, and a maximum storage pressure equal to local hydrostatic head.
- Disaggregation of the porous medium can occur as a result of differential thermal expansion, cement dissolution, hydrolytic weakening of silicon-oxygen bonds, and/or other chemical reactions.
- Thermomechanical permeability changes may take place if air is injected at very high temperatures.

- Leakage of air through caprock due to drying or fracture should not be significant if CAES excess pressure over discovery pressure is 0.5 of caprock threshold pressure or less.
- Regional ground-water flow gradients should be insufficient to significantly distort or displace the air bubble within an aquifer.
- Corrosion of well casings is no more a serious problem than with other oil field practice.
- Rock matrix disaggregation and other geochemical effects could restrict maximum injection temperatures to about 300°C. The absolute upper temperature limit for confined media remains to be identified.
- About $15 \times 10^6 \text{ m}^3$ of air storage is necessary to generate the equivalent of 150 to 200 MWh over 8 to 10 hr.
- At least one redundant overlying caprock formation is desirable.
- Air cycling should involve about 10% of the mass of the air bubble due to back pressure maintenance requirements.
- Water coning must not inhibit air withdrawal.
- Injection well completions within the reservoir rock must provide for an adequate area of stable sandface to avert high air velocities and degeneration due to particulate plugging or geochemical reactions.

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CONTENTS

FOREWORD.	iii
SUMMARY	v
ACKNOWLEDGMENTS	ix
FIGURES	xv
TABLES.	xvii
1.0 INTRODUCTION	1.1
2.0 BACKGROUND INFORMATION	2.1
2.1 RELATIONSHIPS BETWEEN AQUIFER AND SURFACE PLANT	2.4
2.2 REGULATORY CONSIDERATIONS	2.6
3.0 GEOLOGIC ISSUES.	3.1
3.1 GENERAL REQUIREMENTS	3.1
3.2 STRUCTURAL CLOSURE.	3.2
3.3 STRATIGRAPHIC REQUIREMENTS	3.3
3.3.1 Caprock Threshold Pressure	3.4
3.3.2 Permeability	3.5
3.3.3 Porosity	3.6
3.4 LITHOLOGIC REQUIREMENTS	3.6
3.5 HYDROLOGIC REQUIREMENTS.	3.8
3.6 SITE QUALIFICATION	3.8
3.6.1 Initial Screening.	3.9
3.6.2 Stratigraphic Confirmation and Rock Characterization	3.9
3.6.3 Seismic Surveying.	3.10
3.6.4 Confirmatory Drilling.	3.10

3.6.5	Ground-Water Testing	3.11
3.7	APPLICATION OF GEOLOGIC CRITERIA TO POTENTIAL SITES . . .	3.13
3.7.1	Candidate Midwestern Aquifers.	3.14
3.7.2	Feasibility in California.	3.14
3.7.3	Public Service of Indiana Site Development	3.17
4.0	OPERATIONAL ISSUES	4.1
4.1	INJECTION PARAMETERS.	4.1
4.1.1	Temperature.	4.1
4.1.2	Pressure	4.2
4.1.3	Near-Wellbore Desaturation Requirement	4.4
4.1.4	Air Cycling.	4.5
4.2	POTENTIAL IMPACTS WITHIN THE HOST ROCK.	4.5
4.2.1	Wellbore Stability	4.6
4.2.2	Differential Thermal Expansion and Fatigue	4.7
4.2.3	Hydrolytic Reactions	4.8
4.2.4	Particulate Plugging	4.9
4.2.5	Mineral Precipitation.	4.11
4.2.6	Oxidation Reactions.	4.11
4.2.7	Well Completion Considerations	4.12
4.3	OTHER POTENTIAL IMPACTS UPON RESERVOIR BEHAVIOR	4.24
4.3.1	Reservoir Medium Compressibility	4.24
4.3.2	Caprock Stability During Overpressurization. . . .	4.25
4.3.3	Seismic Response	4.26
4.3.4	Ground-Water Flow.	4.26
4.3.5	Effect of Wafering on Bubble Configuration	4.27

4.3.6	Rapid or Unscheduled Air Withdrawal.	4.29
4.3.7	Aquifer Pressure Variations.	4.29
4.4	AQUIFER FIELD MONITORING.	4.30
5.0	NUMERICAL MODELING OF RESERVOIRS	5.1
5.1	FUNDAMENTAL RESERVOIR CHARACTERIZATION.	5.1
5.2	NEAR-WELLBORE DEHYDRATION	5.3
5.3	TWO-DIMENSIONAL FLUID AND THERMAL EFFECTS	5.4
5.4	WATER CONING.	5.6
5.5	STRUCTURAL BEHAVIOR	5.9
5.6	APPLICATION TO PITTSFIELD	5.12
5.6.1	Reservoir Description.	5.13
5.6.2	Bubble Development	5.13
5.6.3	Air Cycling.	5.15
5.6.4	Water Coning	5.15
5.6.5	Thermal Development.	5.16
5.6.6	Dehydration.	5.16
5.6.7	Summary.	5.18
6.0	LABORATORY EXPERIMENTS	6.1
6.1	AUTOCLAVE EXPERIMENTS AT PACIFIC NORTHWEST LABORATORY	6.1
6.2	PERMEABILITY EXPERIMENTS AT TERRA TEK. INC.	6.4
6.3	EXPERIMENTAL WORK AT PACIFIC NORTHWEST LABORATORY	6.5
6.3.1	Measurements of Pittsfield St. Peter Core.	6.5
6.3.2	Porous Media Flow Loop Experiments	6.6
6.4	MECHANICAL PROPERTIES MEASUREMENTS AT LOS ALAMOS NATIONAL LABORATORY	6.10

6.4.1	Reservoir Rock Experiments	6.10
6.4.2	Caprock Experiments.	6.13
6.5	AIR VENTILATION EXPERIMENTS AT UNIVERSITY OF WISCONSIN- MILWAUKEE	6.16
7.0	AQUIFER FIELD EXPERIMENT AT PITTSFIELD. ILLINOIS	7.1
7.1	GEOLOGIC SITESCREENING AND CHARACTERIZATION.	7.1
7.2	SITE DEVELOPMENT.	7.6
7.3	DETAILED RESERVOIR CHARACTERISTICS.	7.15
7.4	EXPERIMENTAL PLAN	7.17
7.5	RELATIONSHIP TO FULL-SCALE AQUIFER STORAGE.	7.19
7.6	FORECAST.	7.20
8.0	STABILITY CRITERIA AND GUIDELINES.	8.1
	REFERENCES.	R.1

FIGURES

2.1	Schematic of an Aquifer System	2.2
2.2	Areas Generally Favorable for CAES in Aquifers	2.3
3.1	Reservoir Pressure Behavior for Leaking and Nonleaking Aquifers	3.12
3.2	Reduction of Effective Closure by Facies Change.	3.13
3.3	Typical Statewide Electrical Load Curve for California	3.15
3.4	Potential Site Locations	3.18
4.1	Barefoot Completion.	4.14
4.2	Underreamed. Open-Hole Gravel Pack	4.15
4.3	Cemented. Perforated Casing.	4.16
4.4	Gravel Pack in Cemented. Perforated Casing	4.17
4.5	Wire-Wrapped Liner Completion.	4.18
4.6	Completion Using an Uncemented. Slotted Liner.	4.19
4.7	Pack/Perf Completion System.	4.20
4.8	Wire-Wrapped Liner Inside Cemented. Perforated Casing.	4.21
4.9	Formation Sand Consolidation	4.22
4.10	Gas Wafering During Initial Injection in Aquifer	4.28
5.1	Single Well Within CAES Reservoir.	5.2
5.2	Water Coning During Reservoir Extraction Cycle	5.6
5.3	Well Finite Element Model.	5.10
5.4	Temperature Distribution at the End of Week 1.	5.10
5.5	Temperature Distribution at the End of Week 26	5.10
5.6	Temperature Distribution at the End of Week 52	5.11

5.7	Lines of Constant Saturation (50%) Versus Radius for Different Time Periods During Bubble Development	5.14
5.8	Thermal Development: Radial Temperature Profiles After Final Weekly Extraction Cycle.	5.17
5.9	Radial Saturation Profiles at Various Times During Simulation	5.18
6.1	Percentage Change in Gas Permeability with Temperature	6.3
6.2	Corrosion Data for Carbon Steel A120 Well Casing Material. . .	6.4
6.3	Permeability Ratio Versus Temperature.	6.6
6.4	Gas Permeability Versus Depth. Yakley Wells.	6.7
6.5	Drying Curve for St. Peter Sandstone	6.8
6.6	Vertical Permeability of St. Peter Sandstone to Dry Air. . . .	6.9
6.7	Mohr Failure Envelopes of Galesville Sandstone for Three Temperatures	6.11
6.8	Coefficient of Sliding Friction on Fracture Planes Versus Effective Confining Pressure for Galesville Sandstone.	6.12
6.9	Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated; Fracture Plane Perpendicular to Bedding	6.14
6.10	Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated; Fracture Plane Parallel to Bedding	6.14
6.11	Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C. Dry; Fracture Plane Perpendicular to Bedding.	6.15
7.1	Structure Contours and Seismic Traverses near Pittsfield. Illinois	7.3
7.2	Structure Identified near Pittsfield, Illinois	7.5
7.3	Injection/Withdrawal Well Completion	7.7
7.4	Locations, Elevations. and Bottom Hole Deviations of Pittsfield Wells	7.8
7.5	Wells "F" and "G" at Completion of Coring.	7.9

7.6	Logging Wells "A", "B", "C", and "D"	7.10
7.7	Injection/Withdrawal, "F", and "G" Well Locations.	7.11
7.8	Sensor Deployment in an Instrumented Interval.	7.12
7.9	Sensor Deployment System	7.13
7.10	Schematic of Surface Facility.	7.14

TABLES

3.1	Suitability Evaluation of the Potential Sites.	3.20
3.2	Relative Ranks of the Potential Sites.	3.21
3.3	Suitability Evaluation of the Final Sites.	3.23
6.1	Corrosion Rates.	6.3
7.1	General Stratigraphy near Pittsfield. Pike County, Illinois	7.2
8.1	Stability Criteria and Guidelines for Aquifer CAES Development.	8.2

FACTORS AFFECTING STORAGE OF COMPRESSED AIR IN POROUS ROCK RESERVOIRS

1.0 INTRODUCTION

Compressed air energy storage (CAES) is a technique for supplying electric power to meet peak load requirements of electric utility systems. It incorporates a modified state-of-the-art gas turbine and an underground reservoir--an aquifer, a salt cavity or a mined hard rock cavern (Doherty 1982). The compressor and turbine sections of the gas turbine would be alternately coupled to a motor/generator for operation during different time periods. During nighttime and weekend off-peak periods, low-cost power would be used to compress air that would be stored in the underground reservoir. During the subsequent daytime peak-load periods, the compressed air would be withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. This concept would reduce the consumption of premium fuels by more than 60% for conventional CAES systems. Some advanced CAES concepts currently under development require no premium fuels.

Geologic reservoirs differ with respect to the degree of air pressure variation. Hard rock excavated reservoirs are conceived as water-compensated with nearly constant pressure to minimize excavation volume. Salt cavities are uncompensated because of the economy of salt excavation and the technical and environmental difficulties inherent in brine compensation; therefore, air stored in salt is subject to pressure variations with cycling. Aquifer storage exhibits water compensation over the long term, but acts as a constant volume-variable pressure system for short-term cycling (Doherty 1981). In the typical water drive reservoir a high permeability may allow movement of the air-water interface that nearly compensates air pressure as in a hard rock cavern (Katz 1975).

Engineering studies have shown that the CAES concept is technically feasible and economically viable (Loscutoff et al. 1979). Compressed air energy storage systems offer several advantages over conventional systems used by utilities for meeting peak load requirements. Replacing current gas turbines with CAES plants could result in annual domestic savings of more than 100 million barrels of oil. The net annual oil saving could be greater in the future due to increased power generation. In addition, a well designed CAES plant should have a smaller adverse impact on the environment than a conventional peaking plant.

Over the 30-year proposed operational lifetime, a CAES system's underground reservoir and wells will be subjected to more than 10,000 injection/withdrawal cycles. Each cycle will involve small incremental fluctuations in reservoir fluid pressure and small temperature fluctuations caused by air compression and expansion. The porous rock reservoir will be subjected to daily contact with both water vapor and air. Under this range of conditions, the selection of the rock mass and the quantification of its material properties and geotechnical characteristics are important factors in selecting a reservoir to minimize the risk of either structural or air/water leakage instabilities.

This report documents a review and evaluation of the geotechnical aspects of porous medium (aquifer) storage. These aspects include geologic, petrologic, geophysical, hydrologic, and geochemical characteristics of porous rock masses and their interactions with CAES operations. The primary objective is to present criteria categories for the design and stability of CAES in porous media (aquifers). The document will also describe analytical, laboratory, and field-scale investigations that have been conducted. This should assist those interested in the concept to generate data necessary to establish a consistent and applicable set of stability and design criteria at a given site.

Section 1 introduces the CAES concept. Section 2 presents background information about natural gas storage in aquifers, differences between

natural gas and air storage, favorable geologic areas, geologic exploration techniques and regulatory considerations. Section 3 treats the geologic issues and includes 1) general (siting) requirements, 2) structural closure, 3) stratigraphic requirements (caprock, permeability, porosity), 4) lithologic requirements, 5) hydrologic requirements, 6) site qualification (initial screening, stratigraphic confirmation and rock characterization, seismic surveying, confirmatory drilling and ground-water testing), 7) candidate midwestern aquifers, 8) feasibility in California, and 9) Public Service of Indiana site development.

Section 4 comprises operational issues. These are examined as possible causes for deleterious changes in reservoir or caprock properties and in reservoir behavior as a whole. Injection parameters (Section 4.1) include temperature, pressure, water displacement and air cycling. Potential impacts within the host rock are treated in Section 4.2. These are classified under 1) wellbore stability, 2) differential thermal expansion and fatigue, 3) hydrolytic reactions, 4) cement dissolution, 5) particulate plugging, 6) mineral precipitation, and 7) oxidation reactions. Other potential impacts upon reservoir behavior (Section 4.3) include 1) compressibility of reservoir medium, 2) caprock stability under overpressurization, 3) seismic response, 4) ground-water flow, 5) effect of wafering on bubble configuration, 6) rapid or unscheduled air withdrawal, and 7) aquifer pressure variations. Section 4.4 identifies field monitoring techniques.

The description of numerical modeling studies in Section 5 briefly summarizes the evolution of aquifer CAES modeling at the Pacific Northwest Laboratory. General modeling results are presented for a dry one-dimensional reservoir, a dry two-dimensional reservoir, a water-bearing one-dimensional reservoir, and a water-bearing two-dimensional reservoir. Structural behavior of the caprock and porous medium under thermally-induced CAES stresses is then treated. Finally, the two-phase models were applied to the planned operation of bubble development, air cycling, and

thermal development in a reservoir similar to that at the field test site at Pittsfield, Illinois.

Section 6 is dedicated to laboratory experiments involving typical reservoir and caprock specimens under simulated CAES conditions. These embrace geochemistry, pneumatic properties, mechanical behavior including fatigue, and ventilation. Corrosion of carbon steel casing materials in warm humid air was also studied.

Section 7 covers the aquifer field experiment at Pittsfield, Illinois. This section describes how the test site was screened, characterized, and developed. Detailed reservoir characteristics are presented. The experimental plan is documented, followed by an explanation of the field study relationship to full-scale aquifer storage and a forecast of additional work planned at the site.

Preliminary design and stability criteria are presented in Section 8. The vital importance of well completion techniques in the reservoir is considered. Although many criteria are assigned numbers, others are handled with qualitative statements. Reservoir properties such as depth, pore volume, and permeability are specified in the light of previous storage experience, CAES requirements or numerical modeling predictions. Most geochemical and local geophysical effects are not amenable to calculation. Many geologic factors will be specific for each candidate site.

2.0 BACKGROUND INFORMATION

Utilities have stored natural gas within porous underground formations for more than 50 years. Over 330 gas storage operations are in service or under development in the United States (American Gas Association 1977). More than 50 gas reservoirs occupy formations that previously contained no hydrocarbons. Collectively referred to as "aquifer storage", these facilities are principally in Illinois, Indiana, Iowa, and Kentucky. Other aquifer storage sites are located in New Mexico, Utah, Washington and Wyoming (Bush et al. 1975). The other reservoirs are sited in old oil and gas fields.

The conditions necessary for natural gas storage are similar to those required for compressed air energy storage systems. Thus, natural gas storage technology is an obvious source of knowledge to guide CAES site feasibility studies. An impermeable caprock, a permeable reservoir and some form of structural trap are required to contain either air or natural gas. An anticlinal or domal sandstone aquifer overlain by an impervious shale or carbonate rock constitutes the typical specified site (Chang et al. 1980). A porous medium storage container is shown schematically in Figure 2.1. Several important differences exist between air storage and natural gas storage conditions (Allen and Gutknecht 1980): 1) air storage involves daily or weekly, rather than seasonal, cycling; 2) air has higher viscosity than natural gas; 3) air storage at elevated temperature would be desirable to increase efficiency of energy recovery; 4) frequent pressure, temperature, and humidity cycles may affect performance of the aquifer and/or caprock; 5) the chemical environment produced by air storage may affect the reservoir formation by oxidation of minerals. Issues related to these differences and the standard issues related to the geologic and hydrologic environment are described in subsequent sections of this document.

State-of-the-art turbomachinery requirements, economics, and load-leveling requirements determine the necessary storage pressure. Target aquifers must be deep enough to provide pressure suitable for turbine

FIGURE 2.1. Schematic of an Aquifer System

operation. This pressure is typically determined by both depth and the hydraulic gradient. The latter can range from 9.8 to 11.77 kPa/m (0.433 to 0.52 psi/ft) of depth depending upon the total dissolved solids in the ground water and the water table level. Confined systems can support internal fluid pressures that vary significantly above or below the normal range. Figure 2.2 shows areas with potential for aquifer storage in the 48 conterminous United States. Even in generally unfavorable regions there may be favorable localized geologic sites that could accommodate CAES systems and, of course, the converse is also true. For example, the potential for porous media storage in San Luis Obispo, Santa Barbara, Ventura, Los Angeles and Orange Counties, California, is not revealed in Figure 2.2. Especially favorable for CAES aquifer systems are those areas in the Midwest that are underlain by relatively well sorted quartz sandstones of lower Paleozoic age.

Geologic uncertainties concerning reservoir integrity and volume will be minimized by initiating a comprehensive test plan that usually includes

- 1) adequate laboratory analyses of caprock air confining capacities

FIGURE 2.2. Areas Generally Favorable for CAES in Aquifers (Stottlemire and Loscutoff 1979, p. 670)

(threshold pressure) and reservoir rock air containment and air transmission capacities (porosity and permeability), 2) seismic surveys to confirm stratigraphic continuity and structural containment of confining rock layers and reservoir rocks, 3) exploratory drilling that will characterize the configuration of the caprock and volume of the reservoir, and 4) pressurization of the reservoir to confirm the storage volume and detect poorly completed or abandoned wells or zones of leakage in the caprock (General Electric Co. 1976).

2.1 RELATIONSHIPS BETWEEN AQUIFER AND SURFACE PLANT

Particular relationships between the aquifer reservoir properties and the surface plant characteristics must be identified and quantified. The discovery pressure, permeability, volume, caprock threshold pressure, and water coning tendency of the reservoir bed(s) relate to rates of air storage and retrieval.

Air injection is enhanced by an increase in overpressure. However, at a given overpressure, flow rate into storage is not constant, but decays somewhat with time (Ayers 1975). In a CAES plant, it is not necessary to charge at a constant rate so long as the desired mass of air can be injected in the allotted time. However, a constant delivery rate should be maintained when discharging air from an aquifer into a gas turbine. Because delivery rate from an individual well also decays with time, a CAES plant with aquifer storage must have a sufficient number of wells to maintain the desired air flow rate as a function of time by adding or controlling well deliveries as needed.

Many aquifers can be used with a fixed turbine/compressor system. The water pressure P_s in the aquifer should be between the maximum compressor discharge pressure P_c (upper limit) and the minimum desired turbine inlet pressure P_t (lower limit). When the aquifer pressure P_s rises to near P_c , the overpressure during charging ($P_c - P_s$) leads to small injection rates; this dictates the number of wells required.

Likewise, when P_s approaches P_t , the driving head for discharge ($P_s - P_t$) is small and this dictates the maximum number of wells necessary to accommodate adequate air delivery. Variations in aquifer hydrostatic pressure (because aquifers are found at various hydraulic heads) can be accommodated by a fixed split gas turbine so long as compressor discharge and turbine inlet design pressures bracket the hydrostatic pressure in the aquifer chosen. An intense study of the geology is required to pinpoint the spread in storage pressures to be found in candidate aquifers.

In a subsequent study, Ayers and Berman (1981, p. 604) concluded that compressed air energy storage in an aquifer reservoir presents unique design problems in matching a given set of rotating machinery with a given reservoir which must meet a given duty cycle. In the case of compensated pressure, variable volume air storage, the air pressure in the water-compensated cavity during inflow or outflow remains essentially uniform. In aquifer storage, air pressure varies with time and may undergo large spatial variation due to flow loss in the storage volume. This is because the aquifer reservoir is a permeable solid whereas the cavity is entirely void volume without restricted channels. In constant volume cavity storage the designer has some latitude in selecting the depth and the nominal air storage pressure and must size the volume of the cavity. In aquifer air storage the designer must utilize the reservoirs as they are found, each having its own unique depth, discovery (water) pressure, permeability, porosity, and usable volume. Since air pressure in aquifer storage is related to discovery pressure, it is not a design variable.

Rotating equipment used in CAES systems, i.e., compressors and gas turbines, possesses unique qualities as well. Once selected, their pressure-flow and power-flow characteristics are set. In order to effectively mate the rotating equipment to the aquifer air storage reservoir, instantaneous values of air pressure and flow at the rotating equipment must follow either the compressor or turbine characteristic curve while, at the same time, corresponding air pressures and flows into or out of the aquifer must satisfy pressure and flow conditions within the

reservoir. This match must prevail over the entire duty cycle. Operation of a plant which deviates considerably from its design duty cycle may cause problems. If the match is poor, either the duty cycle or the electrical design input/output will not be satisfied or the equipment may be damaged.

Ahrens (1978) has identified particular parameters that should be optimized to maximize performance and minimize development cost. These include well number, penetration, spacing and arrangement; bubble thickness; and compression time. Specific capital cost items include surface piping, wells, land, CAES plant, transmission lines, and accessory equipment. The large number of design variables requires the investigation of many tradeoffs to achieve an optimal system.

Ahluwalia, Sharma and Ahrens (1978) divided an aquifer-based CAES plant into two subgroups. Subgroup I comprises the motor, compressor train, reservoir, and piping; subgroup II encompasses the generator and turbine system. The two subgroups are linked by the specific flow rate and design inlet pressure of the turbine. For a given power generation capacity, it is possible to optimize subgroup II with regard to equipment arrangement, heat rate, specific flow rate and turbine inlet pressure. Similar computations using the linking parameters of specific flow rate and inlet pressure can be carried out for subgroup I. The two solutions can then be linearly superimposed to determine the overall optimal plant design.

2.2 REGULATORY CONSIDERATIONS

Federal, state, and local regulations must be reviewed to avoid possible legal and institutional problems. Ball and Harris (1975) described storage rights acquisition, definition difficulties, regulation, mineral rights and options. Legal and institutional factors vary widely among states, counties and cities and must be considered on a site-specific basis. Local public utility commissions, commerce commissions, and environmental protection agencies may be involved in the

permitting process. For example, the Illinois Environmental Protection Agency has jurisdiction over injection well construction and operation. On the other hand, in Maryland, individual counties enact legislation governing underground storage (Weinstein et al. 1978).

The surface projection of a suitable storage formation can be extensive. For example, the Brookville Dome was considered for a conceptual CAES design (National Academy of Sciences 1972). Its closure encompasses 4100 acres. The surface requirements for wells and manifolds were also extensive. The area for several alternative 150-MW systems ranged from 108 to 656 acres. The magnitudes of these subsurface storage and aboveground land requirements create far-reaching legal and institutional issues.

Early in the exploration process for siting a CAES system the designer should provide a basis for predicting compliance requirements. This will provide a model for future projects. Later commercialization will be eased by the precedents established if all requirements are well defined. Experience with natural gas storage projects should be utilized as much as possible.

3.0 GEOLOGIC ISSUES

Geologic issues are defined as those innate geologic characteristics that bear upon storage of compressed air within a porous formation. These include aspects of structure, stratigraphy, petrology, hydrology, geochemistry and seismicity. Preliminary quantitative assessments were made by Stottlemyre and Smith (1979).

3.1 GENERAL REQUIREMENTS

An acceptable structure is usually defined as a dome or doubly plunging anticline into which gas can be injected (Katz and Lady 1976). Other varieties of structural or stratigraphic trap may also be suitable for CAES development. For example, a lenticular sandstone aquifer contained wholly within impervious shale could retain compressed air. A confined lenticular porous carbonate reef structure such as occurs in Silurian strata at the Calcutta Carbon Field in Indiana is also possible (Lang 1975). However, discovery and proof of such traps would likely be difficult because regional structure and stratigraphy may not divulge their locations or boundaries. Geological maps and regional geophysical data are useful in locating broad structural features potentially compatible with CAES requirements (General Electric Co. 1976). However, detailed field study is required to converge the search upon an acceptable site. Subsurface investigation of the local area is essential. This includes exploratory drilling, geophysical exploration, laboratory evaluation of caprock and reservoir rock, and physical and chemical analyses of ground-water pressure, flow rate and composition.

Knowledge gained from past aquifer natural gas storage efforts should be directly integrated into the CAES site-selection processes. For example, sandstones or partially cemented quartzites containing greater than 95% quartz grains are considered best suited for both natural gas and CAES aquifer storage due to their inherently great mechanical and chemical

stability. Limestone and dolomite may also provide useful reservoirs for CAES if porosity, permeability, chemical stability and rock strength are adequate. Exploration for suitable sites should not be restricted to the search for domes (anticlinal) structures. The variety of traps successfully exploited in the oil and gas industry should provide models for alternative exploration targets.

An example by Bervig and Wallace (1978) indicates that, for their candidate porous medium reservoir, a minimum volume of about $15 \times 10^6 \text{ m}^3$ ($530 \times 10^6 \text{ ft}^3$) of air storage is necessary to generate 150 to 200 MW of power over an eight- to ten-hour period. Surface technical criteria include area requirements, topographic relief, and geologic hazards. A minimum of 16 ha (40 acres) of surface space is said to be required for a 150 to 200-MW CAES plant. The site should be free of hazards such as propensities to landsliding, subsidence, and flooding.

3.2 STRUCTURAL CLOSURE

For an anticlinal or domal structure, a closure of greater than 10 m (33 ft) and a thickness greater than 10 m (33 ft) are desirable to minimize areal extent and well numbers. Closure is defined as the lesser of the vertical distance from the top of an anticline to the highest adjoining syncline within the same stratigraphic horizon, or the least vertical decline in the anticlinal axis. Closure is, therefore, the vertical measure of the anticline's least amplitude in three dimensions. Closure defines the volume of the container closed to normal horizontal movement. The centerpoint thickness generally represents the storage zone thickness but can coincide with closure for a thick sequence of storage media. The 10-m (33-ft) minimum thickness allows for adequate air bubble thickness and communication with a perforated or screened casing. These criteria are minimal and should not be construed to mean that greater closure and thickness would be less desirable.

The structural configuration of a porous medium air reservoir may resemble an inverted saucer as was shown in Figure 2.1. In three dimensions, the length to width ratio may vary considerably. Dips of the anticlinal limbs should be much less than 15° to avert the possibility of high angle shear failure and to minimize the probability of faulting. The structure must be doubly plunging (usually approximately elliptical in structure contour plan) to prevent lateral migration of air. During "rest periods" (between injection and withdrawal), the average pressure within the reservoir will equilibrate toward the discovery pressure (native hydrostatic pressure) of the porous medium (Bervig and Pinker 1979).

3.3 STRATIGRAPHIC REQUIREMENTS

The stratigraphic succession normally sought consists of a thick impervious sedimentary formation, such as shale or dense carbonate, overlying a permeable formation such as well-sorted and moderately well-cemented sandstone. The minimum caprock thickness has been set at 6 m (20 ft), but this allows for absolutely no compromise due to faulting, jointing or inferior local facies change. A thicker caprock overlain by one or more redundant caprocks is highly desirable. The caprock must be sufficiently competent and thick to provide an adequate foundation for an airtight concrete seal between casing and wellbore.

The reservoir rock is to be at least 10 m (33 ft) thick. Any thickness up to the quantity of vertical closure can be used to store compressed air.

Caprock imperviousness and reservoir permeability are critical to the feasibility of CAES systems because formation tightness and gas flow rates, respectively, are dependent upon them. Although caprock testing by laboratories is necessary (Rudd 1979), caprock and reservoir permeabilities may not be regionally determinable by standard coring procedures and laboratory testing (Katz and Lady 1976). These analytical difficulties are due to the heterogeneous lithology and structure

prevalent in many geological formations. This inherent variability requires site-specific testing (Weinstein et al. 1978).

In situ permeability measurements of the reservoir are commonly obtained from pump tests, in which water is produced from one well and water levels are measured in other wells located at various radii and depths. Drawdown and filling rates are used to calculate permeability. In addition, caprock permeability is evaluated from piezometer pressures at various levels of drawdown. However, in both cases, formation inhomogeneities can cause misleading results that interfere with system planning. Furthermore, permeabilities may vary significantly with the duration of testing. (These problems are discussed in more detail in Section 3.6.5.)

3.3.1 Caprock Threshold Pressure

Threshold pressure (Allen and Gutknecht 1980) is the maximum pressure differential that can be exerted across a caprock without fluid transmission. Maximum storage pressure, in turn, is the sum of the threshold pressure plus the hydrostatic pressure. Threshold pressure determinations to maximum limits of 5000 to 6600 kPa (725 to 957 psi) provide a very conservative margin of safety for most purposes. Most samples of relatively pure shale caprocks and many samples of carbonate caprock have threshold pressures that exceed this range. Some specimens of both shale and carbonate caprocks have been tested to a maximum level of 20.7 MPa (3000 psi). On the basis of a limited number of samples, Allen and Gutknecht (1980, p. 27) found that Paleozoic shales from the upper Midwest show threshold pressures below 13.8 MPa (2000 psi), but a few extremely dense limestone samples have threshold pressures in excess of 20.7 MPa (3000 psi).

"Delta pressure" is defined as the excess of gas bubble or injection pressure above hydrostatic (discovery) pressure. Delta pressure is not to exceed 50% of the effective threshold pressure for the caprock.

Leakage of the caprock due to temperature elevation, dehydration and fracture may be a minor concern at an operating delta pressure of 50% of the threshold pressure or at an operating total pressure of about 12.0 kPa/m (0.53 psi/ft) of depth. An insulated wellbore or insulated concentric injection tube can be used to protect the caprock from thermal shock. Laboratory tests can quantify the sensitivity of the caprock to temperature cycling and dehydration.

3.3.2 Permeability

Permeability describes the flow rate of a fluid through a solid substance and is expressed in darcy units. One darcy exists when one cubic centimeter of fluid with viscosity of one centipoise flows through a one-centimeter cube in one second under a pressure differential of one atmosphere (101.4 kPa or 14.7 psi). Millidarcies (md) are conveniently used to describe permeabilities of fluids for typical porous media. Water, which has a viscosity of one centipoise, would flow from face to face through a one-centimeter cube of one-millidarcy sand at the rate of 0.001 cc/sec under a pressure drop of 101.43 kPa (14.7 psi) (Katz and Lady 1976). Reservoir rock permeabilities applicable to CAES usually range between 300 and 3000 millidarcies.

Permeability is one of the most important reservoir characteristics because it determines rates of water displacement and air deliverability. High in situ permeabilities enhance the economics of porous medium CAES reservoirs. For a fixed pressure drop during air production, reservoirs of high permeability will require fewer wells to deliver air at the specified flow rate. For compressed air storage, a special premium for high permeability exists because of the need for daily cycling. The work required to displace water or to inject and extract air below 300 millidarcies is excessive (Stottlemire 1978). Therefore, a minimum permeability of 300 millidarcies is required for the storage zone.

It is important to allow for physical or chemical incidents that can diminish permeability. These include thermal expansion, particulate

generation and plugging, mineral precipitation, capillary liquid retention and rock fabric compaction. An initial permeability on the order of 500 to 600 md may be desirable in particular reservoir rocks. If necessary, injection/withdrawal well permeabilities can be enhanced by acid treatment, hydraulic fracturing or increased fluid transfer cross section (by reaming or deepening).

3.3.3 Porosity

Porosity is the fraction of the total rock volume represented by interstices between the mineral grains. Any such "accessible" porosity is available for gas storage. Porosity often ranges from 15 to 25% or more for sandstone but may be as low as 5% for other types of sedimentary rocks.

The porosity of the reservoir must be sufficient to store the required air volume. A porosity of 10% is considered a minimum value for CAES operations (Stottlemire 1978). Most Paleozoic sandstone candidates for CAES have porosities of 15% or more, based upon laboratory results on drill core samples.

3.4 LITHOLOGIC REQUIREMENTS

If an arenaceous reservoir is to be chosen, the rock should be a clean quartz sandstone (Pincus 1980). Pores and other openings must be interconnected in a system providing adequate rates of mass flow. The rock must be chemically and mechanically stable under operating conditions. Coarse sandstones tend to be more pure mineralogically than their finer-grained equivalents.

Any of several factors will decrease the usefulness of the rock as a reservoir for compressed air. With decreasing grain size, the permeability will decrease and the abundance of other minerals is likely to increase. Poorer sorting will also decrease permeability and porosity. Increasing amounts of carbonate cement will likely decrease chemical

stability. How combinations of such changes will act in concert is best addressed initially by laboratory study (Pincus 1982).

Of immediate concern is the role of impermeable zones within the reservoir rock. Seams of shale, parallel to the bedding of the sandstone reservoir, need not have adverse effects. Because most flow will take place parallel to the bedding, the effects of such seams would be to separate the reservoir into overlapping stacks of parallel reservoirs. Around the wellbores, such seams might cause some problems resulting from washouts along the sandstone-shale contact or from differential thermomechanical responses. On the other hand, shale layers may inhibit ground-water coning during air withdrawal (Pincus 1982).

Jointing in the reservoir rock may contribute to porosity and permeability. Vertical joints, or joints perpendicular to the bedding, could act as dams if filled with impermeable materials. Filled joints that intersect impermeable seams could effectively divide the reservoir into blocks of permeable material isolated from each other by impermeable curtains and blankets; such a structure could be undetected even with a detailed exploratory drilling program (Pincus 1982).

Some Cambrian and Ordovician sandstones of the upper Midwest include units that have very desirable physical characteristics for CAES and, in addition, are sufficiently deep, thick, and extensive. Carbonate rocks, particularly those with secondary porosity, may also be satisfactory reservoirs for a CAES system. Spatial variations in permeability and porosity, as well as their chemical susceptibility, render these less desirable than the better quartz sandstones; however, they may prove to be practical where sandstone is absent.

In considering any reservoir rock for CAES, the investigators must give equal attention to the associated caprock's properties. Interactions between the reservoir rock and the caprock must also be considered. For example, volumetric changes in the reservoir rock or the growth of large fractures in the reservoir rock could result in fracturing in the caprock and its ultimate failure as a seal.

Permeability and porosity may also vary gradually through a reservoir rock, particularly parallel to the bedding. This could profoundly affect overall charge-discharge characteristics, and would result in substantially different characteristics for different wells in the same system. A thorough exploration program, especially with adequate drilling (possibly both vertical and inclined) and accompanied by property-testing of the drill cores, would address these problems.

3.5 HYDROLOGIC REQUIREMENTS

The discovery pressure of water within the confined aquifer must be sufficiently high to contain compressed air at the required pressure. Discovery pressure is a function of depth below the water table and water solute chemistry. The hydraulic pressure gradient ranges between 9.8 and 11.77 kPa/m (0.433 and 0.52 psi/ft). Thus, to confine air at 6.9 MPa (1000 psi), the head of water necessary would be 586 to 704 m (1923 to 2310 ft). The mean storage pressure must be equal to the discovery pressure for long time periods, as the bubble will naturally equilibrate to this level. Care should be taken to review regional topography and outcropping, as these can significantly reduce the standing water levels in a continuous formation, resulting in much less hydrostatic head than formation depth would indicate.

In addition, the rate of water flow through the aquifer must be relatively insignificant to avert the possibility of lateral air loss (Chang et al. 1980). Water flow rates can be measured by injection of innocuous tracers and timed water sampling in monitor wells located in various directions and at various distances from the injection well.

The aquifer water should be naturally isolated from potable sources to eliminate facility licensing difficulties.

3.6 SITE QUALIFICATION

Site qualification involves a sequence of steps beginning with economic justification for CAES in an aquifer within a particular

geographic region. The geologic process of site selection proceeds from identification and organization of known information to development of specialized new data that ultimately qualifies or disqualifies possible sites within a geologic "structural province". Before site qualification begins, particular site criteria must be identified that define the structural, stratigraphic, physical and petrologic requirements for the aquifer reservoir and its overlying caprock.

3.6.1 Initial Screening

After a general region of interest has been identified, available geologic data are acquired from federal and state geological surveys, scientific publications, trade journals, drilling records and well logs, and geophysical records. In regions of continuous Holocene or Pleistocene overburden, drilling information is extremely important.

Reservoir exploration methods must delineate structural and stratigraphic features such as folds, faults, joint systems, thickening and thinning of beds, and changes of facies. Reservoir morphology, anisotropy and heterogeneity may affect bubble shape without adversely affecting the stability of containment. However, poorly cemented zones or structurally disrupted zones could cause instability of the reservoir itself or excessive loss or channeling of air.

A vital first step is the acquisition of surface and subsurface rights to explore the geology and to inject air over the life of the project. These rights must be obtained before any subsequent steps in the qualification process can be taken.

3.6.2 Stratigraphic Confirmation and Rock Characterization

An initial borehole is located within the region of interest to log the stratigraphy by visual and field mineralogical methods, obtain core, and characterize the formations by geophysical logging. The stratigraphic succession and formation/member thicknesses are compared with predicted information. Caprock cores are sealed to prevent water loss and transported to a laboratory for measurements of permeability and threshold

pressure. Reservoir cores are sampled to measure ranges in porosity and permeability. Geophysical logs (Rudd and Allen 1980) may include the following: three-dimensional velocity, electric, gamma ray-neutron, density, temperature, computer processed and elastic properties logs. The velocity log is essential if subsequent exploration includes seismic prospecting.

Because of the uncertainty in defining aquifer storage characteristics and deficiencies of analytic methods, the nature and real extent of the structural closure and stratigraphic trap may not be known until the formation is pressurized (Katz and Lady 1976). This is usually done as part of the ground-water testing step (Section 3.6.5).

3.6.3 Seismic Surveying

High-resolution seismic reflection surveying is suited to three-dimensional mapping of velocity discontinuities associated with formation contacts and identification of certain planar structural features such as fault planes. From these subsurface sections potential reservoir structures are identifiable. Usually refraction surveying of the overburden will be necessary to determine its thickness variations and velocity characteristics. These data are applied to reflection arrival times to correct for elastic wave travel times through the overburden. Seismic surveying may be a logical forerunner to drilling, especially if it enables structural evaluation at less cost per unit area and eliminates unpromising structures from the drilling exploration program.

3.6.4 Confirmatory Drilling

Confirmatory boreholes must be drilled to assure the validity of structures identified from seismic sections. Borehole logs are used to develop structure contour maps from which the areas and closures of structural traps can be measured. Of course, thicknesses and physical properties of caprock and reservoir rock are readily determinable from core. If the vertical variations in structure (e.g., degree of vertical folding parallelism or concentricity) are well established, the

confirmatory borehole program may be based upon a key horizon that is much shallower than the reservoir formation. However, if large variations in caprock or other overlying formation thicknesses occur, it will be necessary to directly measure thicknesses at various locations. From these data, isopach^(a) maps can be drawn. Then site qualification may be based upon a favorable coincidence between the structure contour and isopach maps.

3.6.5 Ground-Water Testing

The three dominant ground-water properties directly affecting CAES in aquifers are discovery pressure, potability and regional velocity. Discovery pressure is measured by allowing reservoir water to rise within a piezometric tube that is sealed within the borehole to maintain a closed water system. Potability is determined by water analysis. If the ground water is suitable for human or animal consumption, the state environmental protection agency (or equivalent) may deny injection well construction and operation permits. In most candidate areas, ground-water velocity is not likely to be large enough to seriously distort or deplete the compressed air bubble. Ground-water velocity can be measured by tracer techniques (see Section 3.5).

Pump tests may be used to measure reservoir and caprock in situ permeabilities. (Refer also to Section 3.3.2). Caprock permeability can be evaluated using piezometer pressure measurements with various levels of drawdown. Pump testing of the caprock involves the reduction of pressure beneath the caprock by pumping water from one well while simultaneously observing pressure response, usually in terms of water column height, that occurs in observation wells completed above the caprock. Pump tests are particularly useful for determining gross caprock permeability and identifying major features such as faults. Under ideal conditions, such a test may contribute to the evaluation of several hundreds or even thousands of hectares or acres. A pump test is applicable only in areas

(a) An isopach is a line connecting points of equal bedding or formation thickness, the points having been perpendicularly projected to a horizontal plane.

of somewhat restricted permeability so that ground-water recharge will not equalize the pressure drop in the reservoir beneath the caprock. Pressure observations on shut-in wells can be helpful in finding whether leakage is occurring. Such a pressure survey may indicate a leaking caprock if the pressure falls below the original pressure when the reservoir is shut in. This behavior occurs when the leak rate for the gas exceeds the rate at which water will return to the reservoir, as shown in Figure 3.1.

FIGURE 3.1. Reservoir Pressure Behavior for Leaking and Nonleaking Aquifers (Katz and Lady 1976, p. 177)

A casing leak may be found by observing that the shut-in pressure in a given well is below that of adjacent wells. Annual surveys of individual shut-in well pressures over a 1-week period are recommended. These surveys give precedents for pressure differences between wells. Inspection of such pressures after each survey will identify a well with a

casing leak. When such occurs, simulation of well and reservoir behavior can ascertain the rate of leakage that developed and permit estimation of the gas loss over time (Katz and Lady 1976).

Pressurization of the aquifer with compressed air should be demonstrated before a site is finally committed to full-scale storage. This procedure will test the areal continuity of the caprock and the quality of the water seal. The pressurization testing may reveal fractures and inhomogeneities not previously detected in caprock cores. These structural or stratigraphic flaws may cause large air losses, expanded storage volumes, and process inefficiencies (Jacobein 1972; General Electric Co. 1976). Pressurization will reveal the potential for these problems, and assist developers in avoiding costly mistakes such as that sketched in Figure 3.2.

FIGURE 3.2. Reduction of Effective Closure by Facies Change (Rudd 1979, p. 258)

3.7 APPLICATION OF GEOLOGIC CRITERIA TO POTENTIAL SITES

This section summarizes some of the existing experience in siting aquifer storage in the U.S. The siting process for a utility necessarily concerns itself with a set of issues, both environmental and legal, much wider than the geologic suitability, which is the primary emphasis of this

document. Readers interested in a good summary of these wider issues and the siting methodologies related to them are referred to Beckwith (1983). Those readers interested in the siting process purely from the geologic point of view are referred to the Pittsfield field study portion of this document.

3.7.1 Candidate Midwestern Aquifers

Based on studies conducted at the University of Wisconsin-Milwaukee, three areas in the upper midwestern United States hold promise for CAES in aquifer-type rocks (Pincus 1980, 1982):

- A large area in the southern part of southeastern Minnesota has good potential for storage in Paleozoic sandstones. Candidate reservoir/caprock pairs include Mt. Simon/Eau Claire, middle Eau Claire greensand/upper Eau Claire, and Galesville/Franconia (Marshall 1979).
- Eastern Iowa and southwestern Wisconsin are underlain by three possible reservoir/caprock pairs: 1) Mt. Simon/Eau Claire, 2) Galesville/Franconia, and 3) St. Peter/Glenwood and Maquoketa. Suitable structures appear to be concentrated along the midcontinent gravity high that extends from northwestern Wisconsin through northcentral Iowa to Kansas (Gross 1980).
- Cambrian and Ordovician sandstones along the Kankakee Arch in northern Indiana and Illinois should be considered as potential CAES reservoirs. Some have been used successfully for gas storage, such as the Mt. Simon, Eau Claire, Galesville, and St. Peter (Hopper 1980).

One of the most effective steps to take in selecting and developing sites for CAES is to start with known structures in which fluids, particularly gas, have been stored successfully.

3.7.2 Feasibility in California

A feasibility study, cosponsored by the California Energy Commission and the U. S. Department of Energy, sought to evaluate CAES technology,

economics, and siting in California (Hobson 1978; Hobson et al. 1979). Statewide electrical load curves, typified by Figure 3.3, suggested a strong potential for energy storage.

FIGURE 3.3. Typical Statewide Electrical Load Curve for California

Based on CAES plant operating characteristics, technical and geologic criteria were established for identifying feasible sites. Desired operating pressure levels for the compressed air imposed minimum and maximum depths for the storage formation or caverns. Permeable formations with sufficient volume to provide air storage for the CAES units in the 250-MW size range were designated. These formations were required to have a minimum permeability of 400 millidarcies to enable adequate air flow. These were first applied to all California oil and gas fields as well as candidate hard rock sites distributed throughout the state. However, no existing caverns met the criteria.

All remaining sites were ranked qualitatively for geologic and environmental suitability. Factors included rock type, stratigraphy, structural geology, hydrology, air quality, land use, population density, and areas of biotic significance. Elimination criteria included proximate active faults or location in exclusion areas such as parks or national forests. Gas and oil fields expected to be active producers during the 1980s were also eliminated at this point.

Final lists of preferred sites were ranked quantitatively by calculating index values representing the incremental plant costs in dollars per kilowatt above the cost of a plant sited in "ideal" conditions. The quantitative factors were geologic and locational. The geologic factors considered the effect of the specific site characteristics on capital cost, e.g., rock quality for a granite and permeability for a sandstone. Depth, formation thickness, and lateral extent were also important. The locational factors included site-specific capital cost variables: electrical transmission proximity, road access, fuel pipeline proximity, and land acquisition costs.

Eleven candidate hard rock sites were identified in ten counties. Twelve candidate porous media sites were identified in seven counties. More site-specific drilling, analysis, and testing would be necessary to qualify these candidate sites for actual development.

A conceptual design was developed for porous medium storage in the Glenn County Princeton gas field. The Princeton site is underlain by a sand formation and caprock with sufficient closure to contain 7.85×10^8 scm (2.77×10^{10} scf) of compressed air. The formation is located between 671 and 732 m (2200 and 2400 ft) below the surface, which corresponds to a hydraulic pressure of approximately 6.9 MPa (1000 psia). The Princeton design cycle required 2×10^7 scm (7.1×10^8 scf) of compressed air at approximately 6.9 MPa (1000 psia) storage pressure per CAES unit for 20 hours of continuous operation. The plant design comprising three CAES units was selected, with a unit generation between

200 and 250 MW, giving a total plant capacity of 600 to 750 MW. This size was considered conservative based upon the available void volume, which allowed for a "cushion" of approximately 900% of the cycled air volume to reduce pressure variation as air is discharged from the formation. A low concentration of methane in the aquifer reservoir was found to be neither a potential combustion hazard nor a prohibitive emission.

3.7.3 Public Service of Indiana Site Development

An aquifer site development program by Public Service of Indiana under the direction of T. W. McCafferty was sponsored jointly by the U.S. Department of Energy and the Electric Power Research Institute. The siting study portion was initiated with a first-phase literature review of regional geology to identify sites for compressed air storage in a study area encompassing parts of Illinois, Indiana, Kentucky, and Tennessee (Walke 1980). This review was performed by the Illinois State Geological Survey and the Indiana Geological Survey. The criteria used to identify potential sites included geologic and hydrologic characteristics as follows:

- discovery pressure of 1.38 to 6.9 MPa (200 to 1000 psi)
- aquifer depths of 145 to 732 m (475 to 2400 ft) below plant grade
- sufficient closure and volume for storage of 3.4×10^8 scm (12×10^9 scf) of air at 66°C (150°F)
- permeability of at least 750 millidarcies and preferably greater than 1000 millidarcies
- adequate caprock for storage.

Fourteen potential sites were identified: 10 in Illinois and 4 in Indiana (Figure 3.4). Most Illinois sites were selected from geologic structures known to the Illinois State Geological Survey to have been investigated but not developed for the underground storage of natural gas. Literature on the study region in Indiana was surveyed to identify sites in two stratigraphic horizons.

FIGURE 3.4. Potential Site Locations

In the second phase, the 14 potential sites were first screened to determine their suitability for development of a 1000-MW CAES facility. Three major areas of concern were evaluated: geologic, economic, and environmental characteristics. All 14 sites were reviewed initially to determine the existence of any local prohibitive characteristics. None were identified so all 14 sites were continued. A numerical rating system was developed to identify the most promising sites. Seventeen criteria included 9 for geologic characteristics, 5 for economic characteristics, and 3 for environmental characteristics. Ranking values for each criterion ranged from 1 (least desirable) to 5 (most desirable).

Each group of characteristics was assigned a fraction of points out of a total of 100. These points were then distributed among the criteria within each to provide a set of weighting factors. The value of each criterion was determined by multiplying its weighting factor by the 1-to-5 ranking. Fifty points were distributed among the criteria in the economics grouping. The remaining 50 points were divided equally between geologic characteristics and environmental impacts.

The detailed results of the evaluation are shown in Table 3.1. The 14 sites were then ranked as shown in Table 3.2.

Two criteria were then used to eliminate sites from further consideration: 1) the air reservoir should be able to support a minimum plant capacity of 1000 MW and 2) the total number of wells for a 1000-MW capacity plant should not exceed 2000. Even though the estimated size of a demonstration unit is approximately 250 MW, site development and acquisition costs are estimated to be prohibitive for only one unit.

The application of these two criteria resulted in the elimination of seven sites. Five sites, including all four in Indiana, could not support 1000 MW capacity: Lewis, Paxton, Prairie Creek, Toulon B, and Wadesville West. Two sites, Brocton and Hume, exceeded a total of 2000 wells for site development due to the well selection procedure, which was based on primary permeability. The high number of wells resulted from low core permeabilities for limestone media and low discovery pressures at these sites.

TABLE 3.1. Suitability Evaluation of the Potential Sites

Characteristics	Weight	Numerical Ratings by Site													
		Wapella East	Deland	Media	Parnell	Wadesville West	Brookville	Fishhook	Paxton	Toulon B	Toulon A	Prairie Creek	Lewis	Hume	Brocton
GEOLOGIC															
Caprock	5	5	5	5	5	2	2	2	2	3	3	2	2	5	5
Permeability	5	4	4	4	4	3	4	5	1	3	3	3	4	1	1
Depth to Top of Reservoir	3	4	3	4	3	4	3	3	4	4	4	3	2	3 ^(a)	3
Total Volume	2	4	4	3	4	1	4	3	1	1	3	1	1	1 ^(a)	3
Porosity	2	5	5	5	5	5	5	5	5	5	5	5	5	4	4
Height of Reservoir	2	4	4	3	4	5	4	3	5	5	4	5	5	4	1
Type of reservoir	2	5	5	5	5	4	5	5	4	5	5	4	4	2	2
Presence of residual hydrocarbons	2	5	5	5	5	5	5	5	5	5	5	5	5	3	3
Increase in storage temperature	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5
ECONOMIC															
Wells & piping	41	5	5	5	5	4	3	3	3	3	3	1	1	(b)	(b)
Transmission	4	3	3	2	3	4	4	5	5	1	1	3	1	(b)	(b)
Water	3	5	3	5	3	1	3	3	3	4	4	3	1	(b)	(b)
Surface and sub-surface acquisition		5	5	3	3	3	3	2	5	4	4	1	1	(b)	(b)
Access transportation and topography		4	5	3	5	1	3	3	3	3	3	1	1	(b)	(b)
ENVIRONMENTAL															
Air quality	10	5	5	5	5	5	5	5	5	5	5	1	1	5	5
Land use	9	3	3	4	2	3	4	4	4	3	2	2	3	3	2
Ecology	6	5	5	4	4	3	4	3	3	2	3	4	4	2	2
TOTAL SITE SCORES		461	453	453	436	369	359	357	345	329	328	200	197	---	---

Note: Numerical ratings range from a low of 1 to a high of 5; site scores are the sum of the products of each numerical rating and the weight for each characteristic.

(a) There is conflicting data concerning the estimated volume of the reservoir. This rating is based on the more conservative (smaller volume) of the two.

(b) Economic ratings for Hume and Brocton are not included because cost estimates for these sites were not used in the evaluation.

TABLE 3.2. Relative Ranks of the Potential Sites

<u>Rank</u>	<u>Site</u>	<u>State</u>
1	Wapella East	Illinois
2	DeLand	Illinois
3	Media	Illinois
4	Parnell	Illinois
5	Wadesville West	Indiana
6	Brookville	Illinois
7	Fishhook	Illinois
8	Paxton	Indiana
9	Toulon B	Illinois
10	Toulon A	Illinois
11	Prairie Creek	Indiana
12	Lewis	Indiana
13	Hume	Illinois
14	Brocton	Illinois

The seven final sites--Brookville, DeLand, Fishhook, Media, Parnell, Toulon A and Wapella East--all have generally high ratings (3 or above) for the characteristics evaluated. The top two sites--DeLand and Wapella East--had high ratings for all the characteristics. The other five sites had only a few low ratings.

The Media site received a low rating for transmission costs because the site would require 72 km (45 mi) of transmission corridor to intertie with one of the utility sponsors' transmission systems. However, another utility may have closer transmission lines to the Media site. Parnell received a low rating for land use primarily because of the potential disturbances to the Illinois State Recreation Area at Lake Clinton that might result from aquifer development. Brookville, Fishhook and Toulon A all have questionable caprock integrity. Insufficient or limited caprock data are available for these three sites; therefore, they were given low

caprock ratings. Fishhook also has a very wide, shallow structure that would necessitate acquiring a large amount of land for surface development [about 1175 ha (2900 acres)] and for subsurface rights [about 2511 ha (6200 acres)]. Accordingly, Fishhook was given a low rating in surface and subsurface acquisition.

In the third site investigation phase, the seven final sites were evaluated with respect to their suitabilities for the testing program. This evaluation consisted of determining the field testing activities that would be needed at each site, estimating the costs of these activities, and identifying the environmental impacts associated with the activities at each site. A field testing program should consist of four phases: drilling structure test wells, drilling injection-withdrawal and observation wells, performing an aquifer water pumping test, and performing an air injection test. The purpose of the program would be to confirm the anticipated performance of the site selected so that the final decision on site selection and compressed air energy storage system feasibility could be made with confidence. The site selected for testing should be the best out of the seven final sites for which surface and subsurface rights can be acquired.

The seven final sites were evaluated for the testing program in the same three major areas of concern: geologic, economic, and environmental characteristics. The geologic characteristics included several of the same criteria that were developed for evaluating the 14 potential sites; an additional consideration was the approximate time required to develop a $2.83 \times 10^7 \text{ m}^3$ ($1 \times 10^9 \text{ ft}^3$) test air bubble. The economic characteristics included all costs associated with the four phases of the field testing program. Environmental characteristics included identifying impacts upon cultural resources and ecology resulting from the field testing activities. The results of the evaluation, illustrated in Table 3.3, show that all seven sites are suitable for the field testing program. For each of the three areas of concern--geologic, economic, and environmental--all seven sites received ratings of 3 or higher.

TABLE 3.3. Suitability Evaluation of the Final Sites

<u>Criteria</u>	<u>Wapella East</u>	<u>Deland</u>	<u>Media</u>	<u>Parnell</u>	<u>Brookville</u>	<u>Fishhook</u>	<u>Toulon A</u>
Geologic	4	5	4	5	3	3	3
Economic	5	4	5	4	5	3	3
Environmental	5	4	3	3	3	3	3

Note: Numerical ratings range from 1 through 5.

4.0 OPERATIONAL ISSUES

Most issues affecting storage of compressed air in aquifers lie in the operational area. Operational issues involve injection parameters, potential impacts within the host rock, and other potential impacts upon reservoir behavior.

4.1 INJECTION PARAMETERS

Injection parameters include air temperature, air pressure, air mass flow rate, humidity, water displacement and air cycling characteristics. Interactions between injection parameters and geologic environment give rise to numerous issues, which are addressed in succeeding sections.

4.1.1 Temperature

The first CAES field experiment will begin injecting air at a relatively low temperature, i.e., less than 38°C (100°F). This requires removal of most of the heat of compression prior to injection into the storage reservoir. However, injection of hot dry air can hasten water removal from the working zone by evaporation and transport of water vapor away from the wellbore (Smith et al., 1978). Both effects speed reservoir development. Later experiments will inject air at temperatures up to 200°C (392°F) to examine these effects.

The degree of air hydration is a function of temperature and pressure. High temperature increases the water vapor capacity of air, whereas high pressure lowers this capacity appreciably. A temperature near 93°C (200°F) is desirable for storage at moderate depth; air at this temperature, with a dew point of 66°C (150°F), would vaporize water in the reservoir near the well (Katz and Lady 1976). Continued injection would warm the rock in the vicinity of the wellbore and begin vaporization of the connate or phreatic water. Pilot studies of this operation should be

considered prior to the establishment of a storage facility for air (Katz and Lady 1976). A model CAES system analyzed by Wiles (1979c) shows that the time required for dehydration to a radius of 3 m (10 ft) varies from about 4 weeks for the highest injection temperature (232°C/450°F) to about 32 weeks for the lowest injection temperature (38°C/100°F). The injection mass flow rate was 0.177 kg/sec/vertical meter (0.119 lb/sec/vertical foot) of open wellbore. The average reservoir pressure was 5.07 MPa (50 atm). Injection humidity was varied from 0 to 0.0429 lbm of water/lbm of air. Residual water ranged from 0 to 40% of pore volume. Injection temperatures above 121°C (250°F) are necessary if dehydration to a 6-m (20-ft) radius is to be achieved within one year. The maximum available air temperature for injection would correspond to the limiting output temperature from centrifugal compressors, which is around 232°C (450°F) in standard designs (Wiles 1979c).

Storing a portion of the heat of compression in the formation increases the value of stored energy by reducing the amount of fuel required per unit power on the expansion-power production phase of the cycle. This efficiency increase is motivated by: 1) Fuel Use Act restrictions on the use of premium fuels for the generation of electricity, 2) escalation in premium fuel prices, 3) high injection air temperature to expedite the dewatering of the critical (near-wellbore) zone, and 4) a desire to store air at elevated temperatures in coupled energy concepts such as solar-CAES (Smith et al. 1978). Further, the cost of heat rejection is reduced.

4.1.2 Pressure

The air pressure parameter has three distinctive aspects as noted below.

4.1.2.1 Maximum Charging and Reservoir Pressures

The maximum allowable reservoir pressure will be determined by the thickness and densities of the geological strata overlying the reservoir

formation. A lithostatic pressure gradient of 22.63 kPa/m (1.0 psi/ft) of depth is based on an average density of saturated overburden of 2306.6 Kg/m³ (144 lb/ft³) (Bervig and Pinker 1979). Maximum charging pressure should not exceed 80% of lithostatic, i.e., 18.1 kPa/m (0.80 psi/ft) of depth. If the pore pressure were to exceed lithostatic pressure, the overburden material would experience tensional stress (Stottlemire 1978). This could cause fracturing or parting along bedding planes. Possible consequences might include loss of air, displacement of ground water, and damage to surface structures. To prevent their occurrence and provide a reasonable margin of safety, the maximum reservoir storage pressure should not exceed 50% of lithostatic pressure, i.e., 11.32 kPa/m (0.50 psi/ft) of depth. This value is standard in storage of natural gas in underground reservoirs (Bervig and Pinker 1979).

4.1.2.2 Delta Pressure

The delta pressure is defined as the incremental pressure over discovery pressure. In highly permeable aquifers, low delta pressures of 173 to 345 kPa (25 to 50 psi) may be used for small CAES projects. For natural gas projects, 690 to 2070 kPa (100 to 300 psi) delta pressures are commonly used for Mt. Simon and St. Peter reservoirs in Illinois and Iowa. Frequently, a lower initial delta pressure is used at the start of development, followed by incremental rises with time. Observation wells are used to monitor gas bubble pressures during injection.

The caprock should have a threshold pressure greater than twice the maximum anticipated delta pressure. Threshold pressure is the pressure required to initiate water migration through the caprock. The low permeability of a typical caprock is due to high capillary retention forces associated with a high internal surface area to volume ratio, i.e., very small diameter pores. The pores remain saturated with water so long as the local differential air pressure does not exceed this threshold pressure (Katz and Lady 1976).

4.1.3 Near-Wellbore Desaturation Requirement

A hypothetical cylindrical zone is bounded laterally by a so-called critical radius from a given wellbore. Within this zone, a state of total interstitial dewatering is required. It must be attained rapidly and then continually maintained for the life of the project (Stottlemire 1978). The extent of this near-wellbore region has not been quantified. This region is the volume around the wellbore where "high velocity" air flow and elevated temperatures up to 100°C (212°F) are predicted. Preliminary estimates suggest a 5- to 15-m (15- to 50-ft) radius. Reservoir anisotropy, air injection temperatures, air flow rates, and relative permeabilities will be important parameters in determining the critical radius. It is anticipated that two-dimensional, multiphase, anisothermal fluid flow computer models, used in conjunction with laboratory and field investigations, may be required to define this radius. Dehydration rate may vary inversely with the water content of the injected air. The moisture-carrying capacity of the air will increase dramatically with temperature. Thus, injection of hot dry air will minimize dehydration time. Allowing for some water retention due to nonconnecting porosity and warm air bypass, the water content within the critical zone might remain as high as 1%.

The so-called "working air zone", which encompasses the critical zone, is defined arbitrarily by the maximum radial distance of air penetration during one operational cycle of injection. This distance will possibly be on the order of 9 to 27 m (30 to 90 ft) (Stottlemire 1978). No specific limitation as to liquid water content has been set forth for the region of this working air storage outside the critical zone. Beyond this zone, the residual water content should not significantly affect the operation of a CAES facility. Therefore, interstitial dehydration of the remainder of the working air zone should not be required (Stottlemire 1978; Wiles 1979c). At the lower air flow velocities expected in regions away from injection wells, the residual water may be essentially immobile

in the liquid state and may have only a minor effect on the reservoir porosity and permeability available to air storage and air deliverability.

4.1.4 Air Cycling

In demonstration and full-scale plants, air injection/withdrawal cycles will probably be scheduled once daily. Longer injection periods may occur during weekends and holidays to "top off" the air reservoir. The quantity of air withdrawn and replaced during a cycle is to be not more than 10% of the mass of the air bubble. This restriction is believed necessary to limit pressure decline, prevent water coning, and maintain air bubble integrity.

Air injection and cycling experiments are underway at the Pittsfield, Illinois, field test facility. Initial air injection/withdrawal cycle experiments are planned according to the following schedule: 7 hr injection, 11 hr withdrawal and 6 hr reservoir closure. This cycle will be carried out 5 days per week. The reservoir will be closed on weekends. Air withdrawn from the reservoir is cooler than injected air because of loss of heat during injection, loss of heat to the reservoir rock during storage and loss of heat during expansion/withdrawal. The withdrawn air is likely to be saturated; it may also contain suspended mineral particles. The Pittsfield experiment is described in detail in Section 7.0.

4.2 POTENTIAL IMPACTS WITHIN THE HOST ROCK

The host rock is defined as any formation transected by an injection/withdrawal well or any formation that stores or prevents the escape of compressed air. The potential impacts dealt with here relate to physical or chemical changes within any host rock that are attributable to CAES.

Rock properties that may be sensitive to the CAES environment include mechanical strength, permeability, porosity, compressibility and threshold pressure. Of these, mechanical strength at the sandface and threshold pressure of the caprock may be most critical. The sandface may fail in

compression or shear because of either cyclical or steady-state temperature, pressure and water displacement effects. Overpressurization of the reservoir could cause pneumatic fracturing of the caprock if the geostatic pressure is exceeded.

Permeability and porosity may be decreased due to increases in sandstone compressibility as a function of temperature. Transport of fine particulate fragments and chemical precipitation from solution may also reduce porosity and permeability.

The sandface and caprock should be monitored for aberrations in temperature and pressure to disclose possible deleterious changes in mechanical behavior. Reversible decrease in reservoir permeability may be detected by air mass flow behavior at elevated temperature. Irreversible decrease in reservoir permeability will be detectable through mass flow drop.

4.2.1 Wellbore Stability

Radial heat losses from the injected air stream may take place by thermal conduction through the well casing exposing a thin cylindrical zone within the caprock to elevated temperatures. An experimental program should address the thermal stability of shale and other potential caprock materials, e.g., limestone and dolomite (Stottlemyre 1978).

Silica flour is recommended as a well cementing ingredient to resist temperatures above 110°C (230°F). Steam wells with temperatures near 371°C (700°F) employ 40 to 50% silica flour in cement to enhance strength and stability.

Cement and casing design, with or without insulated strings, can minimize or eliminate most radial caprock heating and prevent damage. Reaming and over-cementing above the injection zone can eliminate thermally sensitive geologic materials near the wellbore. Tests conducted on the compatibilities of caprocks and sealant materials, with results incorporated during completion design, should eliminate potential leakage problems (Allen 1981).

Numerical modeling of caprock behavior (Friley and Doherty 1978; Friley 1980) disclosed that tensile stresses may exist after prolonged operation. Temperature and pressure ranges during a daily cycle were assumed to be 143 to 204°C (289.4 to 399.2°F) and 4.5 to 5.2 MPa (652.2 to 753.6 psi). The upper caprock near the wellbore underwent circumferential tensile stress caused by radial expansion of the hot central caprock mass. In addition, caprock tensile stress was possible due to vertical thermal growth of the central porous zone depending on caprock and media compressibility.

4.2.2 Differential Thermal Expansion and Fatigue

Local differential thermal stress can result from temperature gradients, mineral inhomogeneities, anisotropy of expansion coefficients for individual minerals, and differential thermal expansion between matrix and granular constituents (Allen 1981). If differential stresses at grain boundaries are sufficient, microcracking may cause dislocation or fragmentation of grains. However, preliminary laboratory ventilation experiments on quartzose sandstones using dry air at elevated temperatures and pressures indicated no significant changes in the microstructural fabric of these rocks (Pincus 1979). Few data are available on the thermomechanical properties of sandstones and shales as expressed by their microstructural responses.

Fatigue stress analysis (Friley 1979, 1980) is important because of the large cyclic thermal component to which the porous reservoir may be subjected. Fatigue stresses are concentrated near the wellbore in both porous and caprock regions. Fatigue stresses tend to diminish during initial hot air injection and approach a steady state during 1 year of simulation. Fatigue within the reservoir rock can be caused by alternating values of temperature, pressure, and humidity. This can result in microspalling or fracturing that can generate mobile particulate matter. Alternating air currents may also dislodge poorly cemented grains, especially in the high velocity region near the sandface. Water may enhance fatigue by hydrolysis or capillarity.

4.2.3 Hydrolytic Reactions

Many sandstones contain more than 20% of nonquartz silicate minerals. The end products of hydrolytic reactions include clay minerals. The potential problems associated with clays include reductions in permeability and porosity related to clay swelling (Allen 1981).

During the hydrolysis process, hydrogen ions in solution are exchanged for alkali (Na, K) and alkaline earth (Ca, Mg) cations in the silicate rock minerals. Kaolinite, a common clay mineral, can result from the hydrolysis of potassium silicate by the following simplified reaction:

Other layered silicates or clay minerals such as kyanite, talc, chlorite, illite, and montmorillonite can be similarly produced from silicates such as plagioclase (Na, Ca feldspar), orthoclase (K feldspar), and from primary ferromagnesian silicates. However, kyanite, talc and chlorite are low to medium grade metamorphic minerals that are stable at pressures and temperatures much higher than predicted CAES conditions.

These reactions cannot proceed without water as liquid, vapor or steam. Furthermore, reaction rates are highly temperature-dependent. In essence, elevated temperatures accelerate natural chemical weathering reactions. Because of geometric separation of liquid water and higher temperatures in a CAES environment, silicate hydrolysis is not currently considered a delimiting phenomenon (Stottlemire 1980). Nevertheless, in a CAES reservoir consisting of sandstone high in nonquartz silicates, it might be desirable to ensure that zones containing significant quantities of water or saturated steam are not heated to temperatures much above 100°C. However, insufficient data exist concerning the impact of such hydrothermal reactions to warrant the conclusion that elevated temperatures must necessarily be avoided. The tendency of a specific reservoir rock to yield clay alteration products can be tested in the laboratory. Likewise, the effect of clay swelling can also be examined.

Particular clays, i.e., montmorillonite, mixed-layer species and illite may increase in volume due to ion exchange with ground water (Hewitt 1963; Moore 1960).

In addition to the hydrolytic reactions involving ion exchange with silicate minerals, it is also considered possible for water vapor at elevated temperatures to hydrolyze and weaken chemical bonds between silicon and oxygen (Griggs 1967). If this occurs at the inner tips of preexisting microcracks, these cracks might propagate at stress levels much lower than normally required. Such enhanced crack growth could lead to time-dependent failure. It is speculated that water vapor hydrolyzes the strong Si-O bonds in quartz and such hydrolysis allows microcracks to lengthen and coalesce at reduced levels of bulk effective stress.

Although no data are available to prove hydrolytic weakening occurs under CAES conditions, this phenomenon may contribute to disaggregation and/or fatigue failure. Similarly, hydrolysis, if it occurs, might contribute to inelastic deformation at grain contacts and subsequent increased consolidation and reduced permeability. Evaluation would require testing with dry and humidified air under both static and cyclic thermal loading conditions (Stottlemire, Erikson and Smith 1979).

Despite the various possible reactions involving water and rock minerals, these mechanisms are deemed relatively unlikely in the compressed air environment after bubble development, provided that water coning is avoided during air withdrawal.

4.2.4 Particulate Plugging

Particulate plugging refers to the bridging or lodging of small particles (fines) in the interstices of flow channels in a sandstone or arkose. Such plugging can significantly reduce the permeability of the rock.

Potential sources of particles include 1) indigenous particles or fines (sand and silt), 2) disaggregation products, 3) suspended solids in

the injection air stream, 4) mineral scale and corrosion deposits, and 5) frayed and dispersed clay particles. The relative quantity and availability to the air stream should be evaluated for each source.

The dust load associated with the injection air stream should be less than a few grams per day. The potential for particle entrainment in the injection air stream must be evaluated in the field. Clay swelling and particle dispersion should not be of major concern to a CAES operation so long as the near well zones are maintained free of mobile liquid phase, low salinity waters. Existing loose fines and disaggregated grains appear to be the most important particle sources.

Reservoir damage might be manifested as a filter cake at the sandface or as bridges of plugs within the formation itself (Stottlemire and Smith 1978). The cyclic operation of CAES may minimize the filter cake problem. Particulate plugging adjacent to the wellbore is the most serious from the standpoint of system efficiency. However, the lower density and viscosity of air as compared to water and the relatively low sandface velocities associated with CAES operations are such that particle transport may be minimized within the reservoir (Stottlemire, Smith and Erikson 1979).

Specimens of candidate reservoir rocks (quartz sandstones) were ventilated in laboratory experiments conducted by Pincus (1979) and Cutler (1979) at elevated temperatures and pressures. Porosity and permeability were relatively unaffected (Section 6.5). However, site-specific samples should be tested for susceptibility to particulate plugging, even though sandstones best suited for CAES reservoirs should not encounter significant problems in this area.

Particle entrainment by withdrawn air is also associated with the availability of free mineral particles. This effect must be minimized to prevent damage to the turbine blades, guide vanes and air channels of the CAES surface equipment.

4.2.5 Mineral Precipitation

Water in the near vicinity of the well will be gradually evaporated and recondensed farther out in the formation during the injection phase or transported up the well during the air production phase. As water is evaporated, the remaining ground water may approach saturation with respect to certain dissolved constituents such as calcium carbonate and silica. The result can be precipitation of minerals within aquifer pore space.

Fortunately, the affected regions should typically be small-diameter interstices, dead-end pore spaces, or lenses of low permeability within the storage reservoir. The mineral precipitation should occur only in that volume of rock originally containing irreducible water. This result is expected because this water is essentially immobile in its liquid state (Stottlemyre 1978). Stated otherwise, reduction of porosity in zones containing irreducible water is not likely to alter overall response of reservoir media, because these zones typically exist due to initial and continuing low permeability. Therefore, any mineral precipitation associated with evaporation of irreducible water should not have a significant effect on CAES operations (Stottlemyre, Smith and Erikson 1979).

4.2.6 Oxidation Reactions

Oxygen tends to be deficient or nearly absent in deep natural subsurface environments. However, free oxygen will be concentrated in CAES reservoirs. Particular oxidation reactions may produce relatively insoluble minerals that may, in turn, reduce permeability. If water is present, increased quantities of silicic and carbonic acid may result. Common reactions include the oxidation of ferrous oxides to hematite (Fe_2O_3) or goethite [$\text{FeO}(\text{OH})$].

Of possible concern in shale caprocks is the oxidation of sulfide minerals such as iron sulfide (pyrite) and lead sulfide (galena). Pyrite often occurs in shaley material. The oxidation reaction produces sulfate

ions that can react with water to produce sulfuric acid. How oxidation reactions will affect CAES caprock and reservoir media is not known. Geochemical studies can examine specific reservoir and caprock specimens before and after they are exposed to warm humid air to quantify oxidation reactions. Even if sulfides are oxidized, however, the effect is not likely to occur except near the reservoir-caprock interface (contact).

If bedded shale or anhydrite is present at the interface between the storage horizon and the caprock, this layer may undergo temperature and oxygen-induced physical and chemical changes over a vertical span estimated at a maximum of 1 to 2 m (3.3 to 6.6 ft). Given the high permeability contrast between the storage zone and the transition/caprock zone, the air mass would tend to flow totally within the storage zone. Thus, no advective or convective heat and mass transport mechanisms should be active in the main body of the caprock. Conduction appears to be the only heat transfer mechanism within an intact and competent caprock (Stottlemire 1978).

In a CAES reservoir, corrosion could be a serious problem if the near-wellbore region is not maintained essentially free of liquid water. Damage of casing and surface piping are the most likely results of corrosion (Stottlemire and Smith 1978).

4.2.7 Well Completion Considerations

Straightforward state-of-the-art natural gas storage and oil field technology would be used to construct an aquifer CAES reservoir, once the basic site selection process was completed. Questions concerning a particular location's feasibility for development as a porous medium reservoir would usually be resolved by completion of the geophysical exploration and laboratory and field geological evaluations necessary to qualify the site. Therefore, it was deemed neither necessary nor possible to include within this document a comprehensive review of the well drilling and field development methods, as the literature and practice is widespread and not unique to CAES applications.

The aquifer CAES application does involve some critical aspects that do merit consideration here, however. These include the methods used to complete the injection or production interval and the cementing of casings for high temperature injection and storage. The completion interval is a critical concern for CAES in that high volume flow rates are required and cyclic reversible flow is necessary over a long anticipated plant life. High temperature injection conditions to aid thermodynamic cycle efficiency are also possible. Standard casing cements are also known to deteriorate with temperature, which can result in leakage of air.

4.2.7.1 Injection/Withdrawal Interval Completion Techniques

The types of formations that are likely candidates for aquifer CAES development fall into three broad ranges:

- silica consolidated sandstones - Well-cemented sandstones in which silica cementing exists are prime CAES candidates throughout the United States. These strata have many characteristics that allow relatively trouble-free injection and withdrawal. They can become unconsolidated if acidized with HF or soaked with hot caustic.
- calcium carbonate consolidated sandstones - Other than their susceptibility to failure through HCl acidizing, these rock structures also can be associated with trouble-free operation.
- fractured or solutioned dense sections - These include competent formations that may have natural fractures and solutioning features such as reef limestones or hydraulically-induced fractures.

The completion techniques used in these candidate formation types can vary widely. The following listing, adapted from Jorda (1978), includes the techniques that would generally cover the range of CAES conditions. The order of preference begins with choices for very competent CAES reservoir conditions:

1. barefoot completions - Figure 4.1 illustrates this completion type, which is applicable to fractured dense sections and cemented sandstones where rock compaction or acidizing are not anticipated. The completion interval is unsupported. There is no sand control. The lack of flow restrictions makes this a high-capacity production or injection well. The formation must remain competent with regard to sand production, crumbling by compaction, and rock stress failures. In injection service, deep-bed filtration of particulate matter is possible. Acidizing may cause failure in barefoot completions. Frac treatments are not always recommended for barefoot wells. This completion can be worked over to other configurations, should failure occur.

FIGURE 4.1. Barefoot Completion

2. open hole gravel pack - Figure 4.2 illustrates this very successful system for dense, highly fractured sections, unconsolidated sands, and consolidated sands where maximum productivity is desired. Underreaming enhances performance. Consolidated sandstones where consolidation is expected to be short-lived, or unconsolidated sands, can be effectively completed with open-hole gravel packs. This is a widely-used sand control method; it exhibits a good success ratio and sand control reliability and provides minimum fluid entry restriction. Reserve gravel above the top of the reservoir interval is available if settling or gravel shrinkage during acidizing with HF acid takes place. Frac treatments are not applied to this type of completion. Wire-wrapped screen replacement is possible if required. Acidizing does not present any special problems. This completion is probably the most efficient and reliable design for typical CAES conditions.

FIGURE 4.2. Underreamed, Open-Hole Gravel Pack

3. cemented perforated casing - This completion, shown in Figure 4.3, is typical for dense formations and cemented sandstones. It is typical of Midwest natural gas practice and offers formation support and the ability to complete only part of the interval if desired. Total flow area is reduced compared with barefoot and gravel pack/screened completions. Control of sand using this technique is a complex technical problem currently receiving research attention. Acidizing can be effectively performed, especially if ball sealers are used. Acidizing with straddle tools is very efficient with this completion. Frac treatments in cemented-perforated wells are routine. Sand control screens and gravel pack can be installed at a later date if they are required.

FIGURE 4.3. Cemented, Perforated Casing

4. gravel pack in cemented, perforated casing - Figure 4.4 illustrates the technique used for consolidated and unconsolidated sands where sand production is anticipated. Either the gravel can be squeezed into place, or the screen can be washed down through a gravel-filled hole. With proper design and selection of completion fluids, this pack can be installed with favorable pressure drops in the perforations. Reserve gravel is customarily used above the producing interval top. Acidizing is an acceptable treatment **if** required in this configuration. Pack/screen replacement is possible, and dual zones can be completed where necessary. This is the best solution to sand control problems in basic perforated casing completion.

FIGURE 4.4. Gravel Pack in Cemented, Perforated Casing

5. wire-wrapped liner completion - Figure 4.5 illustrates the technique used for unconsolidated to slightly consolidated sands. This technique is often used as the water well completion method at shallow depths. It is successful when sands are well sorted but performance can degrade dramatically depending on screen design and formation fines after the formation moves to the screen. The formation particles are drawn to the liner by fluid drag forces, and fill the void space of the original borehole. The borehole disturbance can destabilize the zone and cause impairment. The sand size is important: the finer the formation, the smaller the openings must be, and the prevention of impairment due to the completion fluid will be more difficult. Acidizing must be designed with extra care because of the liner configuration.

FIGURE 4.5. Wire-Wrapped Liner Completion

6. uncemented slotted liners - This completion is usually used with unconsolidated coarse sands. Figure 4.6 illustrates the liner hung in the casing with an injection tubing and packer installed above. This method is not considered to be a long-life sand control completion. The completion interval is unsupported, and fluid restriction is low. If the formation is acidized, compacted, or caused to produce solids by some other mechanism, the liner-borehole annulus can fill with the solids. Sand control may be possible, but at the expense of high fluid entry/exit restrictions. The liner can be pulled and replaced in most of the cases where liners plug with solid matter. Acidizing can be carried out without special problems in many instances.

FIGURE 4.6. Completion Using an Uncemented, Slotted Liner

7. "pack/perf" cemented perforated casing - A variation of Option 3 with added control capabilities is illustrated by Figure 4.7. This development is applicable to cased-through perforated completions. Any bypassed movable drilling mud is purged from behind the inflatable packer during inflation. The system has application in any well where conditions require positive control of fluids into or out of a zone without vertical fluid movement in the casing-borehole annulus.

FIGURE 4.7. Pack/Perf Completion System

8. wire-wrapped liner inside cemented, perforated casing - A procedure that is not recommended, but is listed because this combination can salvage some deliverability from a perforated completion with sand control problems is illustrated in Figure 4.8. It has been used by oil operators, but with minimal success. Screen removal for workovers is very difficult once the screen has been sanded in.

FIGURE 4.8. Wire-Wrapped Liner Inside Cemented, Perforated Casing

9. sand consolidation - Immobilizing lightly consolidated and unconsolidated sands using in situ application of plastics (Figure 4.9) has had varying degrees of effectiveness in wells. Systems are available for bottom-hole temperature conditions up to about 280°F and even 350°F. This technique is applied where slotted liners or cemented, perforated casing is in place and sand problems either exist or are anticipated. Long-life reliability is not a

certainty. The chemistry of the consolidating materials (epoxies, phenol-R condensation polymers, and furan) is well documented, but there are problems in field applications due to the inability to properly place various chemical stages throughout the open interval.

Formation sand consolidation usually involves injection of proper pre-flushes, plastic consolidating material (resin solution) and overflushes into an unconsolidated formation so that the natural material is properly cleaned, then chemically cemented to prevent sand flow.

- b. Objective of formation sand consolidation is to cement sand grains together at the contact point. Excess plastic material is displaced from pore spaces by overflush fluid.

FIGURE 4.9. Formation Sand Consolidation

In summary, the completion methods in-hand should be suitable for CAES injection/withdrawal wells. However, each reservoir must be examined carefully and a proper completion technique developed to meet the individual needs of the well.

4.2.7.2 Well Cements for High Temperature

Current CAES compressor trains and conventional operating cycles will require air injection temperatures in the range of only 15 to 80°C. Second-generation thermodynamic cycles currently proposed would benefit significantly if higher temperature air injection can be used to store both mechanical and thermal energy. With conventional systems, higher temperature injection could reduce cooling costs, help efficiency, and simultaneously aid reservoir dehydration and performance. Temperatures in the range of 200 to 250°C are within machinery capability and, based on current knowledge, also do not appear harmful to reservoir media.

Such high temperatures can present problems for cements conventionally used to complete natural gas and oil wells. These cements contain certain hydration products resulting from the curing and solidification process, which can dehydrate at elevated temperature. The consequent shrinkage, loss of strength, and increase in permeability can result in leakage, communication between formations and even blowout of injection wells.

Fortunately, specialized developments in drilling technology specifically address these concerns. The most visible of these efforts have been those related to geothermal energy development. An extensive research program has been underway since the middle 1970s at Brookhaven National Laboratory (Kukacka et al. 1979) to develop new cementing materials for geothermal wells under conditions much more severe than those anticipated in CAES. In addition, more severe conditions have been imposed in the oil field due to the need for secondary and tertiary recovery methods utilizing high temperatures to increase yield from oil fields. Some very sophisticated organic and inorganic systems are being studied and used in the field. However, most of these systems have relatively short lives, are unproven or, having been designed for more severe conditions, might not be economical for CAES application.

One method common to all of these studies does, however, have a significant level of proven success in conditions comparable to those anticipated in CAES applications. This method is the addition of silica flour (SiO_2) in significant quantities (30 to 50%) to standard API oil field cements in addition to the more conventional additives. This results in preferred formation of more stable cementing agents in the cement, which can actually increase cement quality with temperature. Service companies working in the field recommend its use for a wide variety of high temperature (230°F plus) applications (Halliburton, U.S. Patent 2805719). Experience with silica flour additives includes geothermal (Ostroot and Shryock 1964), steam injection (Cain, Shryock and Carter 1966) and thermal recovery (Walker 1962).

The silica flour additive technique is proven and economical. Use of such a system for CAES well cementing is strongly recommended even for situations in which higher temperature injection is not planned: its inclusion will simplify future adaptation of the well for higher temperature use.

4.3 OTHER POTENTIAL IMPACTS UPON RESERVOIR BEHAVIOR

The operating characteristics of a CAES plant will affect reservoir behavior in a variety of ways. These potential impacts are discussed in the following subsections.

4.3.1 Reservoir Medium Compressibility

Sandstone compressibility in a liquid water environment appears to increase as a function of temperature. Available data suggest a 15 to 25% increase in compressibility for Berea sandstone when temperature is increased from 20° to 200°C (68 to 392°F). The percentage increase also depends significantly on the effective stress. No correlations among compressibility, temperature, and rock properties such as composition, cementation, and porosity are reported in the literature (Stottleniyre 1978). That is, a 15 to 25% increase in compressibility does not imply a

corresponding decrease in porosity. However, it appears obvious that any rock volume decrease will cause decreases in porosity and permeability. Laboratory and field testing of reservoir compressibility for various media should be considered if initial field experiments identify this need.

4.3.2 Caprock Stability During Overpressurization

The practice of developing or operating storage reservoirs at pressures above the level corresponding to discovery pressure is called overpressurizing. A storage reservoir maintained at overpressure will continue to grow until equilibrium is attained. The rate will be a function of physical, geometric, hydrologic and geologic parameters of the aquifer.

The absolute pressure limits within an aquifer range between the pressure exerted by the hydraulic gradient with respect to formation equilibrium water table, approximately 9.8 kPa/m (0.433 psi/ft) for pure water, and the pressure of the overburden, approximately 22.63 kPa/m (1 psi/ft) (Katz and Lady 1976). Pressures in excess of the hydraulic head are required to displace water for bubble formation. However, the operating pressure range may be limited because of formation weakness and susceptibility to failure at intermediate pressures (Tek and Wilkes 1966).

In natural gas reservoirs, the caprock is by definition capable of retaining gases at least up to the discovery pressure. Usually the caprock can sustain a significant level of overpressure. Caprock impermeability depends in part upon water saturation. Tek and Wilkes (1966) reported experimental studies of caprock performance in relation to overpressure, water displacement, rock drying and fracturing. If the threshold pressure is exceeded, water is displaced and gas leakage occurs. Overpressure may also physically fracture the caprock or cause major leaks in structurally weak portions of the caprock closure. Excessive overpressure may even cause water to be pushed beyond a hydraulic trap point of the structural closure.

Current CAES design does not require the use of overpressure for storage once adequate bubble volume has been developed. Care must be taken during development to utilize the minimum level of overpressure that can be tolerated with respect to the reservoir development schedule.

4.3.3 Seismic Response

The extremely remote possibility exists that frequent cycling at high temperatures and pressures might stimulate seismic events if the storage reservoir were located near an active fault or fault zone. Information on local faulting and seismicity must be used in the site selection process to exclude regions of known frequent instabilities. Interstitial pore pressures in CAES reservoir media are designed to approach equilibrium conditions, and thus should not be large enough to approach tectonic threshold energy levels.

Seismic activity in the Denver area was induced by pumping fluids into the earth at pressures considerably higher than the lithostatic confining pressure of the host rock. Injection parameters for CAES are not even distantly comparable. In CAES, injection pressures will be less than the sum of the hydrostatic pressure at the reservoir's depth plus 50% of the additional increment of pressure necessary to displace fluids from the caprock (threshold pressure). Pressure will never exceed 80% of the lithostatic pressure. Mean reservoir pressure will be nearly equal to the ground-water discovery pressure.

In conclusion, no significant seismic response is expected from CAES operations. Seismically active areas will be disqualified. Zones with complex structure related to Holocene tectonic activity will not be candidates for CAES. Early commercialization may include monitoring with a geophone net and tiltmeters to satisfy regulatory concerns.

4.3.4 Ground-Water Flow

Maintenance of a stable air cushion may be difficult if a CAES site exhibits significant regional ground-water flow gradients. Moderate flow

rates could warp gas bubble boundaries. Under certain conditions, ground-water movement in confined aquifers can cause stored gases or other fluids to be transported away from the intended storage area (Molz and Bell 1977). Large bubble size with respect to storage formation thickness may partially offset this effect by preventing air loss except at air-water interfaces.

The potential for down-gradient drift problems in air storage systems should be studied only if the best candidate site has high regional flow. The prospects of head gradient control can be developed if significant drift problems are identified.

Ground-water flow rate and direction can be measured by injecting an innocuous tracer into the aquifer and sampling ground water at various azimuths, radial distances and times.

4.3.5 Effect of Wafering on Bubble Configuration

Bubble formation requires formation overpressurization. With continued overpressurization, bubble size will increase continuously. When the formation is inhomogeneous or anisotropic because of fractures, bedding, sorting or other factors causing permeability differentials, wafering or fingering may cause air to move in narrow channels more rapidly than the rate of bubble front advance (Katz and Lady 1976). Gas wafering is shown in Figure 4.10.

Careful startup and bubble development procedures may be necessary to prevent bubble instability or loss of air by fingering migration past the presumed but vulnerable lateral boundary of an anticlinal closure. In this leakage mode, the formation could accept large volumes of air and never reach or maintain pressure. The effective storage volume would be less than the volume estimated from the apparent closure size. Furthermore, possible recovery and return flow rates might be limited because of lost air and the decreased cross-sectional area of flow. Water isolation problems could result due to air bypass.

FIGURE 4.10. Gas Wafering During Initial Injection in Aquifer (Katz and Lady 1976, p. 117)

Reservoir engineering experience from natural gas storage can address bubble development procedures in depth. Core analysis of reservoir media should carefully characterize bedding heterogeneities. Neutron logging and other monitoring devices may detect dynamic bubble boundaries during development and anisotropic growth. Gas wafering should be detectable early in bubble formation. If wafering or fingering presents a serious problem, reservoir engineering methods can be devised to prevent this mode of loss (Weinstein et al. 1978).

4.3.6 Rapid or Unscheduled Air Withdrawal

Unless aquifers have extremely high permeability, water drive may not be sufficient to refill the pore spaces occupied by the air when air is withdrawn rapidly (Allen 1981). This results in a significant pressure drop within the air bubble that may cause problems such as

- compaction due to loss of support
- water coning due to air pressure decrease to less than hydrostatic (see Section 5.4.4).

Unless aquifers have high permeability, reverse water flow will not take place rapidly enough to refill pore spaces previously filled with pressurized air. The aquifer may sustain permanent damage through compaction, loss of permeability and porosity, and consequent storage volume loss. Time delays may also occur as the operational parameters are changed to compensate for delivery losses and repressurization difficulties.

Triaxial stress experiments can be conducted to determine the impacts of rapid pore depressurization on specific media. Cores can be examined before and after rapid depressurization to assess changes in the reservoir fabric. If significant damage occurred, preventive measures could be developed, such as protection by throttling the withdrawal well. In actual field practice, however, it is unlikely that withdrawal wells will be operated without sufficient control to avert unscheduled air withdrawal.

4.3.7 Aquifer Pressure Variations

Water levels in existing wells may fluctuate because of long-term formation pressurization. According to Katz and Lady (1976), operations may cause water levels to rise a few feet at a distance of several miles from the air injection wells due to water movement in the aquifer. This may occur several years after the operation begins. In addition, CAES systems may be adversely affected by unscheduled or scheduled withdrawals

of water from other wells. The hydraulic gradient can be modified by pumping from the confined aquifer, consequently altering the reservoir storage characteristics.

All wells potentially affected by the CAES development should be identified during site selection. The aquifer must be managed in total, and coordination is required among owners if all affected wells are not controlled by the CAES developer. The "storage company" may need to acquire other subsurface rights to limit new well penetrations (Weinstein et al. 1978). Even without total control, an adequate margin of structural closure could protect bubble integrity from unscheduled, limited drawdown from the aquifer. The depth of CAES aquifer systems will usually preclude the possibility of concerns regarding effects on other users.

4.4 AQUIFER FIELD MONITORING

Instruments have been developed for monitoring gas migration from storage. Monitoring CAES in a similar fashion can be undertaken to measure the relative integrity of the reservoir system. Instruments and methods used in gas storage systems and that are applicable or adaptable to CAES include (Katz and Lady 1976):

1. observation wells
 - a. to measure fluid levels or pressures
 - b. to detect gas
 - c. to scan overlying layers for gas entry
2. comparative neutron logs to detect gas in porous rock behind casing
3. temperature logs to detect abnormal gradients caused by expansion of flowing gas
4. spinner surveys to detect gas movement in casing
5. reservoir models to compare with field performance

6. gas saturation logs to determine percentage saturation versus depth
7. monitoring of surface pipes for corrosion.

Prestorage measures include:

1. pump tests to evaluate caprock
2. threshold displacement pressure measurements on caprocks
3. logs of bond between well casing, cement and wellbore
4. downhole casing inspection logs to determine condition of casing
5. gas analyses from shallow water zones to identify natural gas
6. casing inspection surveys prior to running casing
7. cathodic protection of well pipe
8. chemical analyses of water
9. measurement of ground-water flow rate and direction.

In a CAES aquifer reservoir, the main concerns are air confinement, stability of the storage zone, integrity of caprock, stability of the overburden, isolation of CAES operations from potable aquifers and protection of surface water sources. The monitoring procedures recommended for commercial CAES operations could include continuous measurements of temperature and pressure within some or all injection/withdrawal wells; periodic casing inspections of all wells; measurement of vertical and horizontal movements at the surface; monitoring of air mass injection and recovery; and periodic inspections of boundary wells for air leakage and ground-water displacement. In addition, periodic analyses of CAES aquifer water, potable ground waters above the CAES aquifer, and surface waters should be conducted.

5.0 NUMERICAL MODELING OF RESERVOIRS

Modeling has established preliminary stability criteria for CAES porous rock reservoirs (Smith et al. 1978; Doherty 1980). Computer codes have incorporated fluid flow, thermal effects, laboratory data, and literature properties to predict reservoir pressure, temperature, and humidity profiles, and to examine effects of parameter variation on reservoir performance. The following discussion summarizes the results of four modeling studies done by the Pacific Northwest Laboratory.

5.1 FUNDAMENTAL RESERVOIR CHARACTERIZATION

The first study modeled the CAES aquifer reservoir as shown in Figure 5.1 (Smith and Wiles 1979). The model simulated cycling of heated dry air to and from a one-dimensional radial flow field surrounding a single well in porous rock. This study provided fundamental information regarding the performance of a porous medium reservoir for CAES. This information was essential to understanding reservoir behavior and provided a foundation for all subsequent modeling work. Significant results for a prototype reservoir include:

- The parameters with highest impact on hydrodynamic behavior are permeability and mass flow rate per unit thickness of the reservoir.
- Injection of hot air reduces deliverability of compressed air as reservoir temperature increases.
- Efficient reservoir operation may require permeabilities on the order of 500 md or more (Smith, Wiles and Loscutoff 1979).
- Hydrodynamic dependence upon permeability decreases as permeability increases.
- At high flow rates the pressure differential between well and reservoir varies inversely with the well diameter.
- The assumption of Darcy flow may not always be adequate to describe the flow field.

FIGURE 5.1. Single Well Within CAES Reservoir

- Because of the relatively large volumetric thermal capacity of the reservoir rock, most of the thermal energy injected is deposited within a region very near the well.
- The growth of the "thermal pillar" about the injection well is slow. Even after 5 years the region more than 45 m (147.6 ft) from the wellbore is relatively unaffected.
- The average thermal energy recovery to and from the injection zone is about 73% in the first year and about 88% in the tenth year.

- Thermal cycling during charging and discharging is observable to a radius of only about 3 m (9.8 ft).
- Changes in reservoir physical properties have little effect on thermal development, i.e., development of reservoir temperature distributions.

5.2 NEAR-WELLBORE DEHYDRATION

During the development of the cushion air bubble for a CAES reservoir, liquid water will be retained within the bubble by capillary forces and by entrapment in dead-end pores. Water in the vicinity of the wellbore may have a detrimental effect on the operational performance and stability of the reservoir. The presence of water reduces the relative permeability to the flow of air, thereby increasing the pressure gradient required to achieve a given air mass flow rate. If the reservoir is subjected to injection of heated air, the existence of water near the wellbore may enhance geochemical reactions that reduce the absolute permeability. Thus, dehydration of the near-wellbore region is believed to be essential to assure the long-term integrity of the reservoir. To evaluate the parameters important to this dehydration, a model was developed that was based on the assumption of one-dimensional radial flow of an air-vapor mixture. Phase-change of the liquid water was included although the liquid water itself was immobile. The application of this model resulted in the following conclusions (Wiles and Oster 1978; Wiles 1979c):

- Rapid dehydration of the near-wellbore region can be achieved during the bubble development process.
- A sharp interface, known as the "dry front", separates the dehydrated zone from the region still containing liquid water. Outward migration velocity of the dry front varies directly with injection temperature.

- The net dehydration rate of the reservoir decreases as the dry-front moves away from the wellbore.
- Net reservoir dehydration rates increase as injection temperature increases.
- Net reservoir dehydration rates increase as injection humidity is decreased.
- For dry air injection, pore plugging due to local accumulation of liquid phase water should not be a problem.
- Dry air injection minimizes the potential for the occurrence of adverse geochemical reactions associated with the coexistence of high temperatures and liquid water.
- For warm, moist air injection, the potential exists for plugging of the wellbore to occur due to local accumulation of liquid water. However, dehydration of the near-wellbore region can be achieved even though the injection of moist air results in a net increase in the amount of liquid water in the reservoir.
- Significant increases in the storage volume of the reservoir should not be expected to occur due to the dehydration process.
- The presence of residual water will have little effect on temperature cycling and thermal development.
- Evaporation due to dry air injection or condensation from moist air injection will not significantly affect the amount of working fluid or the thermal energy recovery.

5.3 TWO-DIMENSIONAL FLUID AND THERMAL EFFECTS

A dry, two-dimensional model assumed air injection with mass energy transport in both radial and vertical directions (Wiles and Oster 1978; Wiles 1979a, 1979b). The parameters of the analysis included wellbore heat transfer, heat losses to the vertical boundaries of the reservoir, gravitationally induced flows, producing length of the wellbore, and the

effects of nonuniform permeability. The analysis of the wellbore heat transfer included consideration of insulation, preheating (bubble development with heated air), and air mass flow rate. The following conclusions were reached:

- The most important factor in determining the thermal distribution in the porous zone is the forced-convection flow field.
- The producing length of the wellbore establishes the maximum air velocity in the porous zone and strongly influences the total pressure drop in the reservoir.
- The producing length can significantly influence the pressure and temperature distribution in the reservoir. Producing lengths less than the porous zone thickness result in sharp vertical temperature and pressure gradients.
- Heat transfer to the vertical boundaries of the porous zone has a negligible effect on thermal energy recovery and on temperature distributions in the porous zone.
- Thermal energy transport within the caprock and basement rock is entirely by conduction and is extremely slow.
- Reduced vertical permeability does not significantly affect the pressure loss in the porous zone because air flow near the wellbore is predominantly radial.
- Thermal development of the reservoir, caprock, and basement rock are not significantly affected by the presence of a low-permeability layer intersecting the wellbore.

When flow (forced convection) is terminated, the remaining heat transfer mechanisms are conduction in the air and porous rock, conduction to the vertical boundaries, and natural convection. Conductivity of the reservoir rock is the most important.

- Wellbore thermal insulation improves thermal energy recovery by reducing radial heat loss.

- Wellbore insulation exposes the porous reservoir zone to higher temperatures and greater temperature extremes during thermal cycling.
- Preheating the reservoir by injecting heated air during bubble development may improve thermal energy recovery and reduce thermal cycling during initial reservoir operation. The effects of preheating dissipate after about 20 weeks of daily cycling.

5.4 WATER CONING

In reservoirs in which water underlies the air storage zone, the phenomenon known as water coning may occur. Water coning involves intrusion of water into the wellbore or near-wellbore region (Figure 5.2).

FIGURE 5.2. Water Coning During Reservoir Extraction 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 can adversely affect reservoir

operation. The water can reduce the relative permeability or completely block air flow. Because most of the reservoir pressure loss occurs in the convergent region near the wellbore, decreasing the permeability in that area will require a greater pressure differential to maintain a given air mass flow rate. In the most severe case, total communication with the air reservoir could be lost due to water saturation of pores and channels. During the thermal cycling tests, the presence of water in the near-wellbore could enhance geochemical reactions that reduce permeability. This could occur in an oxidizing environment above 75°C (Stottlemyre and Erikson 1980).

An analysis was performed to evaluate the reservoir parameters believed to be important to water coning. The analysis required the development and application of a computer model that solved the equations for two-dimensional, two-phase flow in porous media. The model included the effects of capillary pressure and relative permeability. The air and water were assumed to be immiscible, no phase change was included, and thermal effects were not considered (Wiles and McCann 1981b).

The results obtained for the simulated operation of a CAES reservoir suggest that water coning should not be a severe problem. This is primarily due to the slow response of the water to the pressure gradients and the relatively short duration in which those gradients exist. However, water coning will depend on site-specific conditions, particularly the fluid distributions following bubble development; therefore, a water coning analysis should be included as part of a CAES site evaluation.

The parameters known to have an effect on reservoir pressure response and, therefore, on water coning, were evaluated. The results follow:

- The wellbore producing length may extend to within a few meters of the air-water interface before significant intrusion of water into the wellbore will occur by the conclusion of a single air extraction cycle.

The avoidance of water coning by reduction of the producing length will have a greater impact on the pressure response of thin reservoirs.

The pressure drop across the reservoir is proportional to the air mass flow rate so that more severe water coning will be associated with higher flow rates.

In reservoirs with homogeneous permeability, water coning is more severe for large values of permeability, given a constant pressure drop across the reservoir as a basis for comparison.

- Even a slight reduction in vertical permeability can significantly reduce the severity of water coning.
- A layer of low permeability will inhibit water coning only if the bottom of the wellbore does not extend through the layer.
- The severity of water coning was not particularly sensitive to the capillary pressure and relative permeability functions evaluated by this analysis.

Additional important characteristics of water coning include:

If water enters the bottom of the wellbore, the low flow resistance in the wellbore allows the water level in the wellbore to rise significantly faster than the air-water interface in the surrounding region. Then capillary forces can pull this water into the sand adjacent to the wellbore and ahead of the frontal advance of the air-water interface.

- The reservoir pressure response is affected most by the accumulation of water in the sand immediately adjacent to the wellbore and to a lesser extent by the amount of water in the wellbore.
- Water coning may be described as having two modes. In one, water movement is a response to the sharp pressure gradients near the wellbore. In the second, the water movement is a response to the

average pressure differential across the entire reservoir. In this second mode the air-water interface apparently moves much more slowly.

5.5 STRUCTURAL BEHAVIOR

Numerical analyses were performed to assess the structural behavior of porous rock CAES reservoirs under predicted loading conditions of temperature and pressure. Analyses addressed both the nominal or mean reservoir response and the cyclic response due to charge/discharge operations (Friley 1980). Various geometric and physical parameters were assumed for a generic site. The objective was to determine the gross response of a generic porous medium reservoir.

Structural loadings on the model included lithostatic and an assumed lateral load based on deep midwestern in situ stress data. Thermal and pore pressure loadings were from previously described fluid thermal modeling. Figure 5.3 illustrates the grid distribution of the model. Figures 5.4, 5.5, and 5.6 present temperature profiles during the first year of operation of a site. These results indicate air pressures in the porous zone show little spatial variation, whereas substantial thermal gradients existed in the central portion of the reservoir. Loading conditions at the central portion of the model indicated that thermal loading could be an order of magnitude or more larger than pressure loadings.

The response characteristics of concern structurally included:

- tensile level in the caprock mass, because this could conceivably allow leakage to occur
- fatigue stress in the caprock and porous zone, caused by cyclic loading, as a potential reservoir damage mode
- porous rock stress level in relation to a Mohr Coulomb failure envelope for a typical Lower Paleozoic sandstone.

FIGURE 5.3. Well Finite Element Model

FIGURE 5.4. Temperature Distribution at the End of Week 1 (°C)

FIGURE 5.5. Temperature Distribution at the End of Week 26 (°C)

FIGURE 5.6. Temperature Distribution at the End of Week 52 (°C)

Tensile stress levels in the caprock were observed as possible, due to flexure strain resulting from thermal expansion of the near wellbore storage zone. However, this was found to be highly dependent on the degree of stiffness of the site overburden above the top surface of the caprock.

Fatigue stress analysis was felt to be important due to the relatively large cyclic thermal component to which the porous zone would be subjected. Fatigue stresses in both the porous and caprock regions were found to be concentrated in the vicinity of the wellbore. Fatigue stresses in the porous zone were found to be greater than in the caprock zone. In both regions it was further noticed that fatigue stresses during initial hot air injection tended to diminish and approach a steady-state level as the operation continued during the 1-year simulation.

Nominal (noncyclic) stress levels in the porous zone were studied with reference to a Mohr Coulomb failure envelope developed from testing of Lower Paleozoic sandstones. It was found that the noncyclic stress levels in the porous zone were not sufficient to cause appreciable damage.

The results of the structural analyses performed indicate that the most severely stressed region will likely be in the wellbore vicinity and that this is highly dependent on the length of the completion interval and the placement technique utilized in constructing the well.

5.6 APPLICATION TO PITTSFIELD

Numerical computer models were used to assess the thermohydraulic performance of the CAES field test reservoir at Pittsfield, Illinois. They were also used to verify equipment and instrumentation specifications and to assist in planning the injection and withdrawal schedule (Wiles and McCann 1981a, 1982; Wiles et al. 1982).

Assessment of reservoir performance was based on application of the series of numerical computer models used in the parametric studies leading to the results outlined in Sections 5.1 through 5.4. 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. 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 was considered a critical concern for the Pittsfield test because the storage zone for the test will be very thin with respect to its width and the air-water transition is immediately below the injection well. There is sufficient reservoir closure for a much larger bubble, but time and money restrictions dictate use of a thin bubble.

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

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 the 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).

The field test will be operated in two distinct phases: bubble development and air cycling.

5.6.1 Reservoir Description

The Pittsfield reservoir is a domal trap modeled as a two-dimensional, cylindrical region with the wellbore at the center. The impermeable caprock has 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 representative of upper St. Peter sandstone.

5.6.2 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 would be applied in the field test as a precaution against potential fracturing of the reservoir caprock (Katz et al. 1963).

The bubble development calculation simulated 60 days of continuous air injection. The advance of the 50% saturation front during this process is shown in Figure 5.7. The saturation is defined to be the percentage of pore volume containing liquid water. A 50% saturation indicates that half of the original pore volume of water has been

displaced by air. This value of saturation was chosen because it represents significant displacement of water and significant mobilities of both air and water. As observed by the advance of the 50% saturation front with time, the bubble growth is initially both downward and horizontal. (Note that the horizontal and vertical scales in Figure 5.7 are not equal. The bubble is actually quite flat.) The downward growth slows appreciably as gravitational and capillary forces approach an equilibrium with the bubble pressure. Further bubble growth is primarily horizontal.

FIGURE 5.7. Lines of Constant Saturation (50%) Versus Radius for Different Time Periods During Bubble Development

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 and the bubble continued to expand to hydrostatic equilibrium. The average bubble pressure decreased from about 16 atm to about 12 atm during this time. This analysis indicates the entire air storage zone contains mobile water. This unique feature would not be expected for a full-scale reservoir.

5.6.3 Air Cycling

Experimental testing will continue with several months of air cycling after bubble development. The analysis of cyclic injection and withdrawal of air encompasses three topics: water coning, thermal development, and near-wellbore dehydration. Air cycling begins with the bubble development solution after 30 days of reservoir closure.

5.6.4 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.

In an earlier study, Wiles and McCann (1981b) 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. If the delta pressure is the same for injection and withdrawal, significant differences in flow rate can be expected. 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, and can contribute to and accelerate water entrainment and coning.

Analysis conclusions pertaining to water coning are:

- A daily cycle with equal overpressure for injection and underpressure for withdrawal and a daily mass balance should minimize coning problems.

Greater bubble development to further depress the air-water interface is probably not an effective means to reduce water coning, considering the dramatic additional volumes required in the flat structure.

- The injection/withdrawal interval of the wellbore must be at the top of the structure to minimize water coning.

Although the results suggest that water coning is very possible at the Pittsfield site, much depends on the actual conditions in the air storage zone. In particular, low permeability layers would inhibit vertical water migration.

5.6.5 Thermal Development

Initial thermal development calculations were intended to indicate whether or not a heated region of significant size could be established within the time frame of the field test.

A cycle of 4 hours of injection and 4 hours of withdrawal was used in the calculations. 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 5.8. These profiles were taken along the top of the reservoir at the conclusion of the final extraction cycle for each week.

The results of the preliminary thermal development analysis suggest that some thermal data should be obtainable at the observation wells relatively early in the field test. Obtaining this data will help to quantify thermal properties and the effect of water movement and phase change on the thermal behavior.

5.6.6 Dehydration

Dehydration of the near-wellbore region occurs because injection of undersaturated air results in the air gaining moisture as it moves radially outward. The air finally reaches a radial position where it is saturated at the local pressure and temperature. By this mechanism a dehydrated zone is established around the wellbore. Beyond the so-called "dry front" a transition region is characterized by some saturation increase. 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

FIGURE 5.8. Thermal Development: Radial Temperature Profiles After Final Weekly Extraction Cycle

withdrawn from the reservoir at a saturated state determined by the pressure and temperature of the dry front. By this mechanism, water is also removed from the reservoir through the well bore.

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 for various times after initiation are shown in Figure 5.9. Water coning, not analyzed here, may introduce water to the heated zone around the wellbore, thereby continuously resaturating the near-wellbore region. As a result of continuous, local rehydration fed by water coning, deposition of dissolved solids could seriously impair the deliverability of the reservoir.

FIGURE 5.9. Radial Saturation Profiles at Various Times During Simulation

5.6.7 Summary

This analysis demonstrates the capability of the computer models developed at PNL to analyze the thermohydraulic performance of CAES porous media reservoirs. Unique features of the site may require special attention. These include the low 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.

6.0 LABORATORY EXPERIMENTS

Laboratory experiments were designed to simulate CAES aquifer reservoir conditions as they impact specimens of porous media and impervious caprocks (Stottlemire, Smith and Erikson 1979; Erikson, Stottlemire and Smith 1980; Stottlemire 1980). These experiments were conducted by Pacific Northwest Laboratory (PNL); Terra Tek, Inc. (TT); Los Alamos National Laboratory (LANL); and the University of Wisconsin-Milwaukee (UWM).

6.1 AUTOCLAVE EXPERIMENTS AT PACIFIC NORTHWEST LABORATORY

An experimental study was designed to determine how permeable host rock will be affected by CAES conditions (Erikson, Stottlemire and Smith 1980). Galesville sandstone cores were exposed to four environments: 1) dry air, 2) heated, air-water vapor, 3) heated, nitrogen-water vapor and 4) heated, compressed, liquid water. The simulated CAES environments were maintained in autoclave pressure vessels by controlling temperature, pressure, time, gas concentrations, and liquid volume. The petrologic properties studied were apparent porosity, gas permeability, water permeability, and friability. These properties were measured at ambient temperature and pressure before and after each test.

Geochemical experiments gave the following results:

- The Galesville sandstone exhibited excellent stability in dry air at temperatures from 50° to 300°C (120° to 570°F).
- Significant physical alterations occurred in sandstone samples exposed to liquid water above 150°C (300°F).
- Preliminary experiments had indicated that significant physical alterations occurred in sandstone samples exposed to gas-water vapor mixtures above 150°C. However, these alterations were later proven to be the result of water condensation inside the pressure vessel. In later experiments, samples shielded from dripping water exhibited excellent stability to 300°C.

The porosity and friability of the sandstone samples increased as a function of increased temperature, humidity, and/or testing time.

- The sandstone also exhibited greater changes in gas and liquid permeability with increased temperature, humidity, and/or testing time. However, permeability increases and decreases both were observed.
- Sandstone may be a suitable storage medium for heated humid air provided that elevated temperature zones are relatively free of mobile liquid water.

Figure 6.1 illustrates changes in the gas permeability of sandstone samples as a function of temperature and humidity.

A second autoclave study determined how CAES environments affect standard carbon steel casings (Elmore and Stottlemire 1980; Stottlemire 1980). Unstressed, electrically isolated samples of three carbon steel casings (A120, H40, and A53B) were tested at various humidities, temperatures, and exposure durations. All tests were run at 12.1 MPa (1750 psi) and at temperatures between 50°C and 300°C (120° to 570°F). Humidity was varied from zero to 100%. The effects of salt in the humidified air were also analyzed.

Results of the corrosion study are given in Table 6.1 and Figure 6.2. The only significant corrosion product identified was hematite, Fe_2O_3 . As expected, corrosion rates increased with temperature and decreased with time because of the formation of a protective scale. The rates appear to be acceptable with respect to well casing longevity. Only general corrosion was observed, even in a chloride environment. However, the samples were not exposed to artificial stress conditions in these screening experiments. The question of corrosion scale stability, especially in a cyclical temperature environment, is still unresolved. Based on preliminary evidence, it appears that corrosion products, especially at the lower temperatures, may be susceptible to cracking and sloughing under casing expansion/contraction cycles. It is possible that particles will be entrained in the air stream if corrosion products do not strongly adhere to the metal.

	Corrosion Rates, mm/yr	
<u>Piping Casing</u>	<u>175°C</u>	<u>300°C</u>
A120	0.036 $\pm$ 0.009	0.070 $\pm$ 0.022
H40	0.056 $\pm$ 0.013	0.078 $\pm$ 0.015
H53B	0.064 $\pm$ 0.008	0.063 $\pm$ 0.001

(a) Test conditions: 100% humid air (salt solution reservoir),
12.1 MPa (120 atm), 336 hr.

FIGURE 6.2. Corrosion Data for Carbon Steel A120 Well Casing Material

6.2 PERMEABILITY EXPERIMENTS AT TERRA TEK, INC.

Permeability/compressibility tests for consolidated sandstones under simulated CAES operating reservoir conditions were conducted at Terra Tek, Inc. (Stottlemyre and Cooley 1980). These tests were motivated by previous studies at Stanford University, Texas A&M University, and the University of California at Berkeley, where researchers had observed that the permeability of sandstones to distilled water can decrease by 60% or more over the temperature range of 25° to 150°C (75° to 300°F). However, no systematic change in permeability had been observed for sandstones when

dry gas was used as the working fluid. It is uncertain whether the sandstone response to humidified air would mirror liquid-water or dry-gas results or would fall between the two.

The Terra Tek study focused on the temperature sensitivity of permeability in sand sandstone (Stottlemyre, Cooley and Banik 1981). Ottawa sand and Massillon sandstone samples were exposed to a hydrostatic confining pressure of 150 bars, a pore fluid pressure of 60 bars, and temperature between 25°C and 150°C. Permeability to deionized, deaerated, prefiltered water and calcium chloride solution, bulk volumetric strain, fluid chemistry, and particle carryover were monitored as functions of temperature and time. Potential permeability damage mechanisms, including porosity reduction via internal and/or external particle plugging, were investigated.

Figure 6.3 illustrates results with temperature for Massillon sandstone and unwashed Ottawa sand employing inline upstream filters. Under the relatively low effective stress and temperature conditions used, temperature-induced creep compaction and thermal expansion of constituent minerals have negligible impact on porosity and, thus, presumably also on permeability. Increasing the temperature did enhance the mobilization of internal fines. However, based on the virgin and washed sand tests, the magnitude of the impact on laboratory-scale permeability measurements is concluded to be relatively small. This may not be the case in the field, however, where particle path lengths are considerably longer than those for 10-cm laboratory cores.

6.3 EXPERIMENTAL WORK AT PACIFIC NORTHWEST LABORATORY

6.3.1 Measurements Of Pittsfield St. Peter Core

The permeability of St. Peter sandstone from the Pittsfield field study exploration drilling to nitrogen gas was measured at room temperature and pressure (Erikson 1982). Samples were prepared to allow gas flow both parallel and perpendicular to bedding planes. Permeability

FIGURE 6.3. Permeability Ratio Versus Temperature

as a function of depth is illustrated in Figure 6.4. 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 varied from 12 to 18%.

6.3.2 Porous Media Flow Loop Experiments

Experiments in past years have 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 can be characterized with respect to permeability under a confining pressure, stress-strain behavior, rates of desaturation, and cyclic thermal fatigue (Erikson 1982).

FIGURE 6.4. Gas Permeability Versus Depth, Yakley Wells

Most experiments have measured permeability as a function of temperature, confining pressure, strain, and air humidity. The values of 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 measured the desaturation rate of a St. Peter sandstone sample.

First, the vertical permeability of a hydrostatically loaded St. Peter sandstone sample from a depth of 210 m (689 ft) was measured. The experimental parameters were temperatures of 22°C (72°F) and 93°C (200°F),

confining pressures (hydrostatic) of 8.3 MPa (1200 psi) and 17.3 MPa (2500 psi), and pore air pressure of 1.9 MPa (275 psi). Permeabilities at these temperatures were less than 100 md. 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 decreases with temperature, more experimentation is needed to quantify the significance of this response.

A dehydration curve for the same St. Peter sandstone sample is shown in Figure 6.5. The data were obtained while the sample was isolated at constant values of temperature 93°C (200°F), confining pressure 8.28 MPa (1200 psi), and pore pressure 1.9 MPa (275 psi). Dry air at a specific humidity of 0.01% and a flow rate of 3 to 4 cm³/sec was passed through 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 entrapment by high capillary forces.

FIGURE 6.5. Drying Curve for St. Peter Sandstone

Subsequent permeability experiments were conducted on St. Peter sandstone sample 657 from the Pittsfield injection/withdrawal borehole. The vertical permeability was measured using dry air while the sample was cycled between 21 and 177°C (70° and 350°F) at a constant confining pressure of 8.28 MPa (1200 psi). The data for this temperature cycle are shown in Figure 6.6. The initial permeability at room temperature (160 md) is slightly greater than that of an earlier sample from the Yakley No. 1 borehole. The vertical permeability measured during the heating cycle at higher temperatures is not radically different from values measured at room temperature. However, during the cooling cycle, permeabilities decreased and the vertical permeability measured at ambient temperature after one temperature cycle was approximately 135 md. Therefore, this sample exhibits a small permeability hysteresis in that the permeability did not return to its initial value before heating.

FIGURE 6.6. Vertical Permeability of St. Peter Sandstone to Dry Air

An explanation for the permeability hysteresis 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 can 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. The effects of air humidity on permeability must also be evaluated.

6.4 MECHANICAL PROPERTY MEASUREMENTS AT LOS ALAMOS NATIONAL LABORATORY

Testing of the structural response of typical aquifer sandstone to thermomechanical and cyclic loadings expected within a CAES reservoir were conducted at Los Alamos National Laboratory (LANL). The objectives of these studies were to identify structural failure mechanisms and to provide quantitative data for thermomechanical modeling and reservoir response evaluation.

Sandstone and caprock samples were acquired from the core inventory of the Northern Illinois Gas Company.

6.4.1 Reservoir Rock Experiments

Elastic and strength properties of Galesville sandstone (lower Paleozoic) were experimentally determined at temperatures ranging from 37° to 204°C (99° to 399°F) and effective confining pressures of 0 to 32 MPa (4638 psi). Young's modulus increased with increasing temperature and effective pressure. Poisson's ratio decreased with increasing temperature and effective pressure. Pore space reduction apparent in hydrostatic compression and thermal expansion tests suggests that these changes are a direct result of densification of the sandstone with either increasing temperature or pressure.

The triaxial compressive strength tests are summarized in Figure 6.7 in the form of a shear stress versus effective normal stress plot for the temperature range 37 to 204°C (99 to 399°F). Combinations of shear stress

and normal stress that plot above the experimentally determined strength envelopes are unstable; those below the envelopes are stable. Nonlinearity of the envelopes compared to Berea sandstone is due to plastic deformation of the dolomitic cement in Galesville sandstone. Expected operating ranges of stress for a porous medium CAES reservoir shown in Figure 6.7 indicate a substantial safety factor. However, coefficients of sliding friction along fractures (Figure 6.8) determined in the LANL experiments indicate that sliding movement along preexisting faults, joints, or bedding planes may be possible under certain stress conditions. Values of friction decrease with increasing temperature and pressure so that any such effects are likely to occur, if at all, near an injection well. Any movement of this type could have the beneficial effect of reducing injection impedance.

FIGURE 6.7. Mohr Failure Envelopes of Galesville Sandstone for Three Temperatures (Blacic, Halleck and D'Onfro 1979)

FIGURE 6.8. Coefficient of Sliding Friction on Fracture Planes Versus Effective Confining Pressure for Galesville Sandstone

Experiments to evaluate effects of cyclic stress on elastic constants and strength (Blacic, Halleck and D'Onfro 1979) indicate that, for up to 1000 cycles, there is generally no significant change in elastic constants of Galesville sandstone. However, at 10,000 cycles there are indications of damage in both Young's modulus and Poisson's ratio. The changes are generally consistent with the densification interpretation given previously; that is, modulus increases and Poisson's ratio decreases. No effect on ultimate compressive strength due to low stress cyclic loading could be discerned within the rather large scatter of data for this property.

Results of the LANL reservoir rock experiments indicated that increasing temperature, effective pressure, and cyclic stressing all densify the sandstone. This could result in an increasing injection/retrieval impedance with time. However, this effect may be

counterbalanced by sliding motion along preexisting joints, cracks, or bedding planes; this motion is likely to be enhanced by increasing temperature and pressure leading to a reduced reservoir impedance. In conclusion, no structural phenomena have been identified that would prevent successful operation of a porous CAES reservoir.

6.4.2 Caprock Experiments

The tensile strength of Kinderhook dolomitic (Carboniferous Paleozoic) shale was measured under dry and water-saturated conditions at 23°C (73°F) and 93°C (199°F). The samples were tested in a Brazil test fixture that could be immersed in a heated water bath. The higher temperature tests were allowed to equilibrate approximately 30 minutes before loading. All samples were from a continuous core section; in most cases, alternating samples along the core were tested at 23°C (73°F) and 93°C (199°F) to reduce sample variability effects.

Tensile strength of Kinderhook shale is quite variable (Figures 6.9 and 6.10) but the variation appears to be correlated with inhomogeneities in samples. Strong regions are associated with the presence of iron sulfides and weak regions with coal veins or bedding plane weaknesses due to presence of fossils or coring damage. There is a marked (50%) reduction in tensile strength of Kinderhook shale at 93°C (199°F) compared to 23°C (73°F). Because all tests were water-saturated, this weakening is probably not a result of clay contraction but caused by generation of pore pressures due to pore water and differential thermal expansion of the rock constituent minerals. This effect might cause weakening at higher temperatures if pore pressures exceeded the local rock confining pressure.

The samples tested parallel to bedding (Figure 6.10) are only slightly weaker than those tested perpendicular to bedding (Figure 6.11). However, this finding may not be significant because the test sample dimensions are very small compared to caprock dimensions.

When shale samples are air-dried at room temperature, small cracks form, mostly parallel to bedding. These cracks first open and then partially close again on further drying. Initial cracking is noticed

FIGURE 6.9. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated; Fracture Plane Perpendicular to Bedding

FIGURE 6.10. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated; Fracture Plane Parallel to Bedding

FIGURE 6.11. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Dry; Fracture Plane Perpendicular to Bedding

within 10 minutes after drying begins. Although cracking would tend to weaken samples in tension, this effect appears to be more than offset by a strengthening of the rock matrix materials as shown in Figure 6.11. Average tensile strength parallel to bedding at 23°C (73°F) is approximately three times higher in dry samples than in water-saturated samples. This is probably the result of an increase in the inherent strength of clay minerals when they are partially dehydrated (i.e., all loosely bound water is removed). Additional drying at 93°C (199°F) further increases tensile strength. In fact, the samples become brick-like. The large scatter in tensile strength data of dry samples compared to data for water-saturated samples is probably due to inhomogeneous cracking upon dehydration.

The LANL caprock experiments demonstrated that the tensile strength of a water-saturated shale caprock may be reduced by a factor of two or more at modestly elevated temperatures. The weakening mechanism should be positively identified so that implications and possible mitigating procedures can be evaluated.

6.5 AIR VENTILATION EXPERIMENTS AT UNIVERSITY OF WISCONSIN-MILWAUKEE

In studies at the University of Wisconsin-Milwaukee, quartz-dominated sandstones of the Berea, Jordan, St. Peter, Mt. Simon and Franconia formations were identified as CAES reservoir rock candidates. Samples were variously obtained from outcrops and drill cores in Illinois, Indiana, Iowa, Minnesota, and Wisconsin (Pincus 1980).

The ventilation equipment provides for reversible flow testing of confined samples using dry, heated, compressed air (Cutler 1979). Parametric ranges used were air temperature, 110° to 200°C (230° to 392°F); confining pressure, 550 to 5170 kPa (80 to 749 psi); air pressure drop across specimens, up to 1100 kPa (159 psi); and 2000 to 3000 cycles.

Seven mechanical and physical properties were measured before and after tests: Young's modulus, compressive strength, porosity, permeability, specific heat, thermal conductivity, and linear thermal expansion. Microstructure size, shape, arrangement and orientation of grains, pores, and microfractures and porosity also were evaluated before and after tests. Optical diffraction analysis was used to represent input microstructural orientation and spatial frequency data in polar coordinates. Statistical analysis included analysis-of-variance, multiple regression, and paired t-tests (Pincus 1982).

The following specific conclusions were drawn:

- Permeability is usually increased somewhat by ventilation. Rocks with smaller original permeabilities show the larger increases. Displacement of fine-grained poorly cemented material may explain this effect.

- No significant changes in either microstructure or porosity were associated with ventilation (Cutler 1979).

There was no indication of significant deterioration of the rocks after cyclic ventilation or heating. Although the mechanical properties of the rocks seemed to be affected by cyclic ventilation, no systematic changes in their values were recognizable.

- Rock type is the most important independent variable affecting Young's modulus and compressive strength. Possibly the least influential independent variable is mean flow-through air pressure.
- Among the sandstones least affected were two specimens of St. Peter that were also the purest quartz sandstones studied.
- Thermal properties are relatively unaffected by cyclic ventilation.

The following general conclusions were reached:

- Permeability, porosity, Young's modulus and compressive strength--the most important properties for CAES--are not adversely affected by cyclic ventilation under temperatures within the CAES range and confining pressures approaching the lower end of the CAES range.
- Cyclic displacement of an air-water interface in St. Peter specimens gave results consistent with those for dry-air ventilation.
- Petrologic variations, e.g., mineralogic composition and grain size, are more important than experimental parametric variations, e.g., flow rate and temperature.
- To characterize the structure and lithology of the potential reservoir rock and associated caprock, subsurface drilling and core recovery are needed.

In conclusion, the best candidate reservoir rock appears to be a clean quartz-sandstone, medium- to coarse-grained, well-sorted, and moderately cemented with silica. Thus, moderately well-cemented St. Peter sandstone, although less porous and permeable than poorly cemented St. Peter sandstone, may be better suited for use as a CAES storage medium because of superior strength and lower potential for particulate plugging.

7.0 AQUIFER FIELD EXPERIMENT AT PITTSFIELD, ILLINOIS

An initial conception for a small-scale field test of an aquifer structure was described by Doherty (1979). Details of the current aquifer field experiment as developed from this concept at Pittsfield, Illinois, have recently been presented by Allen and Doherty (1982). The Pittsfield Aquifer Test, as it is now known, was conceived to fulfill four objectives:

- Demonstrate the feasibility of storage and cyclic injection/retrieval of warm compressed air involving 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, thermal energy recovery, water production, and entrainment of mineral particulates.

7.1 GEOLOGIC SITE SCREENING AND CHARACTERIZATION

Eleven candidate sites were identified in the Illinois Basin (Allen, Trapp and Jensen 1981). These were chosen for screening on the basis of stratigraphy, structure, accessibility, and favorable lithology. Eight criteria were used to rank candidate sites: 1) available detailed exploration data; 2) absence of petroleum higher in the structure; 3) reservoir bed sufficiently shallow for economical field experiment; 4) reservoir bed sufficiently deep to retain air at suitable pressure; 5) absence of known structural deficiencies such as faulting; 6) horizontal continuity of the reservoir; 7) history of caprock containment; and 8) absence of shale lenses within the reservoir.

The Pittsfield dome in Pike County was ranked as the most favorable structure for detailed exploration. The general stratigraphy of this local region is shown in Table 7.1 (Rudd and Allen 1980). The Pittsfield dome is a doubly plunging anticline extending about 25 km (17 mi) west-northwest of Pittsfield (Trapp and Jensen 1981). A suitable caprock sequence consists of the Joachim dolomite (10 m thick), the Platteville dolomite (34 m thick) and the Galena limestone (42 m thick), which successively overlie the permeable St. Peter sandstone (69 m thick). All of these formations are Ordovician. The St. Peter/Joachim contact is 197 m (645 ft) below ground surface. Two second-order closures were described 3.2 and 8.1 km (2 and 5 mi) west-northwest of Pittsfield. These were tentatively identified from structure contour mapping of the uppermost Silurian as shown in Figure 7.1. Within the St. Peter, these closures are potential reservoirs for injection, storage, and withdrawal of compressed air.

TABLE 7.1. General Stratigraphy near Pittsfield, Pike County, Illinois

<u>System</u>	<u>Formation</u>	<u>Rock Type</u>	<u>Thickness</u>
Pleistocene	-	Loess, till alluvium	0 - 30 m
Mississippian	Keokuk-Burlington	Cherty limestone	0 - 15 m
	Kinderhook	Shale and limestone	15 - 50 m
Silurian	-	Limestone	15 m
Ordovician	Maquoketa	Greenish shale	50 m
	Galena Platteville Joachim	Limestone and dolomite	90 m
	St. Peter	Clean, poorly to moderately well-cemented sandstone	70 m

FIGURE 7.1. Structure Contours and Seismic Traverses near Pittsfield, Illinois

Structural site characterization proceeded in three stages: initial drilling, seismic surveying, and confirmatory drilling (Allen, Trapp and Jensen 1981). The first hole was drilled roughly midway between the apparent closure centers to supply 1) seismic velocity data for the sedimentary bedrock Paleozoic formations; 2) continuous core to verify the stratigraphy and provide reservoir and caprock specimens for laboratory examination; 3) density, temperature, electric, and gamma ray-neutron logs to characterize formations and contacts; and 4) aquifer discovery pressure, which is the effective pressure of containment.

Testing of St. Peter reservoir core disclosed satisfactory fluid storage and flow characteristics. Average gas permeabilities were approximately 700 md in both vertical and horizontal directions. Average porosity was 20%. Threshold pressures and vertical permeabilities measured on core from the Platteville and Joachim formations prove this

combined caprock sufficiently impervious to contain compressed air during the lifetime of the field test. Threshold pressures in the Platteville often exceeded 5.52 MPa (800 psi).

The equilibrium water level in this first borehole was 91.5 m (350 ft) below ground level. This is equivalent to a discovery pressure of 1.38 MPa (200 psi) at the reservoir top. Discovery pressures measured near the top of the easterly second-order dome were between 1.035 and 1.104 MPa (150 and 160 psi).

Fifteen linear miles of seismic reflection surveying were conducted along eight east-west and north-south trending lines as shown in Figure 7.1. In addition, refraction surveys were made to measure overburden velocity and thickness variations. These parameters were factored into reflection data reduction. Final seismic data confirmed the secondary anticline 3.2 km (2 mi) west of Pittsfield and provided estimates of 300 m (984 ft) for diameter and $9 \text{ m} \pm 2 \text{ m}$ ($29 \text{ ft} \pm 6.6 \text{ ft}$) for closure. The second small anticline, 8.1 km (5 mi) west-northwest of Pittsfield, was not so well defined.

A second deep borehole was drilled to begin confirming the structure, to obtain additional samples of caprock and reservoir rock, to measure discovery pressure within the structure, and to procure water samples for water quality analysis. Dominant anions were Cl^- , SO_4^- , and HCO_3^- . Significant quantities of boron, silica, strontium, and ammonia were found. The pH was 8.07. Threshold pressures and vertical permeabilities measured on Joachim/Platteville core disclosed acceptable air retention characteristics. Six shallow holes were subsequently drilled to delineate the anticline by locating the height of the Silurian-Ordovician interface above mean sea level. The upper Ordovician Maquoketa shale, a diagnostic key bed, was used for four reasons: 1) few existing wells penetrate the St. Peter; 2) the Silurian interval varies considerably in thickness; 3) the stratigraphic interval between Maquoketa and St. Peter is nearly constant; and 4) exploration costs were reduced by minimizing hole depths.

The combined interpretation of drilling and seismic reflection results has identified the structure shown in Figure 7.2. Nearly 15.2 m (50 ft) of closure are indicated within an area of 263.3 ha (650 acres). This small dome trends east-west in contrast to the west-northwesterly trend of the Pittsfield anticline. The structural top is relatively rounded. Structural gradients along the flanks were 0.17 to the east, 0.020 to the south, and 0.011 to the west. Total structural closure was more than 24.4 m (80 ft).

FIGURE 7.2. Structure Identified near Pittsfield, Illinois

The combined data from lithologic and gamma logging of boreholes, seismic reflection surveying, and historical records disclosed significant small-scale variations in structure and stratigraphy, including anticlinal traps with potential for confining compressed air (Allen, Trapp and Jensen 1981).

The site screening and characterization program was concluded with the boring of two deep holes into the upper region of the anticlinal structure. These were made to assure structural applicability of the Ordovician Maquoketa shale (i.e., stratigraphic conformity and parallel folding), to measure discovery pressure, to acquire added caprock and reservoir rock for testing, and to acquire reservoir water for chemical analysis.

Water withdrawn from the St. Peter sandstone contained 3555 mg per liter total dissolved solids. Dominant cations were Ca^{++} , Mg^{++} , K^+ and Na^+ .

7.2 SITE DEVELOPMENT

Before site development started Pacific Northwest Laboratory obtained an injection well construction permit from the Illinois Environmental Protection Agency.

Site development included all aspects of design and installation of the injection/withdrawal (I/W) well, the monitoring well field, surface compressor plant, monitoring system components, utility access, provision for water rejection, physical access for drilling rig and equipment trucks, and post-test coring (Istvan 1981). PB-KBB, Inc., of Houston, Texas coordinated site design, surface plant construction, well field development and monitoring systems with various subcontractors.

The I/W well was drilled and cased in June 1981 (Istvan 1982). A schematic cross section is shown in Figure 7.3. The perforated air injection section is designed to protect the uppermost "green" St. Peter sandstone from erosion during air withdrawal intervals.

FIGURE 7.3. Injection/Withdrawal Well Completion

The monitoring well field, shown in Figure 7.4, consists of two near-wellbore 7-in. diameter closed-instrument wells designated "F" and "G", and four outer 2-718-in. diameter logging/sampling wells designated "A", "B", "C" and "D". Schematic cross sections of the closed-instrument and logging/sampling wells are shown in Figures 7.5 and 7.6. All wells have been surveyed to ascertain bottom locations.

FIGURE 7.4. Locations, Elevations, and Bottom Hole Deviations of Pittsfield Wells

Locations of well tops and bottoms are shown in Figure 7.7 for the I/W, "F" and "G" wells. The closed-instrument wells were designed to monitor pressure, temperature, formation water saturation, and air humidity at radii approximately 4 m and 10 m from the injection/withdrawal well. Details of sensor deployment are shown in Figures 7.8 and 7.9. The most dramatic impacts on the subsurface geologic regime will take place near the injection point. The more distant logging/sampling wells will be monitored by periodic wireline logging, water sampling, and almost continuous wellhead air pressure measurement. Sensor selection, design, calibration and installation were completed by Energy Resource Management of Tucson, Arizona (Hostetler et al. 1982). The surface facility houses the electronics and data acquisition equipment associated with these wells.

FIGURE 7.5. Wells "F" and "G" at Completion of Coring

FIGURE 7.6. Logging Wells "A", "B", "C", and "D"

FIGURE 7.7. Injection/Withdrawal, "F" and "G" Well Locations

FIGURE 7.8. Sensor Deployment in an Instrumented Interval

FIGURE 7.9. Sensor Deployment System

Drilling the monitoring wells has afforded two by-product benefits: added structural information, and cores of caprock and reservoir rock representative of the intended storage zone (Istvan 1981). Visual logs and geophysical logs show good agreement with respect to the depths to geologic contacts. The stratigraphic interval between the uppermost Ordovician Maquoketa formation (key marker bed) and the St. Peter sandstone top varies by only 4 m over 3.5 km linear distance. The latest drilling indicates that this variation is continuous and subject to interpolation, thereby increasing the accuracy of mapping the St. Peter/Joachim contact configuration. The structural interpretation from this added drilling confirms the nearly east-west elongated dome.

A natural gas-powered compressor system was designed because natural gas is the least costly energy alternative at Pittsfield. It comprises an air compressor and receiver, dehydrator, air heater, solid particle sampling manifold, outlet muffler, flow and pressure controls, and sensors to measure temperature, pressure and humidity. The compressor package was fabricated by CSI, Inc.; the surface metering skid was developed by BOC Engineering. Both firms are based in Midland, Texas. The injection system is operated from a building erected at the injection/withdrawal wellhead.

A schematic of surface equipment, shown in Figure 7.10, is representative of air circuitry and monitoring (Allen, Kannberg and Doherty 1981). A small test section was installed between the pressure meter and injection wellhead, to enable screened retention of fine particulate minerals suspended within the withdrawn compressed air. An inordinately high volume of particulates per unit time of air withdrawal could indicate loss of rock competence at the wellbore. This test section will also be used to perform corrosion studies during both injection and withdrawal of air.

FIGURE 7.10. Schematic of Surface Facility

Injection pressure at the wellhead is monitored and controlled automatically. Control valves and an overpressure relief system prevent the pressure from exceeding the maximum permissible 2070 kPa (300 psi). The injection pressure controls the compressed air injection rate into the St. Peter formation. The maximum injection pressure is less than 50% of calculated overburden pressure. Temperature is measured at the wellhead; if the temperature exceeds 200°C (392°F), the system will be automatically shut down. Failsafe shutdown will also be triggered by overpressure within the injection system. Any indication of significant reservoir or caprock fracturing or granular deterioration will be cause for system shutdown.

7.3 DETAILED RESERVOIR CHARACTERISTICS

Mineralogic, rock mechanical and hydrologic characteristics of reservoir component beds were determined from cores taken during well field development. The Platteville and Joachim formations comprise the secondary and primary caprocks. The Platteville formation is a fine-grained limestone, which contains thin illitic shale laminations and becomes dolomitic toward the contact with the Joachim formation.

The Joachim is primarily fine-grained dolomite. Fine fraction x-ray diffraction analysis indicates that the dolomite is either ferroan or ankeritic (PB-KBB, Inc., and David K. Davies and Associates 1983). Illite, calcite, anhydrite, pyrite, and marcasite are present. Vugs and fractures are generally filled by calcite and minor amounts of galena, sphalerite, and pyrite or marcasite. Scanning electron microscope examination revealed abundant intercrystalline pore spaces. These pores are generally not interconnected, which accounts for the relatively high porosities (maximum of 36%) and low permeabilities (0.03 to 71 md) of samples tested.

Triaxial compressive strengths under a 70.3-kg/cm² (1000-psi) confining pressure varied from 198 to 1201 kg/cm² (2,813 to 17,083 lb/in²) and unconfined uniaxial compressive strengths varied from 226 to

765 kg/cm² (3,215 to 10,880 lb/in²). These data indicate that the Joachim formation can withstand the pressures to which it will be subjected during air injection and cycling. Samples with open vugs and open vertical fractures failed under substantially lower loads than did samples of compact dolomite or limestone. Sandy dolomite samples, representative of the Joachim-St. Peter formation transition zone, exhibited uniaxial compressive strengths of 150 and 196 kg/cm² (2140 and 2790 lb/in²). These strengths did not, however, represent in situ conditions because no confining pressures were applied (PB-KBB, Inc., and David K. Davies and Associates 1983).

The uppermost 2- to 3-in (6.6- to 10-ft) thick green St. Peter sandstone is poorly to moderately well-sorted and medium- to coarse-grained (average grain diameter of the coarse mode = 0.44 to 0.63 mm); the quartz grain size is bimodally distributed. The sandstone contains an abundant fine-grained detrital matrix, about 27% of the rock, which was co-deposited with the coarser quartz. Quartz grains exhibit concavo-convex or point contacts and occasionally grains appear to "float" in the matrix. Fine fraction x-ray diffraction analysis revealed 4 to 32% illite. Potassium feldspar (0 to 27%) was absent in only one sample. Calcite, marcasite, sericite, pyrite, ankerite, and anhydrite occur sporadically. Scanning electron microscope examination revealed that most of the illite occurs as laminated clay. Potassium feldspar is generally present as an authigenic precipitate on quartz grains and within the pore system. Marcasite and pyrite are distributed unevenly in the pore system. Porosities of green sand samples vary from 10.0 to 23.0%. Horizontal permeabilities vary from 2.1 to 6100 md, and vertical permeabilities vary from 0.9 to 3900 md. The permeability of the green sand appears to be controlled by the depositional matrix, which is laminated horizontally. Thus, vertical permeabilities are less than horizontal permeabilities. One green sand sample was subjected to uniaxial compressive strength testing. The strength at failure of 82 kg/cm² (1170 psi) was the smallest of all samples tested but not representative of in situ conditions (PB-KBB, Inc., and David K. Davies and Associates 1983).

The underlying white St. Peter sandstone is medium-grained (0.37 to 0.45 mm on average) and moderately well-sorted. Quartz grains exhibit concavo-convex or point contacts. Vertical fractures are either open or filled by calcite. The white sand is composed primarily of monocrystalline quartz (85 to 87%) and is cemented by silica. A detrital clay matrix was detected in only one sample. Fine fraction x-ray diffraction analysis showed illite (17 to 59%) and potassium feldspar (3 to 17%) in all samples. Other mineral phases include marcasite, pyrite, and anhydrite. Scanning electron microscope examination revealed illite as fibers that bridge pore throats and partially isolate pores. The porosity ranges from 9.7 to 20.9%. The horizontal permeability varies from 13 to 5200 md, and the vertical permeability varies from 78 to 2900 md. Permeability variations are controlled by cementation patterns, with poorly cemented samples exhibiting greater permeabilities than well-cemented samples. Uniaxial compressive strength was 413 kg/cm² (5880 psi) for one specimen (PB-KBB, Inc., and David K. Davies and Associates 1983).

7.4 EXPERIMENTAL PLAN

The basic test plan is to develop a bubble within the Pittsfield structure over a period of months and then conduct controlled cyclic testing at successively higher temperatures within this developed reservoir. Before air injection was begun, Pacific Northwest Laboratory obtained an Operation Permit from the Illinois Environmental Protection Agency. Air bubble development then began by injecting very dry air with relative humidity near zero at a temperature close to that of the natural reservoir. This required dehydration and cooling to reject most of the heat of compression. Air is being injected near the top of the St. Peter sandstone over an interval of approximately 2.5 m (8.2 ft). The injected air is monitored for relative humidity, temperature, pressure, and mass flow rate at the surface. The air injection pressure is permitted to be less than 2070 kPa (300 psi) with a flow rate limit of approximately 35.4 scfm (1250 scfm). This enables displacement of ground water within the aquifer, which has a discovery pressure of 1035 to 1104 kPa (150 to 160 psi).

The closed-instrument wells were designed to supply continuous data concerning temperature, pressure, relative humidity and percentage of water saturation in rock as functions of time and location as far as was practicable within existing subsurface equipment technology (Hostetler et al. 1982). 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. The actual rate of bubble growth is monitored by recording sampling/logging well pressure responses and neutron logging at three radial positions.

The final bubble dimensions are to be sufficiently large to enable short-term cyclic withdrawal and injection without causing large variations in the bubble's areal extent or thickness. The surface projection of the bubble is anticipated to be on the order of 40 ha (100 acres); thickness, as determined by formation dip, will range from 7.6 to 9.2 m (25 to 30 ft) at the injection well. Cyclic injection and withdrawals will constitute small fractions of the bubble total volume.

Air cycling was prescribed to simulate the volume flow rate of the unit length of a producing section of one well of a full-scale CAES aquifer installation. Definition of exact cycle period, injection temperatures, injection pressures, mass flow rates, air humidity, and number of cycles at each temperature depends on the specific characteristics of the reservoir. A series of numerical models developed at PNL during previous research were used in preliminary test planning, but actual operations will dictate conditions (Allen, Kannberg and Doherty 1981). The currently planned operations call for one cycle per day with 7 hr injection, 11 hr withdrawal, 6 hr rest and equal air masses injected and withdrawn. The injection pressure will never exceed 50% of the minimum laboratory measured threshold pressure, integrated for the total caprock thickness (Wiles and McCann 1982).

The baseline test matrix for air cycling 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 (Allen, Kannberg and Doherty 1981; Wiles and McCann 1981a). 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.

Post-test coring of the reservoir rock and caprock is 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.

7.5 RELATIONSHIP TO FULL-SCALE AQUIFER STORAGE

The Pittsfield experiment was developed to fulfill the four objectives outlined in the opening of this section. The first purpose is to gather fundamental data. Resources did not permit development of a full-scale test, nor was such a test required. However, certain aspects of the test do reflect full-scale conditions. The injection/withdrawal well has been designed to accommodate thermal cycling and to store thermal energy. The injection volume flow rate and temperatures are consistent with full-scale conditions. The experimental results can also be contrasted with natural gas storage experience to determine differences in geochemistry, cycling period, temperature and fluid viscosity (Allen 1981).

Particulates withdrawn through the screened reservoir can be trapped and analyzed. The results will enable evaluation of rock fabric damage due to ventilation, thermal cycling, and chemical reaction. These data, coupled with physical measurements in the near-wellbore closed-instrument wells, will measure the attrition beyond the well screen. Sand-fixing by in situ permeable cementation may be required.

Reservoir receptiveness to air injection will be measured by mass flow rate at controlled pressure levels during bubble development and cyclic injection. Permeabilities of cores will be measured before and after test. Geochemistry of the cores will be evaluated in relation to permeability.

Caprock samples will be taken from pre-test and post-test cores. These will be compared for mineral content, permeability, threshold pressure, and fracture pattern.

The applicability of numerical modeling to physical reservoir development will be studied. Temperature, pressure, and humidity will be measured continuously for air withdrawn from the I/W well. In addition, the percentage of water saturation will be measured by neutron logging in outer air sampling/logging wells. The measurement system has been designed to disclose any tendency toward water coning during air withdrawal. Some outlying wells will be closed-in to enable measurement of internal well air pressure as it responds to the air pressure wave and air/water interface migrations, both of which will emanate from the I/W well screen section.

Of particular importance are air mass flow and temperature during release of air from the reservoir. Both are to be monitored with time to assess reservoir recovery efficiency.

7.6 FORECAST

The Pittsfield Aquifer Field Test will involve simulation of aquifer 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, output energy flow rates, 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 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.

8.0 STABILITY CRITERIA AND GUIDELINES

The stability criteria and guidelines for aquifer CAES development are summarized in Table 8.1 under the following categories: geological environment, reservoir characteristics, operating characteristics, host rock stability, reservoir behavior, and federal and state compliance. Using Table 8.1 as a checklist will ensure that potential system developers give consideration to the wide range of topics that should be noted.

Although well field design, well design and reservoir well completion are not emphasized in this document, it is important to recognize the vital function of the well completion and air passage cross section. Whether the well completion uses a welded wire screen, a perforated casing, or gravel-packed reamed-out region in combination with a screen, some geometric arrangement of apertures, regular or irregular, comprises the critical flow area of the wellbore-reservoir intersection. This is the critical and dominating restriction that must be considered in designing an aquifer CAES system.

Many standard design techniques for well completion are available in oil and natural gas practice to result in minimum restriction designs. The limitation of air transfer area between injection/withdrawal borehole and air storage formation can also be relaxed by enlarging the drill hole within the reservoir by reaming and backfilling the reamed-out volume with coarse, nearly round and uniform diameter quartz pebbles. The injection/withdrawal zone should be as long as feasible.

In friable formations it may be necessary to treat the reservoir rock adjacent to the wellbore by either an organic (resin) or inorganic (silica lock) injection. This treatment could be carried out before reaming to prevent collapse of the incompetent reservoir rock.

In an acceptable well completion, particulate plugging is preventable near the wellbore because air velocities through the wellbore-reservoir interface can be made insufficient to transport available loose fine grains from the formation.

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TABLE 8.1. Stability Criteria and Guidelines for Aquifer CAES Development

Category	Requirement	Qualification
<u>Geological Environment</u>	Closed anticline or dome involving impervious shale or carbonate caprock conformably overlying a sandstone aquifer; alternative stratigraphic or solution-type traps may be considered.	Analysis of existing geological data, seismic surveying, exploratory drilling, hydrology testing, core measurements, geophysical logging
<u>Reservoir Characteristics</u>		
a. Porosity	10% or greater	Core analysis; must not include irreducible water content
b. Permeability to gas	300 md minimum	Core analysis, pump tests
c. Vertical closure	10 m or more (30+ ft)	Exploratory drilling
d. Centerpoint thickness	10 m or more (30+ ft)	Exploratory drilling
e. Depth to reservoir	Between 200 and 1500 m	Exploratory drilling
f. Volume	$2 \times 10^6 \text{ m}^3$ ($70 \times 10^6 \text{ ft}^3$) or more of pore volume (for 200 MW/10 hrs) (~10,000 lb of air per MW hr)	Exploratory drilling, core analysis
g. Radius	ca. 1000 m (3000+ ft)	Exploratory drilling
h. Caprock effective thickness	10 m (30 ft); must ensure integrity of air reservoir and adequately anchor airtight seal between casing and well-bore.	Exploratory drilling, core measurements and hydrology testing; greater thickness or multiple caprocks will enhance air retention.

TABLE 8.1. Continued

Category	Requirement	Qualification
i. Caprock slope	< 15" to minimize potential for movement on glide planes	Seismic surveying, exploratory drilling
j. Discovery pressure	20 to 80 bar (300 to 1200 psi)	Depth measurement of water in casing at equilibrium
<u>Operating Characteristics</u>		
a. Injection temperature	Higher than reservoir ambient temperature but not over 250°C	Heat rejection from compressed air, continuous temperature monitoring
b. Mean storage pressure	20 to 80 bar (300 to 1200 psi)	Must be close to discovery pressure at base of bubble, which varies from 9.8 to 11.8 kPa per meter of depth below the water table.
c. Maximum charging pressure	Not over 18.1 kPa per meter of depth (0.8 psi/ft)	Must not exceed 80% of overburden pressure to prevent hydraulic or pneumatic fracturing.
d. Delta pressure	Not over 50% of caprock threshold pressure	Continuous pressure monitoring and preinjection core analysis
e. Water saturation	0 to 1% in critical near wellbore zone; residual saturation acceptable in working zone	Continuous saturation monitoring

TABLE 8.1. Continued

Category	Requirement	Qualification
<u>Host Rock Stability</u>		
a. Wellbore stability through caprock	Wellbore-caprock interface shall not deteriorate over the design life of the reservoir	Design for cyclical thermal and pressure loadings with high temperature events and other geothermal design features.
b. Differential thermal expansion	Reservoir rock must not deteriorate significantly due to differential thermal expansion-induced fatigue of grains and cementing materials.	Petrographic examinations and mechanical strength measurements of reservoir rock before and after exposure to simulated and actual field conditions
c. Hydrolytic reactions	Significant hydrolysis causing alteration of feldspars to clay minerals or hydrolytic weakening of Si-O bonds in quartz is to be prevented.	Selection of reservoir and caprock sequence should eliminate members high in feldspar and ferromagnesian minerals. Hydrolytic weakening, if a problem, could be minimized in the critical zone by appropriate gravel packing.
d. Cement dissolution	Loss of cement within the reservoir rock must not threaten its integrity during the design life.	The effects of heated water vapor on siliceous and carbonate cements should be quantified.

TABLE 8.1. Continued

Category	Requirement	Qualification
e. Particulate plugging	Significant reductions in permeability must not occur due to air transport of pre-existing fines, disaggregated grains, corrosion products or geochemical reaction products.	Laboratory ventilation experiments should duplicate field cycling conditions to qualify reservoir rocks.
f. Mineral precipitation	Minerals precipitated from residual water evaporation must be restricted to non-channelized portions of the reservoir rock.	Reduction of porosity in zones containing irreducible water is not likely to alter overall response of reservoir media because these zones typically exist within high capillarity pores
g. Oxidation reactions	Mineralized zones rich in pyrite, galena, ferrous oxides, manganous oxides, or other minerals subject to oxidation, should be avoided.	Mineralogical examination of reservoir rock and caprock will preclude association of CAES with significant concentrations of oxidizable deposits
<u>Reservoir Behavior</u>		
a. Compressibility	A significant decrease in permeability and porosity must not take place due to increased compressibility of quartz sandstones at high temperature.	Laboratory and in situ testing of compressibility of CAES reservoir media is necessary.

TABLE 8.1 Continued

Category	Requirement	Qualification
b. Overpressurization	The maximum level of overpressure must be specified before air injection.	Laboratory and pump tests involving caprock determine the allowable level of overpressure.
c. Seismic response	Site selection procedures will exclude seismically active areas.	Geophone nets and tiltmeters can be installed at a site to quantify possible seismic behavior.
d. Ground-water flow	Ground-water flow must neither transport the air bubble out of the intended storage area nor severely distort the bubble shape.	Field measurement of ground-water flow rates can be done by tracer injection and recovery at various azimuths, radial distances and times.
e. Bubble configuration	Gas bubble must not be dissipated by wafering or fingering along highly permeable zones that cause loss of air from the structural trap.	Core analysis of reservoir media will characterize bedding heterogeneity. Neutron logging and other monitoring devices will help define gas bubble growth and ultimate shape. Bubble development and monitoring methods should consider this possibility.
f. Water coning	Radial and vertical migrations of ground water toward the wells must not interfere with air withdrawals over the life of the CAES reservoir.	Field experimentation coordinated with numerical modeling will define limiting conditions. Sufficient air storage zone thickness, the presence of horizontal impervious layer(s) or edge water drive can eliminate water coning as a concern.

TABLE 8.1. Continued

Category	Requirement	Qualification
g. Rapid air withdrawal	Reservoir control must be adequate to preclude damage through compaction caused by rapid loss of pressure.	Cores should be taken for structural analysis to determine the effects of pore depressurization rates compatible with CAES operations. Reverse water flow rates should be measured. Throttling devices may limit withdrawal rates.
h. Aquifer pressure variations	Aquifer pressure must not be influenced by water withdrawals from water wells within the CAES region.	The aquifer must be managed in total. The storage company may need to acquire other subsurface rights to limit new well penetrations.
<div>87</div> Federal and State Compliance (Hendrickson 1981)		
Underground injection control-Safe Drinking Water Act-1974	A state or Federal EPA permit will be required within the standards of 40 CFR 146. An area-wide multiple well permit as in 40 CFR 122.39 is applicable to aquifer CAES.	Most probably regulated at the SEPA level; an environmental assessment or impact statement, including geologic evaluations and operational considerations, would most probably provide the permit basis. Construction and operational recordkeeping would be required.
Environmental impact statement	Depending on ownership and financial responsibility, NEPA EIS may be required of the cognizant Federal agency or the state EPA may require an EIS or both.	The reservoir aspects of an EIS would be adequately addressed by U.S. regulatory documentation.

TABLE 8.1. Continued

Category	Requirement	Qualification
State ground-water protection regulations	Check state environmental, health, geologic and commerce regulation.	Specific to the individual state
State well drilling and abandonment regulations	Check with state geologic, mineral and commerce agencies for applicable regulations and permits.	Obtain permit, provide detailed records and logs during construction, and provide logging, sampling and geologic information as required.

REFERENCES

- Ahluwalia, R. K., A. Sharma and F. W. Ahrens. 1978. "Design of Optimum Aquifer Reservoirs for CAES Power Plant." In proceedings Compressed Air Energy Storage Symposium, Vol. 1, pp. 295-325, CONF-780599, National Technical Information Service, Springfield, Virginia.
- Ahrens, F. W. 1978. "The Design Optimization of Aquifer Reservoir-Based Compressed Air Energy storage-systems." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 404-415, CONF-781046, National Technical Information Service, Springfield, Virginia.
- Allen, R. D. 1981. "Basis for Compressed Air Energy Storage (CAES) Field Test at Pittsfield, Illinois." In Proceedings of the International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, Vol. 2, pp. 573-583, CONF-811066, National Technical Information Service, Springfield, Virginia.
- Allen, R. D., and T. J. Doherty. 1982. "The Aquifer Compressed Air Field Experiment at Pittsfield, Illinois." In Proceedings of AIAA/EPRI International Conference on Underground Pumped Hydro and Compressed Air Energy Storage, A Collection of Technical Papers, pp. 215-222. AIAA CP 826, American Institute for Aeronautics and Astronautics, New York, New York.
- Allen, R. D., and P. J. Gutknecht. 1980. Porous Media Experience Applicable to Field Evaluation for Compressed Air Energy Storage. PNL-3294, Pacific Northwest Laboratory, Richland, Washington.
- Allen, R. D., L. D. Kannberg and T. J. Doherty. 1981. "Aquifer Field Test for Compressed Air Energy Storage." In Proceedings of the 16th Intersociety Energy Conversion Engineering Conference, pp. 978-983. American Society of Mechanical Engineers, New York, New York.
- Allen, R. D., J. S. Trapp and T. E. Jensen. 1981. "Site Characterization for Injection of Compressed Air into an Aquifer." In Proceedings of the 22nd U.S. Symposium on Rock Mechanics, pp. 417-421. Massachusetts Institute of Technology, Cambridge, Massachusetts.
- American Gas Association. 1977. "The Underground Storage of Gas in the United States and Canada." Committee on Underground Storage, Twenty-Seventh Annual Report on Statistics, New York, New York.
- Ayers, D. L. 1975. "Adapting Available Aquifers to Compressor and Turbine Needs for Compressed Air Energy Storage." In Proceedings of the Workshop on Compressed Air Energy Storage Systems, pp. 278-304, ERDA-76-124, CONF-75-1242, National Technical Information Service, Springfield, Virginia.

Ayers, D. L., and P. A. Berman. 1981. "Problems in Reservoir-Rotating Equipment Matching in Aquifer CAES." In Proceedings of International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, Vol. 2, pp. 604-612, CONF-811066, National Technical Information Service, Springfield, Virginia.

Ball, D., and R. L. Harris. 1975. "Legal and Practical Aspects of Air storage in Aquifers." In Proceedings of the Workshop on Compressed Air Energy Storage Systems, pp. 408-433, ERDA-76-124, CONF 75-1242, National Technical Information Service, Springfield, Virginia.

Beckwith & Associates. 1983. Review of Environmental Studies and Issues on Compressed Air Energy Storage. PNL-4460, Pacific Northwest Laboratory, Richland, Washington.

Bervig, D. R., and R. W. Pinker. 1979. "An Assessment of Compressed Air Energy Storage (CAES) for the Kansas Utility System." In 1978 Compressed Air Energy Storage Symposium Proceedings, Vol. 1, pp. 127-177, CONF-780599, National Technical Information Service, Springfield, Virginia.

Bervig, D. R., and F. Wallace. 1978. Geologic Assessment of Compressed Air Storage Sites in Kansas. Black and Veatch, Kansas City, Missouri.

Blacic, J. D., P. H. Halleck and P. D'Onfro. 1979. "Thermo-Mechanical Properties of Galesville Sandstone." In Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 150-155, CONF-790854, National Technical Information Service, Springfield, Virginia.

Bush, J. B., Jr., P. M. Jarvis, D. A. Plionis, R. D. Andersen, J. L. Ash, A. S. Mitchell, G. E. Engleson and E. J. Sosnowicz. 1975. "An Assessment of the Technical and Economic Feasibility of Compressed Air Energy Storage." In Proceedings of the Workshop on-Compressed Air Energy Storage Systems, pp. 14-72, ERDA-76-124, CONF 75-1242, National Technical Information Service, Springfield, Virginia.

Cain, J. E., S. H. Shryock and G. Carter. 1966. "Cementing Steam Injection Wells in California." J. Petroleum Technology, April, pp. 431-436.

Chang, G. C., P. A. Thompson, R. D. Allen and W. V. Loscutoff. 1980. "Underground Compressed Air Energy Storage for Electric Utilities." In Rockstore 80, Proceedings International Symposium on Subsurface Space, Vol. 2, pp. 579-585. Pergamon Press, Oxford, England.

Cutler, R. M. 1979. Laboratory Studies of Compressed Air Energy Storage on Selected Reservoir Rock and Caprock. M.S. Thesis, Geology, The University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

- Doherty, T. J. 1979. "Complementary and Potential CAES Field Studies." In Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 176-181, CONF-790854, National Technical Information Service, Springfield, Virginia.
- Doherty, T. J. 1980. "Reservoir Stability Studies." In Proceedings of the Mechanical, Magnetic and Underground Energy Storage 1980 Annual Contractors' Review, pp. 185-191, CONF-801128, National Technical Information Service, Springfield, Virginia.
- Doherty, T. J. 1981. "Air Storage Systems." In Proceedings of International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, Vol. 2, pp. 455-468, CONF-811066, National Technical Information Service, Springfield, Virginia.
- Doherty, T. J. 1982. "Reservoir Stability Studies." In Proceedings of the Mechanical, Magnetic and Underground Energy Storage 1981 Annual Contractors' Review, pp. 39-45, CONF-810833, National Technical Information Service, Springfield, Virginia.
- Elmore, R. P., and J. A. Stottlemire. 1980. Corrosion of Well Casings in Compressed Air Energy Storage Environments. PNL-3429, Pacific Northwest Laboratory, Richland, Washington.
- Erikson, R. L. 1982. "Porous Media Experimental Tasks." In Underground Energy Storage Program 1981 Annual Report, Volume II. Technical Summaries, pp. 101-107. PNL-4281, Pacific Northwest Laboratory, Richland, Washington.
- Erikson, R. L., J. A. Stottlemire and R. P. Smith. 1980. An Experimental Study of the Response of the Galesville Sandstone to simulated CAES Conditions. PNL-3399, Pacific Northwest Laboratory, Richland, Washington.
- Friley, J. R. 1979. "Structural Response of a Generic Porous Site." In Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 158-165, CONF-790854, National Technical Information Service, Springfield, Virginia.
- Friley, J. R. 1980. Structural Analysis of Porous Rock Reservoirs Subjected to Conditions of Compressed Air Energy Storage. PNL-3231, Pacific Northwest Laboratory, Richland, Washington.
- Friley, J. R., and T. J. Doherty. 1978. "Thermo Mechanical Stress Analysis of Porous Rock Reservoirs." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 349-354, CONF-781046, National Technical Information Service, Springfield, Virginia.

General Electric Company. 1976. Economic and Technical Feasibility Study of Compressed Air Storage. ERDA-76-76, Schenectady, New York.

Griggs, D. T. 1967. "Hydrolytic Weakening of Quartz and Other Silicates." Geophys. J. Astron. Soc. 14:19-31.

Gross, D. 1980. Compressed Air Energy Storage in Cambro-Ordovician Sandstones of Eastern Iowa and Southwestern Wisconsin. M.S. Thesis, Geology, The University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

Halliburton Company, U. S. Patent No. 2,805,719.

Hendrickson, P. L. 1981. Legal and Regulatory Issues Affecting Compressed Air Energy Storage. PNL-3862, Pacific Northwest Laboratory, Richland, Washington.

Hewitt, C. H. 1963. "Analytical Techniques for Recognizing Water Sensitive Reservoir Rocks." J. Pet. Tech., August, pp. 813-818.

Hobson, M. J. 1978. Feasibility of Compressed Air Energy Storage as a Peak Shaving Technique in California, Vols. 1 and 2. Acres American, Inc., Buffalo, New York.

Hobson, M. J., E. G. Heath, A. J. Giramonti and W. A. Adent. 1979. "Feasibility of CAES in California." In Proceedings of the Compressed Air Energy Storage Symposium, Vol. 1, pp. 179-212, CONF-780599, National Technical Information Service, Springfield, Virginia.

Hopper, J. W. 1980. The Effects on Rock Properties of Cycling Heated Compressed Air in Selected Rocks, with Emphasis on Thermal Properties. M.S. Thesis, Geology, The University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.

Hostetler, D. D., J. A. Istvan, S. J. Philips, S. W. Childs and E. R. Cheatham. 1982. "Subsurface Instrumentation at the CAES Field Test Facility, Pittsfield, Illinois: Instrument Plan." In Proceedings International Conference on Underground Pumped Hydro and Compressed Air Energy Storage. A Collection of Technical Papers, pp. 223-236. AIAA CP 826, American Institute of Aeronautics and Astronautics, New York, New York.

Istvan, J. A. 1981. "Compressed Air Energy Storage Aquifer Field Test Conceptual Design, Construction, and Operation." In Proceedings of the International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, Vol. 2, pp. 584-591, CONF-811066, National Technical Information Service, Springfield, Virginia.

- Istvan, J. A. 1982. "Compressed Air Energy Storage (CAES) Aquifer Field Test--Conceptual Design, Construction and Operation." In Proceedings of the 1981 Mechanical, Magnetic and Underground Energy Storage 1981 Annual Contractors' Review, pp. 69-73, CONF-810833, National Technical Information Service, Springfield, Virginia.
- Jacobeen, F. H., Jr. 1972. "Seismic Evidence for High Angle Reverse Faulting in the Coastal Plain of Prince George and Charles County, Maryland." Geological Survey Information Circular IC 13, U. S. Geological Survey.
- Jorda, R. M. 1978. State of the Art in Well Completion Technology as Applied to Geothermal Development. SAND78-7008, National Technical Information Service, Springfield, Virginia.
- Katz, D. L. 1975. "Compressed Air Storage for Electric Power Generation." In Proceedings of the Workshop on Compressed Air Energy Storage Systems, pp. 127-144, ERDA-76-124, CONF 75-1242, National Technical Information Service, Springfield, Virginia.
- Katz, D. L., and E. R. Lady. 1976. Compressed Air Storage, pp. 139-169. Ulrich's Books, Inc., Ann Arbor, Michigan.
- 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, p. 129. The American Gas Association, New York, New York.
- Kukacka, L. E., J. Fontana, T. Sugama, T. J. Rockett, R. S. Kalyoncu, D. K. Curtice, G. L. Kalousek, E. R. Fuller, A. Zeldin, N. Carciello, W. Reams, B. E. Simpson and D. M. Roy. 1979. Cementing of Geothermal Wells Progress Report No. 12 January-March 1979. BNL 51048, Brookhaven National Laboratory, Upton, New York.
- Lang, W. J. 1975. "Compressed Air Storage Considerations for Reef-Type Aquifer Structures in Indiana." In proceedings of the Workshop on Compressed Air Energy Storage Systems, pp. 258-277, ERDA-76-124, CONF 75-1242, National Technical Information Service, Springfield, Virginia.
- Loscutoff, W. V., et al. 1979. Pacific Northwest Laboratory Annual Report for 1978 to the DOE Division of Energy Storage Systems. PNL-2935, Pacific Northwest Laboratory, Richland, Washington.
- Marshall, T. B. 1979. Compressed Air Storage in Paleozoic Sandstones of Southeastern Minnesota. M. S. Thesis, Geology, The University of Wisconsin- Milwaukee, Milwaukee, Wisconsin.
- Molz, F. J., and L. C. Bell. 1977. "Head Gradient Control in Aquifers Used for Fluid Storage." Water Resources Research. 13(4):795-797.

- Moore, J. E. 1960. "Clay Mineralogy Problems in Oil Recovery." The Petroleum Engineer, February, pp. B-40-B-47.
- National Academy of Sciences. 1972. Report on the Feasibility of a More Coherent National Policy for the Governance of Underground Space. Washington, D. C.
- Ostroot, G. W., and S. Shryock, Jr. 1964. "Cementing Geothermal Steam Wells." Paper presented at Society of Petroleum Engineers of AIME 39th Annual Fall Meeting, October 11-14, 1964, Houston, Texas.
- PB-KBB, Inc., and David K. Davies and Associates. 1983. Pre-Test Geological and Geochemical Evaluation of the Caprock, St. Peter Sandstone, and Formation Fluids, Yakley Field, Pike County, Illinois. PNL-4564, Pacific Northwest Laboratory, Richland, Washington.
- Pincus, H. J. 1979. Underground Compressed Air Energy Storage Rock Mechanics and Geology Components, Annual Report 10/1/78 to 9/30/79. University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.
- Pincus, H. J. 1980. Underground Compressed Air Energy Storage, Rock Mechanics and Geology Components, Annual Report 10/1/79 to 9/30/80. University of Wisconsin-Milwaukee, Milwaukee, Wisconsin.
- Pincus, H. J. 1982. "Criteria of Structural Geology and Rock Mechanics for the Storage of Heated Compressed Air in Aquifers." Rock Mechanics, Suppl. 12, pp. 237-246.
- Rudd, N. 1979. "Evaluation of Caprock for Underground Compressed Air Energy Storage." In 1978 Compressed Air Energy Storage Symposium Proceedings, Vol. 1, pp. 243-278, CONF-780599, National Technical Information Service, Springfield, Virginia.
- Rudd, N., and R. D. Allen. 1980. "Field Studies of Porous Rock Reservoirs." In Proceedings of the Mechanical, Magnetic, and Underground Energy Storage 1980 Annual Contractors' Review, pp. 227-233, CONF-801128, National Technical Information Service, Springfield, Virginia.
- Smith, G. C., J. A. Stottlemire, L. E. Wiles, W. V. Loscutoff and H. J. Pincus. 1978. FY-1977 Progress Report--Stability and Design Criteria Studies for Compressed Air Energy Storage Reservoirs. PNL-2443, Pacific Northwest Laboratory, Richland, Washington.
- Smith, G. C., and L. E. Wiles. 1979. "Analysis of Underground Porous Reservoirs for Compressed Air Energy Storage." In 1978 Compressed Air Energy Storage Symposium Proceedings, pp. 327-367, CONF-780599, National Technical Information Service, Springfield, Virginia.

- Smith, G. C., L. E. Wiles and W. V. Loscutoff. 1979. Numerical Analysis of Temperature and Flow Effects in a Dry, One-Dimensional Aquifer Used for Compressed Air Energy Storage. PNL-2546. Pacific Northwest Laboratory, Richland, Washington.
- Stottlemyre, J. A. 1978. Preliminary Stability Criteria for Compressed Air Energy Storage in Porous Media Reservoirs. PNL-2685, Pacific Northwest Laboratory, Richland, Washington.
- Stottlemyre, J. A. 1980. "Investigating Air/Water/Rock Interactions in a CAES Porous Rock Reservoir." In Proceedings of Mechanical, Magnetic and Underground Energy Storage 1980 Annual Contractors' Review, pp. 220-226, CONF-801128, National Technical Information Service, Springfield, Virginia.
- Stottlemyre, J. A., and C. H. Cooley. 1980. "Temperature-Induced Permeability Alterations in Unconsolidated and Consolidated Aquifer Media." Paper presented at 15th Intersociety Energy Conversion Engineering Conference, August, Seattle, Washington.
- Stottlemyre, J. A., C. H. Cooley, and G. J. Banik. 1981. "Temperature Sensitivity of Ottawa Sand and Massillon Sandstone Intrinsic Permeabilities." In Proceedings of 22nd Annual Rock Mechanics Symposium, pp. 115-119, Massachusetts Institute of Technology, Cambridge, Massachusetts.
- Stottlemyre, 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.
- Stottlemyre, J. A., R. L. Erikson and R. P. Smith. 1979. "Permeability and Friability Alterations in Quartzose Sandstones Exposed to Elevated Temperature Humidified Air." In Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 130-137, CONF-790854, National Technical Information Service, Springfield, Virginia.
- Stottlemyre, J. A., and W. V. Loscutoff. 1979. "Environmental Concerns for Compressed Air Energy Storage in Porous Media Systems." In 1978 Compressed Air Energy Storage Symposium Proceedings, Vol. 2, pp. 667-686, CONF-780599, National Technical Information Service, Springfield, Virginia.
- Stottlemyre, J. A., and R. P. Smith. 1978. "Potential Air/Water/Rock Interactions in a Porous Media CAES Reservoir." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 355-362, CONF-781046, National Technical Information Service, Springfield, Virginia.

- Stottlemire, J. A., and G. C. Smith. 1979. "Stability Criteria for Compressed Air Energy Storage in a Porous Rock Reservoir." In Proceedings of the Compressed Air Energy Storage Symposium, Vol. 1, pp. 213-242, CONF-780599, National Technical Information Service, Springfield, Virginia.
- Stottlemire, J. A., R. P. Smith and R. L. Erikson. 1979. Potential Petrophysical and Chemical Property Alterations in a Compressed Air Energy Storage Porous Rock Reservoir. PNL-2974, Pacific Northwest Laboratory, Richland, Washington.
- Tek, M. R., and J. O. Wilkes. 1966. New Concepts in Underground Storage of Natural Gas, pp. 12-13, The American Gas Association, New York, New York.
- Trapp, J. S., and T. E. Jensen. 1981. Geologic and Hydrologic Input to Feasibility Study for Battelle Pacific Northwest Laboratories. D&M Job No. 09781-002-07, Dames & Moore, Park Ridge, Illinois.
- Walke, W. C. 1980. Compressed Air Energy Storage Preliminary Design and Site Development Program in an Aquifer. Characterize and Explore Potential Sites and Prepare Research and Development Plan. Final Draft Task 2 - Milestone Report, Volume 1 of 3, Sargent & Lundy, Chicago, Illinois.
- Walker, W. A. 1962. "Cementing Compositions for Thermal Recovery Wells." J. Petroleum Technology, February, pp. 139-142.
- Weinstein, K. D., et al. 1978. Geologic Issues Related to Compressed Air Energy Storage Systems. Booz, Allen, and Hamilton, Inc., Bethesda, Maryland.
- 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. "Two-Dimensional Fluid and Thermal Analysis of Dry Porous Rock Reservoirs for CAES." In Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 140-147, CONF-790854, National Technical Information Service, Springfield, Virginia.
- Wiles, L. E. 1979c. The Effects of Water on Compressed Air Energy Storage in Porous Rock Reservoirs. PNL-2869, Pacific Northwest Laboratory, Richland, Washington.

- Wiles, L. E., R. L. Erikson, R. D. Allen and T. J. Doherty. 1982. "Numerical and Experiniental Analyses of the Porous Medium Reservoir at Pittsfield, Illinois." In Proceedings of the 1981 Mechanical, Magnetic and Underground Energy Storage Annual Contractors' Review, pp. 59-68, CONF-810833, National Technical Information Service, Springfield, Virginia.
- Wiles, L. E., and C. A. Oster. 1978. "Fluid Flow and Thermal Analysis for CAES in Porous Rock Reservoirs." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 337-347, CONF-781046, National Technical Information Service, Springfield, Virginia.
- Wiles, L. E., and R. A. McCann. 1981a. "Prediction of the Thermohydraulic Performance of Porous Media Reservoirs for Compressed Air Energy Storage." In Proceedings of the International Conference on seasonal Thermal Energy Storage and Conipressed Air Energy Storage, Vol. 2, pp. 595-603, CONF-811066, National Technical Information Service, Springfield, Virginia.
- Wiles, L. E., and R. A. McCann. 1981b. Water Coning in Porous Media Reservoirs for Compressed Air Energy Storage. PNL-3470, Pacific Northwest Laboratory, Richland, Washington.
- Wiles, L. E., and R. A. McCann. 1982. "Prediction of the Thermohydraulic Performance of Porous Media Reservoirs for CAES in Support of the Field Test at Pittsfield, Illinois." In Underground Energy Storage Program, 1981 Annual Report, Volume II - Technical Summaries, pp. 85-99. PNL-4281, Pacific Northwest Laboratory, Richland, Washington.

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