Annual Report for 1980

Compressed Air Energy Storage Technology Program

June 1981

**Prepared for
Division of Physical and Chemical Energy
Storage
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

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

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

The views, opinions and conclusions contained in this report are those of the contractor and do not necessarily represent those of the United States Government or the United States Department of Energy.

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

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

Price: Printed Copy \$_____*; Microfiche \$3.00

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

3 3679 00059 8526

COMPRESSED AIR ENERGY STORAGE
TECHNOLOGY PROGRAM

ANNUAL REPORT FOR 1980

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

June 1981

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

Pacific Northwest Laboratory
Richland, Washington 99352

PREFACE

This is the Compressed Air Energy Storage Technology Program Annual Report for 1980 from the Pacific Northwest Laboratory (PNL) to the DOE Divisions of Physical and Chemical Energy Storage Systems and Electric Energy Systems. The report describes all of the major research funded under this program during the period March 1980 to March 1981.

The report is divided into two segments: Reservoir Stability Studies and Second-Generation Concepts Studies. The first represents research performed to establish stability criteria for CAES reservoirs while the second reports progress on research performed on second-generation CAES concepts. The report consists of project reports authored by research engineers and scientists from PNL and numerous subcontractors including universities, architect-engineering, and other private firms. For additional information on any of the projects in this report, contact the authors of the articles.

Activities of the researchers whose work is described in this annual report are broader in scope than the articles indicate. In addition the contributing staff at PNL has also responded to numerous requests from DOE for planning and special assistance during the year.

Credit for this annual report goes to the many engineers and scientists who performed the research and wrote the individual project reports, to the project managers who directed the research, and to Sue Arey who assembled, typed and assisted in editing the annual report.

The work described in this report represents one segment of a continuing effort to encourage the commercialization of advanced technology for utility storage. The results reported here rely on earlier studies and form the basis for continued efforts to develop CAES technology.

L. D. Kannberg
Project Manager
Compressed Air Energy Storage

SUMMARY

The compressed air energy storage (CAES) concept includes near- and mid-term technologies for central station electric utility applications. This concept greatly improves the effectiveness of a gas turbine using petroleum fuels and could reduce petroleum fuel consumption of electric utility peaking plants by more than 100 million barrels of oil per year (in 2000 AD) if pursued aggressively. Studies show that the CAES concept is technically feasible and economically viable.

To facilitate technological development and commercialization of CAES, this program plan has been prepared at the request of the U.S. Department of Energy's (DOE) Division of Physical and Chemical Energy Storage Systems (PCESS).

The CAES Technology Program has evolved into two major elements of research and development: CAES Reservoir Stability Studies and Second-Generation CAES Concepts Studies. Because long-term reservoir stability is crucial to the commercialization of CAES systems, the CAES Reservoir Stability Studies receive major emphasis in the early phases of the program. In recognition of the fact that even the modest petroleum fuel requirements of a conventional CAES system may be an obstacle to large-scale acceptance, Second-Generation CAES Concepts Studies will dominate the research and development activity during the latter phases of the program. The Second-Generation CAES Concepts Studies also include a number of technologies suitable for wider application than the utility market.

The objectives of the program are:

- CAES Reservoir Stability Studies - Develop stability criteria for large underground reservoirs in salt domes, hard rock, and porous rock used for air storage in utility applications.
- Second-Generation CAES Concepts Studies - Develop second-generation CAES technologies that require little or no petroleum fuel for operation.

The principal elements of the CAES Technology Program and the general schedule for meeting the above goals is shown in the Technology Development Schedule given in Figure A.

The strategy of accomplishing the goals and objectives of the CAES Technology Program are discussed in the Introduction. A milestone schedule for fulfilling the goals of the program is given in Figure B. Progress in the reporting period is summarized below.

A. Reservoir Stability Studies

a. Porous Media Reservoirs

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

Numerical modeling in the FY-80 reporting period focused on the development and parametric application of a two-dimensional two-phase flow model to evaluate bubble development processes, prediction for water coning, and completion interval length. Model development was completed at the end of the fiscal year; some model application work has continued in support of the field test activity. Results indicate water coning, which depends mostly on reservoir pressure gradients, is not a serious operational problem for CAES in aquifers, given typical cycle times and rates presently envisioned. The longer-term bubble development models compare well with natural gas storage methods and will be used to predict field study responses.

Model application to the field test is presently being coordinated with the field study contractors. The predictive modeling will include thermal fluid modeling, desaturation process modeling, and the above described two-phase models.

FIGURE A. Compressed Air Energy Storage Technology Program Technology Development Schedule

FIGURE B. Compressed Air Energy Storage Technology Program Milestones

Porous media laboratory studies eliminated several unknowns as major CAES concerns for aquifer storage. It was shown that porous rock exposed to CAES conditions remained a viable storage medium for long periods of time even at over 150°C. Although some increase in friability was observed for high-temperature humid-air atmospheres, lack of confinement may limit the applicability of test results for CAES reservoirs. Exposure of numerous types of porous rock to dry air ventilation at modest temperatures and pressures continued to show little impact on rock properties. A flow facility for porous rock desaturation and cyclic ventilation with moist air was designed and constructed and is

presently completing startup. Interim testing at external laboratories has been completed, and all porous media experimental activities are now concentrated at PNL.

Structural testing of porous rock at elevated temperatures at another national laboratory pointed to increases in strength for caprock materials as temperature was increased when some level of dessication was permitted, although data scatter was severe.

The porous media field study plan approved in early FY-1980 was implemented during this reporting period. Exploration activities were completed, including leasing activities, preliminary and confirmatory drilling, seismic investigations, and final site selection. Environmental activities are under way with submittal of application for construction permit to Illinois EPA and initial preparation on injection permit under way. An operations contractor was selected via a competitive procurement process which was slowed somewhat by the strong and excellent response from industry. PB-KBB of Houston, Texas, is at present completing contract initiation and breaking into the field study project team with design interaction of well systems and surface facilities. Construction is planned for the remainder of FY-1981.

b. Hard Rock Caverns

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

Re/Spec Inc. is the lead contractor in hard rock cavern studies. Their tasks during this reporting period were to complete all generic numerical and experimental studies, along with associated methodology

development, and to carry out a confirmatory evaluation of the Acres American design for hard rock CAES caverns performed for Potomac Electric Power Company under the demonstration programs. Revision and updating of the stability criteria are continuing as work progresses.

In the numerical studies, models were developed with capability to structurally characterize a rock mass and to simulate excavation processes and cyclic thermoelastic and pressure loading typical of CAES. They could also account for water compensation. Using these models in a series of parametric numerical simulations of generic materials and conditions it was found that multiple caverns could be located in competent rock at 750 m without cavern collapse. Substantial strength reductions due to local rock failure or thermal shock do not alter this conclusion. Air leakage was found to be affected by stress ratio but predictable and insignificant for most conditions. A review of European experience supported these conclusions. An evaluation of the PEPCO design indicated that the shape, support system, and stability of the cavern will be sufficient for CAES operations, and the design results in favorable fatigue response.

Laboratory studies indicated that strength reductions can be expected in the tensile and compressive strength of rock masses subjected to a CAES cavern environment. The percentage loss of failure strength of the rock decreases with increasing mean stress, and most of the damage will be caused in the first few cycles, indicating that a rock mass would shake down quickly to stable behavior. Although the compressive and tensile strengths are adversely influenced by a CAES cavern environment, the reduced failure strength of initially intact hard rocks is sufficiently high to indicate that a CAES plant could be operated satisfactorily. It has also been demonstrated that foliated and/or jointed rock masses require special attention and assessment of strength requirements and strength values become quite site specific. The PEPCO Sykesville gneiss, a rock having highly anisotropic strength, was found to be stable under CAES conditions with careful design.

No field studies are planned in hard rock at this time because of the site-specific nature of problems and the possibility of satisfying general in situ testing needs by examining the field experience of other types of geotechnical projects.

c. Salt Cavern Reservoirs

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

Numerical modeling of salt during the reporting period was a continuation and extension of the previous work on the stability criteria for CAES caverns in salt. Elevated temperature and boundary deterioration due to air penetration are critical parameters which were analyzed. The major conclusions of previous work were that 1) caverns which are well designed and constructed are very stable, and 2) cyclic loading strains can be approximated conservatively by utilizing the strain resulting from the most severe deviatoric stress encountered during cycling.

The present numerical work included model modification and benchmark calibration for elevated temperature effects. Then a series of thermal and thermomechanical analyses to evaluate cavern response, and response predictions for the Louisiana State University in-mine slant borehole tests were performed. Elevated temperatures to 200°F were found to alter response but not significantly affect long-term stability. Air penetration was assessed as a local stability problem that would not affect general long-term stability. All numerical work related to salt caverns was completed, and presently final reports are being prepared for publication.

Laboratory studies of salt response to CAES conditions presently include laboratory-scale and in-mine, bench-scale testing. Triaxial cyclic thermal and mechanical testing is being performed in six triaxial

cells for salt specimens from several Louisiana salt mines, the Huntorf site in West Germany, and Kansas and Nevada bedded salt. Cyclic mechanical loading results in strain cycling that is very small in response to cyclic stress having a larger range, but much greater strain is exhibited during elevated temperature portions of thermal cycling. Acoustic emission patterns appear to trace cyclic strain very closely, showing potential as a technique for in-situ monitoring of salt cavern stability. Tests in boreholes in the floor of the Jefferson Island salt mine were initiated during FY-1980, but this facility was lost during a mine flooding accident early in FY-1981. Slant boreholes in pillars of the Cote Blanche mine are now being prepared for testing to replace the lost facility with minimal impact on early FY-1982 completion of the program.

Field study plans for salt were prepared and submitted for approval, but a decision was made to defer the salt field studies indefinitely. It is felt that operational experience at Huntorf, in conjunction with the present experimental and numerical efforts, provides a sufficient basis to predict salt response and therefore to design stable, operational, solution-mined salt caverns for air storage.

B. Second-Generation Concepts Studies

The primary thrust of the Second-Generation Concepts Studies is to identify, evaluate, and promote technological development of concepts that require very little or no petroleum fuels for firing of the turbines. Two approaches have been pursued. One is to reduce or eliminate the fuel consumption by integrating thermal energy storage (TES) with CAES. The other is to look at alternate fuels. The most logical candidate for alternate fuel is coal, used with CAES through fluidized bed combustion (FBC) or through coal gasification (CG). Activity during the reporting period concentrated on examining these concepts (Figure B), technical and economic screening of concepts, and recommending to DOE which, if any, of these concepts should be promoted.

a. Thermal Energy Storage Integrated with CAES

Previous studies at PNL, the Massachusetts Institute of Technology, and the Central Electricity Generating Board (England) have shown that the cost of the TES component for an adiabatic or hybrid CAES/TES plant would be high. However, the resulting CAES/TES system could be cost competitive under certain conditions. As a result, this concept was subjected to preliminary engineering design and cost analysis studies completed in the reporting period by Acres American, Incorporated (Acres) and PNL. The Acres study concentrated on the adiabatic CAES concept. A similar, though more rigidly defined, study of hybrid CAES was performed by United Engineers and Constructors (UE&C) for the Electric Power Research Institute (EPRI). These studies were completed in February of 1981.

The Acres study was broader than the United Engineers and Constructors' study in that it was not limited to a specific cycle. Parametric analyses and optimization within the performance limits of available or easily modified turbomachinery were required. Cycles having one, two, and three TES stages were considered. The two-stage arrangement was selected on the basis of minimum cost. Direct-contact sensible heat storage was selected over indirect-contact sensible heat storage, latent heat storage, and thermochemical storage because of the early stage of development of latent and thermochemical systems and the high capital costs of indirect-contact heat storage.

The two TES stages were located at different depths below ground, each in a low-temperature, pressurized cavern. Since the TES silos (eleven in each cavern) did not have to support large pressure differentials, they could be made at a lower capital expense. This design poses certain problems with operation and maintenance on the vessels and fill replacement. Another concern is pipe expansion in the 1300 ft of high-pressure, hot gas piping between the surface and the lower TES stage. The solution was to fix the TES piping at the TES level and allow the piping to

expand upward through sleeves in the shaft pressure-cap. The sleeves were to be dry lubricated. The TES system cost ranged from \$51 million to \$196 million based on the type of fill material. The iron oxide selected had a cost of \$54 million or about \$2694/MBtu (\$9/kWh_t).

Particle carry-over was determined to be a problem at all mass flow rates. Gas cleanup was considered unavoidable and was included in the design.

The charging ratio for this concept is 1.48 for an 800-MW plant. This has the effect of reducing the round trip thermodynamic efficiency to 22%, consistent with a heat rate of 15,540 (Btu/kWh). The principal advantage of the concept is that it uses no petroleum fuel.

Direct capital cost for the 800-MW plant is \$561/kW (1979 dollars), compared to a comparable conventional CAES plant cost of \$411/kW. However, at a 20% capacity factor the adiabatic CAES has a 15% levelized cost advantage over conventional CAES, given that both plants have a 30-year life.

Acres identified several areas requiring further R&D. These areas included TES performance, design, hot gas cleanup, hot gas piping, particulate generation, and bed volume reduction rates, and consideration of machine configurations having fewer machines, possibly on a single drive train. For the future, higher-temperature compressors, especially axial, would improve performance markedly.

b. Fluidized Bed Combustion (FBC) Integrated with CAES

The integration of FBC with CAES offers a promising solution to replacing petroleum fuel with coal. Several other techniques using coal to fire turbines were examined but most were secondary in potential to FBC. FBC technology is progressing rapidly in conjunction with advanced steam, gas turbine, and combined-cycle plants. However, the integration of FBC with CAES presents a number of issues that would not arise in

non-CAES studies. Specifically, a CAES/FBC system requires an air heater, a system that has to withstand daily cycling, very high pressures in the tubes (up to 70 bars), and the most efficient CAES design, a high pressure (up to 20 bars) combustor. For these reasons a detailed economic and technical feasibility study of CAES/FBC was undertaken. A contract was awarded to the United Technologies Research Center beginning in August 1978 and ending in December 1980.

The PNL-funded study by United Technologies Research Center of coal-fired FBC/CAES systems concluded that such systems should be technically feasible and economically attractive (particularly at higher capacity factors) for peak power generation. An open bed PFBC/CAES system was recommended as the best candidate for early commercialization because of relatively low technological risk, moderate cost, and reasonable round trip heat rate. However, the authors identified numerous technical areas requiring R&D. Most relate to PFBC and are common to other power generation applications utilizing PFBC. These areas (which are being extensively studied in the U.S. and abroad) include, turbine blade erosion and corrosion, effective hot gas cleanup, deposition on heat transfer surfaces, coal and sorbent feeders, fuel distribution, distribution of combustion and fluidizing air, combustor containment, and depressurization systems for spent sorbent and fuel ash. For CAES applications, special concerns include control systems for load following, rapid transients, and system reliability. Resolution of these issues is not likely to occur in the next few years although steady inroads are being made.

c. Coal Gasification (CG) Integrated with CAES

The integration of CAES with coal gasification could result in a synergistic combination of two technologies: one that produces a very expensive synthetic fuel and one that uses fuel very efficiently (4,000 Btu/kWhr of electricity for a conventional CAES plant). However, in addition to being expensive, a CG plant is also inflexible in operation. New cycles must be examined in order to take advantage of the operating characteristics of a CAES/CG plant.

The feasibilities of a number of CAES/CG system concepts have been investigated by several power equipment manufacturers and architect-engineering firms (notably UTRC for EPRI). Independent analysis at PNL and ENTEC Research Associates (under PNL contract) supported their conclusion that it is unlikely that an integrated CAES/CG plant can be operated in a daily cycle operation such that the CG plant will be shut down and maintain a "hot" standby condition. This is made based on the projected longer response time and potential operating problems resulting from frequent shut down and start up. These operational problems may include the thermal stress on materials, formation of undesirable liquid products, and excess corrosion and embrittlements in a coal gasifier environment. However, potential exists that a continuously fired CAES/CG would provide a technically feasible, cost effective option for peak power generation.

d. Development and Component Demonstration

PNL was charged with providing recommendations and supporting rationale for selection of the most promising second-generation concept for aggressive R&D efforts. The recommendation required detailed review of the technical feasibility of the various second-generation concepts as well as the relative economics. The studies described in earlier sections provided the technical analyses and capital costs. But these studies incorporated varying operating and economic assumptions depending on the ground rules for the studies and the inherent requirements of each concept. These were normalized by PNL researchers and combined with technical findings to provide relationale for component R&D recommendations.

The technical and economic findings supported the recommendation of adiabatic CAES as the concept most suitable to early commercialization. Other concepts offer significant promise for the mid to late 1990s, particularly if related fossil technologies mature. A program for evaluation of optimal TES bed materials was initiated as a result

of these findings, and reports on the testing planned as part of this program are included in this annual report.

C. Summary of Accomplishments

Main accomplishments (corresponding to milestones) during the reporting period include the following:

- Completed generic numerical studies and model development work in hard rock, salt, and porous media studies (September 1980).
- Completed generic laboratory studies in hard rock and porous media (September 1980).
- Initiated and completed the exploration phase of the aquifer field test (January 1980).
- Initiated operations contracting and awarded the major construction and operations contract for the aquifer field test.
- Completed design and construction of the porous media flow facility and initiated operational acceptance testing.
- Completed an engineering and economic study of adiabatic CAES in hard rock (Conceptual Design and Engineering Studies of Adiabatic CAES with Thermal Energy Storage, M. J. Hobson et al., Acres American, Inc., March 1981).
- Completed an engineering and economic study of FBC integrated into CAES (Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System, Volumes 1 - 3, A. J. Giramonti, et al, PNL-3686 (UTRC R80-954490-20), United Technologies Research Center, East Hartford, CT, June 1980); (Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System - System Load Following Capability, A. J. Giramonti et al., UTRC R80-954490-29, United Technologies Research Center, East Hartford, CT, January 1981).

- Submitted recommendations to DOE-HQ on development and component demonstration of second-generation CAES concepts (An Assessment of Second-Generation Compressed Air Energy Storage Concepts, Pacific Northwest Laboratory, Richland, WA, March 1981).
- Prepared and released an RFP for ultra-high-head pump turbine development in coordination with EPRI.

CONTENTS

PREFACE	iii
SUMMARY	v
A. RESERVOIR STABILITY STUDIES.	vi
B. SECOND-GENERATION CONCEPTS STUDIES	xii
C. SUMMARY OF ACCOMPLISHMENTS	xvii
FIGURES	xxiii
TABLES.	xxvii
1.0 COMPRESSED AIR ENERGY STORAGE TECHNOLOGY PROGRAM	1
1.1 BACKGROUND.	1
1.2 PURPOSE	1
1.3 RATIONALE	2
1.4 GOALS	3
1.5 OBJECTIVES.	3
1.6 PROGRAM APPROACH AND STRUCTURE.	3
1.7 MAJOR PROGRAM MILESTONES.	5
1.8 RESOURCE REQUIREMENTS	8
2.0 CAES RESERVOIR STABILITY STUDIES	11
2.1 INTRODUCTION.	11
2.2 GOALS	12
2.3 OBJECTIVES.	13
2.4 STRATEGY.	13
2.5 RESERVOIR STABILITY STUDIES PROJECT DESCRIPTIONS.	14
2.5.1 Porous Media Studies	14
2.5.2 Salt Studies	23
2.5.3 Hard Rock Studies.	26
3.0 SECOND-GENERATION CAES CONCEPTS STUDIES.	31
3.1 INTRODUCTION.	31
3.2 GOALS	31
3.3 OBJECTIVES.	32
3.4 STRATEGY.	32
3.5 SECOND-GENERATION CONCEPTS STUDIES PROJECT DESCRIPTIONS .	33
3.5.1 Conceptual Design/Economics Studies.	33

3.5.2	Component Evaluation and Development.	35
3.5.3	Second-Generation Concepts Assessment and Support	36
4.0	PROGRESS SUMMARIES.	39
4.1	RESERVOIR STABILITY STUDIES.	41
4.1.1a	Bubble Development and Water Coning in Porous Media Reservoirs for CAES	43
4.1.1b	Porous Media Experimental Tasks.	55
4.1.1c	Assessment of Thermomechanical Properties of Caprock and Reservoir for Compressed Air Energy Storage in Porous Media	65
4.1.1d	Effects of Air Ventilation on Porous Rock. . . .	73
4.1.1e	Field Studies of an Aquifer Reservoir.	81
4.1.2a	Numerical Modeling of Compensated Compressed Air Energy Storage Systems	91
4.1.2b	Laboratory Testing of Hard Rock Specimens Subjected to Loadings and Environmental Conditions Appropriate to a Compressed Air Energy Storage Cavern.	101
4.1.2c	Analytical Model for CAES Reservoirs	113
4.1.3a	Laboratory Tests of Salt Specimens Subjected to Loadings and Environmental Conditions Appropriate to a Compressed Air Energy Storage Reservoir.	115
4.1.3b	Numerical Modeling of Behavior of Caverns in Salt for Compressed Air Energy Storage. . . .	121
4.1.4	Compressed Air Energy Storage Environmental Control Concerns	127
4.2	SECOND-GENERATION CONCEPTS STUDIES	129
4.2.1a	Engineering Study of Adiabatic CAES.	131
4.2.1b	Coal-Fired Fluid Bed Combustion Augmented Compressed Air Energy Storage Systems.	141

4.2.2a	Line by Line Assessment of Principal Subsystems, Equipment Items and Components of Compressed Air Energy Storage Systems. . . .	149
4.2.2b	Adiabatic CAES Development, Thermal/Chemical Screening Tests	157
4.2.3a	Conceptual Design/Economic Assessments.	161
4.2.3b	Economic Assessment	165

FIGURES

A. Compressed Air Energy Storage Technology Program Technology Development Schedule.	vii
B. Compressed Air Energy Storage Technology Program Milestones .	viii
1. Department of Energy Programs to Pursue Development of CAES .	2
2. Compressed Air Energy Storage Technology Program, Subprogram Approaches	4
3. Compressed Air Energy Storage Technology Program Functional Organization.	6
4. Compressed Air Energy Storage Technology Program Technology Development Schedule.	7
5. Compressed Air Energy Storage Technology Program Milestones .	8
6. Compressed Air Energy Storage Technology Program Funding Requirements.	9
7. Water Coning During Reservoir Extraction Cycle.	44
8. Definition of Well Grid	50
9. Saturation Profiles After 35 Hours of Air Injection	52
10. Saturation Profiles from R-Z Model for Various Radial Nodes (m)	53
11. Percent Change in Gas Permeability with Temperature	59
12. Corrosion Data for Carbon Steel A120 Well Casing Material . .	60
13. Permeability Ratio for Ottawa Sand at 25°C and 150°C.	62
14. Permeability Ratio of Massillon Sandstone at 25°C and 150°C .	63
15. Permeability Ratio Versus Temperature	63
16. Mohr Failure Envelopes of Galesville Sandstone for Three Temperatures. The shaded semicircle represents states of stress for an operating porous medium CAES reservoir	67
17. Coefficient of Sliding Friction on Fracture Planes vs. Effective Confining Pressure for Galesville Sandstone	68

18. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated. Fracture plane is perpendicular to bedding.	70
19. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated. Fracture plane is parallel to bedding	71
20. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Dry. Fracture plane is perpendicular to bedding.	71
21. Structure Contours and Seismic Traverses near Pittsfield, Illinois.	86
22. Structure Identified Near Pittsfield, Illinois.	89
23. Temperature Isotherms (°C) Around a CAES Cavern for Different Operational Cycles.	93
24. Principal Stress Trajectories Around a CAES Cavern for Different Operational Cycles.	94
25. Support Requirements for the PEPCO Caverns as a Function of Rock Quality	98
26. Failure Zones Around the PEPCO Caverns After Initial Excavation.	99
27. Mohr Failure Envelopes for Milbank Granite.	105
28. Mohr Failure Envelopes for Oneota Dolomite.	106
29. Cyclic Stress-Strain Curves for Milbank Granite	107
30. Modulus Decay Curve for Milbank Granite	107
31. Tension-Compression S-N Curve for Milbank Granite	108
32. Variation of Compressive Strength of Sykesville Gneiss with Foliation Angle.	109
33. Status Triaxial Compression of Bryan Mound Dome Salt.	117
34. Typical Data for Cyclic Pressurization of Boreholes in Salt Mine	118
35. Simulation Run Summary for Axisymmetric Case -- Maximum Boundary Displacement Versus Time. B.C.=Base Condition; C.C.=Control Case	124

36. Air System Flow Diagram.	136
37. PFBC/CAES Bed Temperature Response	145
38. Fuel Rate Requirement.	146
39. Power Response	147
40. Recuperator Temperature Response	148
41. Simulated TES Material Environment Reaction Column	158
42. Comparison of the CAES Technologies under Base-Case Conditions	169
43. Comparison of Conventional and Adiabatic CAES Against Alternative Peaking/Intermediate Load Technologies	170
44. Comparative Economic Performance of CAES and UPHS under Base-Case Conditions. All storage units are sized for 10 hours storage. Plant lifetime is assumed to be 50 years. The CAES turbomachinery and TES fill (adiabatic CAES) are assumed to be replaced at 25 years	171
45. Comparison of CAES Technologies under a High Fuel Oil Price Escalation Assumption. (10% vs. 7% for Coal and Compression Energy).	172
46. Comparison of the Economic Performance of CAES Technologies under Municipal Financing (Cost of Capital = 8%; Fixed Charge Rate = 12%)	173

TABLES

1. Outline of Reservoir Stability Studies.	15
2. Outline of Second-Generation Concept Studies.	34
3. Reference Conditions.	46
4. Air Injection and Water Displacement After 35 Hours of Simulated Bubble Growth Using Different Model Geometries. . .	51
5. Corrosion Rates (mm/yr)	60
6. Comparison of Oil-Fired CAES, Adiabatic CAES, and Combustion Turbines, 1990 Levelized Busbar Cost (mills/kWh) .	137
7. Key PFBC/CAES Power Plant Operating Characteristics	143

1.0 COMPRESSED AIR ENERGY STORAGE TECHNOLOGY PROGRAM

1.1 BACKGROUND

Compressed air energy storage (CAES) is a technique that transfers energy from off-peak to peak demand time for electric utility systems. It incorporates modified state-of-the-art gas turbines and underground reservoirs---aquifers, salt cavities or mined hard rock caverns. The compressor and turbine sections of the gas turbine are alternately coupled to a motor/generator for operation during different time periods. During nighttime and weekend off-peak periods, base load plants not using petroleum fuels provide energy to compress air which is stored in the underground reservoirs. During the subsequent daytime peak-load periods the compressed air is withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. Because the turbine is not required to drive a compressor, this concept reduces peaking plant consumption of petroleum fuel by more than 60 percent. Some second-generation CAES concepts do not require any petroleum fuels at all.

1.2 PURPOSE

Studies have shown that the CAES concept is technically feasible and, for utilities with the proper power generation mix, economically viable. Compressed air energy storage systems offer several advantages over conventional systems used by utilities for meeting peak load requirements. Energy storage offers a degree of flexibility and control in system operation (e.g., frequency stabilization). It can be considered as a spinning reserve. It can be started rapidly, and is thus available as supplemental generation in times of emergency. EPRI has estimated that an aggressive program to implement CAES could result in savings of up to 100 million barrels of oil annually by the year 2000. The net annual oil saving would be greater in the future due to growth in the demand for power.

Compressed air energy storage plants are not limited to the same degree of siting difficulties faced by conventional pumped hydro plants. Finally, a well-designed CAES plant should have a smaller adverse impact on the environment, in terms of emissions, than a conventional gas turbine peaking plant.

1.3 RATIONALE

In view of the concept's potential benefits, the Department of Energy has undertaken a comprehensive research and development program to accelerate commercialization of this technology. Department of Energy programs to pursue commercialization of CAES are depicted in Figure 1.

For conventional CAES systems, a key question is related to long-term cavern stability. To provide the utilities with a high degree of confidence in the CAES concept, it is necessary to pursue a comprehensive technology research and development program on guidelines for design of CAES reservoirs. A key question to CAES technology commercialization is

FIGURE 1. Department of Energy Programs to Pursue Development of CAES

the dependence of CAES plants on petroleum fuels. The technology dependence on petroleum fuels could become a major barrier to large-scale implementation of CAES technology. Thus, it is necessary to identify and examine second-generation CAES concepts.

1.4 GOALS

The CAES Technology Program is charged with promoting development of CAES technology for electric utility applications. The primary motivation is the annual conservation of more than 100 million barrels of oil. Two major program goals have therefore been established:

- Determine long-term reservoir stability criteria for CAES operating conditions
- Identify, determine feasibility of, and develop second-generation CAES concepts that minimize the need for, or do not require, petroleum fuels for firing of the CAES plant turbines.

1.5 OBJECTIVES

In response to the goals and needs of the CAES Technology Program, two major research and development elements were formulated. These are the Reservoir Stability Studies and Second-Generation Concepts Studies. The primary objectives of the two major program elements are as follows.

- Reservoir Stability Studies
Develop stability criteria for large underground reservoirs used for compressed air storage.
- Second-Generation Concepts Studies
Develop advanced CAES technologies that require little or no petroleum fuels for operation.

1.6 PROGRAM APPROACH AND STRUCTURE

The CAES Technology Program is broken into two main elements, recognizing the widely varying missions required by the program

objectives. Each of these subprograms has adopted a different approach to reach its respective objectives. The approaches employed are shown schematically in Figure 2.

In the case of reservoir stability criteria, the analyses were initiated by state-of-the-art surveys, proceeding to increasingly focused numerical modeling and laboratory studies, concluding with field tests if necessary. Throughout the process successively more complete stability criteria are generated, culminating with the completion of field testing.

CAES TECHNOLOGY PROGRAM

FIGURE 2. Compressed Air Energy Storage Technology Program, Subprogram Approaches

This is the approach that has been adopted for determination of the stabilities of salt cavities, hard rock caverns, and porous rock aquifer reservoirs for CAES.

The approach used in second-generation concepts studies is to examine the engineering feasibility and economics of each candidate concept in two stages of increasing detail. Between each stage of analysis, each concept is examined and judged on its technical viability and economic competitiveness with other CAES concepts and energy storage technologies. Only concepts showing high probability of successful development and eventual commercialization are retained for detailed equipment or component evaluation and eventual demonstration.

Functionally, PNL's charge as the lead laboratory is to provide program planning and management. In addition, PNL scientists and engineers are involved in a number of technical studies in support of the program. The functional program organization is shown in Figure 3.

The emphasis in the early phase of the program is on the Reservoir Stability Studies. In FY-1983, the emphasis will shift to the Second-Generation Concepts Studies. This is shown in the schedule diagram in Figure 4 (as shown earlier in the Summary). This figure also indicates the long-range planning in the program and the interrelationships between the various projects within the program.

1.7 MAJOR PROGRAM MILESTONES

To achieve the established objectives and to measure progress, a number of major milestones have been established for this program. These milestones are shown in Figure 5. The most critical are the completion of reservoir stability studies in FY-1983 and initiation of second-generation CAES concept testing in FY-1981.

FIGURE 3. Compressed Air Energy Storage Technology Program Functional Organization

FIGURE 4. Compressed Air Energy Storage Technology Program Technology Development Schedule

FIGURE 5. Compressed Air Energy Storage Technology Program Milestones

1.8 RESOURCE REQUIREMENTS

To achieve the program objectives, expenditures of up to \$18.1 million may be required for the period FY-1979 to FY-1984. Figure 6 shows the annual funding requirements by the two major program elements. The Reservoir Stability Studies are winding down and are to be virtually completed in FY-1983. The Second-Generation Concepts Studies are scheduled to be accelerated in FY-1982. It should be noted, however, that there is a large degree of uncertainty in this part of the program.

FIGURE 6. Compressed Air Energy Storage Technology Program Funding Requirements

2.0 CAES RESERVOIR STABILITY STUDIES

2.1 INTRODUCTION

The unique aspect of the CAES concept is the use of subsurface geology as an economical large-scale pressurized air storage element. For a nominal design, air at pressures between 4 MPa (40 bar) and 8 MPa (80 bar) is to be stored in the underground reservoirs and cycled on a daily basis. The reservoirs may be operated in either an uncompensated (constant volume) or compensated (constant pressure) mode where compensation is accomplished with a water column. Three broad classes of rock have been identified as candidate hosts for CAES reservoirs: hard rock, porous rock, and salt.

The type of host rock is an important factor in the choice of modes for CAES operation. Excavation costs in hard rock nearly exclude operation of an uncompensated storage system. Operation of a compensated system requires relatively low storage temperatures (less than $\sim 100^{\circ}\text{C}$) to avoid boiling and large vapor plumes when warm water reaches the surface. Storage in salt (primarily domal) can be either compensated or uncompensated, although uncompensated is more acceptable because of brine storage problems at the surface and concerns about control of solution, precipitation and erosion of the salt. The only operational CAES peaking power plant, at Huntorf in West Germany, uses an uncompensated salt cavity. Compressed air energy storage in salt is also generally restricted to lower temperature, less than 80°C at this point, because creep closure of the cavern is greatly accelerated at higher temperatures. Compressed air energy storage in porous media operates in a damped, compensated mode. It is uncompensated for short cycle times, but the longer term approach to equilibrium with a specific discovery pressure in the storage system is a compensated response. No major structural problems have been identified with storage of air in porous media at less than 150°C . Storage of the heat of compression within the rock formation is being investigated for temperatures to 300°C through numerical, experimental and field evaluations.

Temperature and geochemical effects could restrict air storage temperatures to levels that would not allow sufficient energy recovery to be feasible. Therefore, the upper temperature limit for stable reservoir operation remains to be resolved.

Storage of natural gas and oil in underground reservoirs has been practiced for nearly 50 years. In most instances, this storage has involved seasonal cycling of gas and oil with low mass flow rates and at low temperatures relative to potential CAES reservoir operation. Compressed air energy storage reservoirs will be subjected to daily cycling of air with attendant temperature, pressure, and humidity fluctuations. The CAES reservoirs must remain stable and operational under these conditions over periods of 30 to 50 years. Thus, while previous gas storage experience is valuable, little data exist for specific CAES operating conditions.

The resolution of the above issues could substantially improve the commercial viability of CAES. The Reservoir Stability Studies were established to resolve those issues.

2.2 GOALS

The goal of the Reservoir Stability Studies is to establish criteria for long-term stability of underground CAES reservoirs. These criteria are intended to be guidelines and check lists that utilities and architect-engineering firms may use to evaluate reservoir stability at candidate CAES sites. These criteria will be quantitative where possible, qualitative where necessary, and will provide a focal point for CAES relevant geotechnical knowledge, whether developed within this program or available from petroleum, mining or other geotechnical practices using rock materials.

Whenever possible the Reservoir Stability Studies have been directed to meet the needs identified by utilities participating in the CAES DOE/EPRI Demonstration Program. These utilities are endeavoring to incorporate CAES into their generating system.

2.3 OBJECTIVES

The objectives of the Reservoir Stability Studies for this reporting period have been:

- Complete investigative numerical and laboratory studies in hard rock, porous rock, and salt necessary to develop reservoir stability criteria.
- Initiate field studies of porous media to demonstrate proof of principle in situ and to validate reservoir stability criteria.

Successful completion of the objectives will permit the finalization of reservoir stability criteria.

2.4 STRATEGY

Early in the program a strategy was developed for reaching our objectives and establishing reservoir stability criteria. It was recognized that a significant amount of research would be required because of the unusual and unique operating conditions and rock behavior encountered in each type of CAES reservoir. The program strategy developed had four major activities for CAES in each rock type.

- State-of-the-Art Survey: To establish preliminary reservoir stability criteria and identify areas requiring research and development.
- Numerical Modeling: To parametrically evaluate the response and stability of CAES reservoirs under a wide variety of CAES operating and geotechnical conditions. These results will be used to guide activities in other phases of the program.
- Laboratory Testing: To examine issues not presently amenable or appropriate to numerical modeling; provide data for use in numerical models; and investigate fundamental rock mechanics, thermal, and fluid, and geochemical phenomena as appropriate to CAES.
- Field Studies: To corroborate numerical modeling and laboratory analyses to provide accurate estimates of reservoir response to CAES conditions; to examine geotechnical issues not amenable

to evaluation with numerical modeling or laboratory testing; and to verify the existing reservoir stability criteria and amend them as necessary.

This strategy was designed to meet the goal of the Reservoir Stability Studies and to interface with other CAES-related activities being carried on by DOE, EPRI, and private concerns. Figure 3, presented earlier, highlights the scheduled reservoir stability activities and how they relate to scheduled activities by other groups. Special efforts were made to schedule activities to coordinate with the DOE/EPRI and utility-sponsored CAES Demonstration Studies.

2.5 RESERVOIR STABILITY STUDIES PROJECT DESCRIPTIONS

Summaries of all tasks within this project and their progress are presented below with short preliminary comments giving perspective to the later project reports. More detailed summaries by project participants are presented in Chapter 4. Table 1 provides an outline of the Reservoir Stability Studies Program.

2.5.1 Porous Media Studies

Natural gas has been stored in porous rock formations for more than 50 years, and the conditions required for natural gas storage are similar to those for CAES. However, CAES requires daily cycling, as compared to annual cycling for natural gas. Further, air has at least twice the viscosity of natural gas, and air storage may have economic advantages if it can be stored at elevated temperatures within the porous matrix. These requirements result in a large number of unknowns regarding CAES in porous rock reservoirs.

The concerns related to CAES porous media reservoir stability are being addressed by numerical, laboratory, and field studies. These concerns include:

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

TABLE 1. Outline of Reservoir Stability Studies

<u>Title</u>	<u>Contractor</u>	<u>Funding Level (FY-81)</u>	<u>Status</u>
Porous Media Studies			
• Update of Preliminary Stability Criteria	PNL	\$ 10,000	On Schedule
• Numerical Studies of Porous Rock Reservoirs	PNL	35,000	On Schedule
• Laboratory Studies of Porous Media			
- Aquifer Field Test Support	PNL	100,000	One month behind
- Porous Media Flow Facility	PNL	55,000	One month behind
- Porous Rock Ventilation Studies	University Wisconsin-Milwaukee	2,000	Complete
- Thermomechanical Properties of Reservoir Rock	Los Alamos Scientific Laboratory	3,000	Complete
- Geochemical Response of Porous Media	Terra Tek	-0-	Complete
• Field Studies of Aquifer Reservoir			
- Legal, Regulatory, and PNL Support	PNL	68,000	On Schedule
- Site Acquisition and Qualification Contractors	(Many)	232,000	Complete
- Exploration Geological Control	Dames & Moore	110,000	Complete
- Design, Construction and Operation	PB-KBB	695,000	On Schedule
- Field Study Environmental Support	PNL/EV	N/A	On Schedule
Salt Studies			
• Numerical Studies of CAES Salt Caverns	Serata Geomechanics	24,000	Complete
• Laboratory and In Situ Studies of Domal Rock Salt	Louisiana St. Univ.	101,000	One month behind
Hard Rock Studies			
• Numerical Studies of CAES Hard Rock Caverns	Re/Spec	30,000	Complete
• Laboratory Studies of Hard Rock	Re/Spec	20,000	Complete
Champagne Effect Studies			
• Numerical Studies of Champagne Effect	Rowe & Associates	10,000	On Schedule
• Laboratory Studies of Champagne Effect	Rensselaer Polytechnic Institute	25,000	In Contracting

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

These concerns are addressed by a series of technical tasks described below. The initial task also covers the other reservoir types.

- Update of Preliminary Stability Criteria
Principal Investigator - T. J. Doherty, R. D. Allen, PNL

This task is the central receiving point for all information generated under the Reservoir Stability Studies Project. Data generated from numerical, experimental, and field studies projects are integrated into the existing stability criteria generated during the state-of-the-art surveys which have been completed. These documents, one each for salt dome solution-mined reservoirs, compensated excavated hard rock reservoirs, and porous media reservoirs, will be the condensed final product of the Reservoir Stability Studies. Interim versions of the criteria are being updated and revised during FY-1981. Final versions of the hard rock and salt criteria will be issued during early FY-1982, and an interim version of the porous media criteria will be released at the same time. Final stability criteria for porous media will be issued at the completion of the porous media field study.

- Numerical Studies of Porous Rock Reservoirs
Principal Investigator - L. E. Wiles, PNL

The objective of this modeling task is to characterize the fluid, thermal, and structural behavior of porous media reservoirs. Structural modeling and a series of thermal fluid models have been completed and reported in prior years. Effort during this reporting period concentrated on development of two-phase, two-dimensional isothermal models that evaluated the air-water interface of the reservoir, including capillary and gravity effects. The purpose of this type of model is to evaluate the bubble development process during start-up and to evaluate pressure-

driven operational transients, such as water coning, that can affect the cyclic response of the reservoir. Development of all versions of this model was complete in FY-1980. Effort since then has concentrated on applying all the models to the Aquifer Field Test planned for Pittsfield, Illinois. A prediction plan was formulated and analysis based on site exploration data initiated.

- Laboratory Studies of Porous Media

Laboratory studies in porous media have been directed at identification and evaluation of the effects of air injection on typical reservoir, caprock, and well materials. Dry air injection, the effect of moisture and moist air, and the geochemical and thermomechanical response of porous media were investigated for varying temperature ranges anticipated for conventional and advanced CAES reservoirs. Facilities to do these sorts of tests simultaneously to determine total environmental response to CAES conditions did not exist. Therefore, the experimental program was structured to evaluate separately, under as close a simulation as possible, the responses of reservoir materials to temperature, ventilation, the geochemical environment anticipated, and the cyclic structural loadings expected. These separate effects studies are essentially complete at this time. Simultaneously, the need for full environmental response of the media resulted in the planning, design, and construction of the porous media flow facility, which has full triaxial stress, temperature, and air-water vapor flow control capability as well as instrumentation and control systems to allow long-term testing. This facility is completing acceptance tests, and its first test plan in support of the aquifer field test is beginning. The technical subtask efforts for this reporting period are summarized below.

- Aquifer Field Test Support
Principal Investigator - R. L. Erikson

This subtask has consisted of test planning, casing materials evaluation, Pittsfield core evaluation, and testing in support of field studies permitting activity and operations planning. Its major activity

will be evaluation of the desaturation mechanisms, the permeability alterations, and the structural response of the Pittsfield materials using the porous media flow facility. Conclusions to date are that unconfined aquifer materials are reasonably stable in the presence of warm, moist, static air.

- Porous Media Flow Facility

Principal Investigator - M. A. McKinnon, et al

This subtask has consisted of design, construction, and acceptance testing of the porous media flow facility. The work is essentially complete and the facility is presently completing its operational acceptance testing. The facility, with its cell designed for standard core has the capability to induce triaxial stresses with confining (radial) loads up to 10,000 psi (70 MPa) and axial loads up to 80,000 psi, fluid pore pressures up to 1,500 psi (10 MPa), temperatures up to 550°F (300°C), pore fluid relative humidities from 0 to 100 percent, and flow rates of up to 1.53 in.³/sec. (25 ml/sec). Sample size is 2-1/8 in. (5.4 cm) in diameter and 4 in. (10 cm) long. A deformation jacket uses LVDTs to measure each sample's axial and circumferential displacements. Additional instrumentation monitors and controls inlet temperature, pressure, mass flow rate, and humidity. These parameters are also measured and recorded at the outlet. The instrumentation and control system are connected to a data acquisition and system control computer to ensure test quality and data tracking. Samples can be readily moved to analyze the flowing fluids for solutes and suspended material. Support facilities provide information on the fabric texture, general microstructure, and mineralogy of the solid samples. The system is adaptable to both manned and automatic operation, allowing for both short- and long-term testing.

- Porous Rock Ventilation Studies

Principal Investigator - H. Pincus, University Wisconsin-Milwaukee

This subtask, initiated in FY-1977 and completed in FY-1980, evaluated the effect of cyclic air ventilation on various porous rock materials. Samples gathered from a variety of typical surface and subsurface sources

were subject to moderate temperature and confining pressure and cyclic dry air flow. Effects on permeability, strength, and thermal properties were determined before and after flow, and alterations to the microstructure were monitored. Conclusions were that dry air cycling did have an effect on the porous media, but that the effect was generally modest and identifiable with a particular rock property. Optimal storage media were identified as clear quartzose sandstones.

- Thermomechanical Properties of Reservoir Rock
Principal Investigator - J. Blacic, Los Alamos Scientific Laboratory

The purpose of this subtask is to assess the effects of temperature, effective pressure, and cyclic stress on the elastic constants and strength properties of porous materials during loading and to evaluate thermal effects on caprock competence. All work on this study, initiated in FY-1979, will be completed during FY-1981. Results indicate that there are observable changes in porous rock properties indicating that increasing temperature, effective stress, and cyclic stresses tend to densify the material. This influences porosity and permeability, but test results indicate that the net effect is fairly minor. These tests, which included all environmental effects except moist air flow, also showed significant change in structural properties, but these should not be detrimental to reservoir performance. The net result of the study was identification of structural properties under in situ conditions. In this process no phenomena were discovered which would prevent successful operation of a CAES porous media reservoir. Tensile strength of shale caprock materials was found to be highly dependent on saturation, with increasing dehydration resulting in increasing strength. This indicates that care should be taken when planning and designing well completion systems through such caprocks.

- Geochemical Response of Porous Media
Principal Investigator - C. Cooley, Terra Tek, Inc.; J. A. Stottlemire, PNL

This subtask, completed at the end of FY-1980 was directed at identifying geochemical and microstructural mechanisms at operating temperatures and

determining their impact on permeability and porosity of porous media reservoir materials. The majority of this testing was performed by Terra Tek Inc., with PNL overseeing and also conducting selected tasks. Pore volume reduction due to particle cement plasticity, point contact compression, etc., was determined to have a small-to-insignificant effect in permeability alteration. The solutioning of silica into reservoir fluids can result in anomalous viscosity alterations that result in the appearance of significant permeability change. This was determined to be insignificant for CAES conditions. In addition, thermo-mechanical fragmentation due to CAES thermal cycling was determined to be a minor concern with respect to alteration of permeability. It was found that many reported permeability alteration experiments in the literature may be the result of laboratory contamination of samples, and this was prevented. The major remaining mechanism which requires evaluation is particulate generation resulting in pore plugging within the material itself. Reservoir material propensity for this mechanism is treatable, and this tendency can be evaluated with the porous media flow facility.

- Field Studies of an Aquifer Reservoir

The goal of the field studies is to validate the numerical and laboratory methods and tools developed within the program by in situ experiment. The objective of this task is to design, construct and test in the field a reduced-scale air reservoir system in a prototype geologic medium. Planning and preliminary site selection were completed during the last reporting period. The major efforts during this period consisted of confirmation of the site and initiation of the design, construction, and operations contract. Confirmation consisted of acquiring exploration and operation rights to the property, determining and acting on all legal and regulatory responsibilities within the jurisdictions concerned, and performing drilling, logging, seismic surveying, and core evaluation studies to confirm the proper geological

structure. In addition, a scope of work for design, construction, and operation of the field test was prepared; proposals were solicited; and an initial contract award was placed, initiating design and construction activity. Progress within the various subtasks in the Aquifer Field Test are listed below.

- Legal, Regulatory and PNL Support
Principal Investigator - R. D. Allen, et al.

Responsibilities under this subtask include selection and administration of subcontracts for exploration, design and construction, and operation of the field test and preparation and implementation of all documents required to satisfy legal or regulatory agencies having jurisdiction over field test activities.

During the exploration phase, contracts were let and administered for a geological representative, drillers, seismic survey crews, land leasing firms, core evaluation labs, and logging crews. Land leasing and easements were prepared, and information from the exploration activities was assembled into the construction permit. This was submitted to the IEPA and was favorably received by them.

The final activity under this task was preparation of the scope of work, solicitation of proposals, and award of contract for design, construction, and operations. The RFP was prepared and issued during FY-1980. A number of well-prepared proposals were reviewed, and contractor selection was completed and defended during early FY-1981. PB-KBB of Houston, Texas, was selected from a strong field. An initial contract was placed with them and they have begun design and construction. The long-term contract is undergoing bid review and external scrutiny but will be in place during FY-1981.

- Site Acquisition and Qualification Contractors

A number of specialized firms were involved in site qualification and acquisition during this reporting period. A partial listing with a brief word on their field study activities follows.

- Coates Field Services, Tulsa, OK, Land leasing activities
- Campbell, Furnall, Moore, and Jacobsen, Attorneys at Law, Mt. Vernon, IL, Illinois legal consultant
- D&G Drilling, New Lenox, IL, Exploration core drilling
- Compagnie Generale De Geophysique (CG&G), Houston, TX, Seismic surveying
- Geo Engineering, Mt. Vernon, IL, Core evaluation
- Dames and Moore, Chicago, IL, PNL field geological representative.
 - Exploration Geological Control
Principal Investigator - N. Rudd, Dames & Moore

The objective of this subtask was to provide expertise in geological and exploration matters in the field. Neilson Rudd and Dames & Moore were identified as well qualified, and they also had local experience. This contractor represented PNL and acted as the technical lead on all field exploration activities. Activities included supervising and logging for all drilling activities, interpretation and review of logging and seismic data, and constant contact to interface with and make recommendations to PNL staff during the field study exploration activities.

All exploration activities were completed. A specific location on a confirmed structure was determined, and this information and much supporting data was prepared and submitted to PNL. This report contributed strongly to the injection permit documentation.

- Design, Construction and Operation
Principal Investigator - PB-KBB

This subtask has just recently been initiated. Activities to date have included submission of detail design information for construction, permit documentation, submission and approval of injection well detail design and schedule tasks, preliminary design, and equipment selection for both the surface facility and instrumentation task to allow initiation of procurement. Plans have injection well completion in July 1981 and facility construction and operation initiated in FY-1982.

- Field Study Environmental Support
Principal Investigator - M. A. Beckwith, PNL

This subtask, which is funded by the Office of Environmental Compliance and Overview of DOE, is providing environmental support to legal and regulatory activities and making recommendations and reviewing technical requirements for the field study from an environmental viewpoint.

The most notable activity in this reporting period was the careful coordination of efforts with the Illinois Environmental Protection Agency in the preparation, submittal, and follow-up of the field study injection permit.

2.5.2 Salt Studies

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

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

CAES activities in domal salt reservoirs consist of numerical and experimental studies. The laboratory studies include in-mine correlation of experimental data and testing of core from the Huntorf facility.

Due to funding limitations and the fact that there is some operational experience in the Zechstein domal salt from the operation of the Huntorf CAES facility, it was decided that the program would forego field study activities in compressed air energy storage.

- Numerical Studies of CAES Salt Caverns
Principal Investigator - S. Serata, Serata Geomechanics Inc.

The numerical modeling of CAES salt caverns was performed by a contractor who also contributed to the geotechnical evaluation of the Huntorf facility. The work completed during this report period was a continuation of the previous work on general stability criteria for CAES caverns in salt. It included elevated temperature and boundary deterioration due to air penetration as critical parameters to be analyzed, and was divided into four basic sections: 1) model modification and testing, 2) a benchmark thermomechanical stress problem formulated by PNL, 3) parametric analysis of temperature-related parameters affecting stability not covered in previous work, and 4) simulation of the LSU borehole testing station at the Jefferson Island mine. The major findings of the study include:

- The REM/*HEAT* (structural/thermal) code is capable of simulating thermal conduction, cyclic temperature and pressure, thermomechanical loading, solution mining simulation, and non-linear temperature-dependent viscoplasticity.
- For cavern temperatures to 200°F, CAES caverns were found to be highly structurally stable in the long term (10^4 days).
- Air penetration is expected to affect primarily the local stability of CAES caverns and not significantly alter global stability.
- The LSU borehole analysis indicated that the REM code can be used to model highly site-specific geometries and loading conditions. The code can be continuously calibrated to data obtained in the field.

The work performed during this reporting period was completed in December of 1980. As model development, and some level of application of the modeling technique to the in-mine experiments has been carried out, this basic activity is considered complete. Some additional work for the FY-1981 reporting period was planned to widen the areas of proven application of the model, but budget redistribution eliminated this from further consideration.

- Experimental Studies of Domal Rock Salt
Principal Investigator - R. L. Thoms, Louisiana State University

Robert Thoms and Louisiana State University have been involved in numerical, geophysical, and laboratory studies of salt domes and domal rock salt for nearly as long as scientific and engineering principles have been applied to their utilization. Experience ranging from petroleum storage to solution and mechanical mining to nuclear waste isolation evaluations provide a solid technical basis for extension of Gulf Coast salt dome usage to the unique situation of CAES.

The experimental program at LSU is a continuation of activities initiated three years ago. The experimental program includes both laboratory and in-mine evaluations of salt response. These activities were scheduled to be complete in early FY-1982, at which time the revised version of the preliminary design and stability criteria previously submitted by LSU will be finalized.

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

An in-mine borehole study to evaluate in situ salt response to pressurization and cycling was initiated during this reporting period. Diametral deformations and acoustic emissions were monitored during testing. Correlation of these in situ tests with the laboratory studies would provide solid validation of simple and straightforward laboratory techniques. In addition, in-mine activities included permeability evaluations to determine the effect of core drilling on core permeability versus in situ permeability. Unfortunately, testing was under way at the Jefferson Island mine when that facility was flooded by a poorly located Texaco drill rig exploring for oil. Equipment losses were small but significant, but project staff on-site at the time escaped uninjured. The in-mine facility has been relocated at the Cote Blanche mine and every effort has been made to get the facility operational and make up lost time, the major casualty. The general conclusion is that the domal rock salt is an excellent candidate for CAES development within reasonable temperature and rock mechanical limitations and that the material will be predictable and monitorable.

2.5.3 Hard Rock Studies

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

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

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

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

Re/Spec Inc., a highly qualified geotechnical research and engineering firm located in Rapid City, SD, is the lead contractor in hard rock cavern studies. Re/Spec Inc. previously completed the state-of-the-art survey and issued preliminary stability criteria for hard rock CAES. Their task during this reporting period was to complete all generic numerical and experimental studies, along with associated methodology development, including confirmatory numerical evaluation of the Acres American design for hard rock CAES caverns performed for Potomac Electric Power Company under the Demonstration Program. Revision and updating of the stability criteria is continuing as work progresses and a final version will be completed in early FY-1982.

Major geotechnical concerns related to compensated CAES in hard rock examined during FY-1980 included: 1) determination of rock properties and behavior under cyclic thermal, pore liquid saturation, and mechanical loading conditions, 2) determination of the effect of local rock failure on cavern stability, 3) evaluation of the relative value of rock structural improvement methods, and 4) determination of the impact of fracture networks on global air leakage. Studies to address these issues have been initiated with progress summarized below.

In addition, a support task to evaluate the response of the air-water system was initiated. High air saturation conditions could result from the wide range of pressure to which the compensating fluid is exposed during its movements. It was postulated that head reduction transients could result from air coming out of solution in the compensating leg. This could affect either the feasibility or the cost of compensated CAES, depending on the seriousness of the transient. A numerical study was initiated with Rowe and Associates of Bellevue, Washington, and model confirmatory experimental work is being planned at Rensselaer Polytechnic Institute.

- Numerical Studies of CAES Hard Rock Caverns
Principal Investigator - A. Fossum, Re/Spec Inc.

Numerical model development initiated in FY-1978 was completed during FY-1980. Re/Spec capabilities include the ability to structurally characterize a rock mass, including its jointing system and anisotropy, with engineering accuracy. The sequential excavation process typical of economical heading and bench mining techniques, which CAES would utilize, can be modeled. This is necessary to determine the state of stress around the CAES caverns before operations begin. Thermal modeling, which includes the effect of a cavern filling with cold water then cycling to full pressurization with warm air, determines loading for the thermo-elastic structural model, which then can evaluate the effect of CAES loads on the excavation.

Numerical models were applied to parametric analyses which involved both operating conditions and rock properties. For generic materials and conditions it was found that multiple caverns could be located in competent rock at 750 m without failure even after substantial strength reductions due to local rock failure or thermal shock were simulated. Models also included an air leakage model that simulated secondary permeability through joint apertures, which is quite dependent on the local state of stress in the rock material. For most generic CAES

conditions and materials, air leakage was found to be coupled to the stress ratio parameter, but it was low enough to be ruled out as a major operational concern.

Review of European experience and model validation using field data supports these conclusions. Results of an evaluation of the PEPCO design indicate that the shape, support system, and stability of the cavern will be sufficient for CAES operations, and the design results in favorable fatigue response.

- Experimental Studies of Hard Rock for CAES
Principal Investigator - A. Fossum, Re/Spec Inc.

The purpose of this project is to perform laboratory studies of a range of hard rock materials in an environment simulating CAES conditions in order to identify cyclic or long-term degradation mechanisms that could affect cavern stability.

Structural and thermal properties were gathered or determined, and coordinated with numerical studies to assess the critical properties and operating parameter ranges for CAES. A suite of core, generally igneous and metamorphic with some sedimentary, was assembled as a broad range of generic CAES candidates. General rock mechanics evaluation and a special test series were run. Dry and saturated tests assessed the influence of compensation wetting. Samples were thermally cycled and load cycled under confinement and the properties recorded and assessed.

Conclusions are that strength reductions can be expected in the tensile and compressive strengths of rock masses subjected to a cyclic wet/dry and thermal CAES cavern environment, but insignificant change was observed in shear strength or friction angle. The percentage loss of failure strength of the rock decreases with increasing mean stress, and most of the damage will be caused in the first few cycles, indicating that a rock mass would shake down quickly to stable behavior. Fatigue stress ranges that could be anticipated in a well-designed cavern system should also have minimal impact on past shake-down running. The compressive and tensile strengths are adversely influenced by a CAES cavern environment;

the reduced failure strength of most initially intact hard rocks is sufficiently high to indicate that a CAES plant could be operated satisfactorily. It has also been demonstrated that foliated and/or jointed rock masses require special attention, and assessment of strength requirements and strength values become quite site specific. The PEPCO Sykesville gneiss was evaluated and found to be a highly anisotropic material.

The operational conditions based on the Acres PEPCO design were used to establish the test series for this core. The material was found to be usable as long as careful design and construction methods are employed.

3.0 SECOND-GENERATION STUDIES OF CAES CONCEPTS

3.1 INTRODUCTION

The CAES plant at Huntorf and the conventional CAES plants currently under consideration by U.S. utilities require a petroleum fuel for the firing of the air from storage before its expansion in the turbines. The amount of petroleum fuel consumed could be as much as 60% less than required by peaking plants currently in use.* Although this reduction is substantial, uncertainties in the future supplies of petroleum fuels make it desirable to reduce the dependence of CAES plants on petroleum fuels further or to entirely eliminate it.

The Second-Generation Studies program was undertaken to evaluate and develop new CAES concepts that require little or no petroleum fuels. An early preliminary screening of various ideas resulted in the placement of principal programmatic emphasis on three concepts. These are 1) a CAES system with a coal-fired fluidized bed combustion process, 2) a CAES system with a coal gasifier, and 3) an adiabatic CAES system which uses thermal energy storage to return the heat of compression to the expanding air. In addition, other concepts have been examined in somewhat lesser detail. These have included concepts which integrate a CAES plant with solar energy and with a coal-fired steam plant.

3.2 GOALS

The goal of the Second-Generation Studies is to develop one or more second-generation concepts to the extent that it could be demonstrated by the public utility industry in the latter half of the 1980s. This goal will be attained through 1) the development of advanced designs, 2) economic studies, 3) equipment development and demonstration, and 4) the wide dissemination of the results of these activities to the public utility industry.

*The Huntorf CAES plant required 5500 Btu of fuel per kilowatt-hour (Btu/kWh) of electricity produced. Current conventional CAES plant designs require about 4000 Btu/kWh. Simple cycle gas turbines used for peaking power require about 12,000 Btu/kWh.

3.3 OBJECTIVES

The specific objectives of the Second-Generation Studies are:

- Identify and screen second-generation CAES concepts that have potential for reduced consumption of petroleum fuels.
- Establish the feasibility of including thermal energy storage in CAES.
- Establish the feasibility of integrating coal-fired fluidized bed combustion with CAES.
- Examine the feasibility of integrating coal gasification systems with CAES.
- Evaluate and develop advanced CAES equipment and components.

3.4 STRATEGY

The strategy of Second-Generation Studies is to identify one or more concepts that will merit demonstration by the utility industry before 1990. The concept chosen must compete successfully with present intermediate and peaking plant technology. Program resources will focus on known concepts to assure adherence to schedule.

The basic methodology employed in this program involves the examination of all identified, viable, second-generation CAES concepts and the performance of preliminary technical and economic screening to select those that show the most promise. Then preliminary engineering design and detailed technical and economic analyses are performed to realistically assess the viability of these concepts. When the detailed analyses are complete, the selected second-generation CAES concepts are screened for relative comparison with each other and with other energy storage technology. Based on this screening process, recommendations are to be made to DOE regarding specific equipment and component development activities that must be undertaken to accomplish the goals of this program.

3.5 SECOND-GENERATION CONCEPTS STUDIES PROJECT DESCRIPTIONS

Summaries of the scopes and contractual status of various projects included in the Second-Generation Concepts Studies are provided below. An outline of the program is shown in Table 2.

3.5.1 Conceptual Design/Economics Studies

Based on early screening studies, three concepts were identified as having promise for early commercialization. These concepts included adiabatic CAES (ACES), CAES with fluidized bed combustion (CAES/FBC) and CAES integrated with coal gasification (CAES/CG). Major conceptual design efforts and economic studies were undertaken to provide convincing data regarding the economic and technical viability of these concepts. These tasks are outlined below.

- Conceptual Design and Engineering Studies of Adiabatic CAES with Hard Rock Caverns
Principal Investigator - M. J. Hobson, Acres American, Inc.

The purpose of this task is to perform a preliminary engineering and economic study of the adiabatic CAES concept using a water compensated mined cavern in hard rock for air storage. This study includes the evaluation and selection of the most appropriate technology for the regenerative air heaters which store and return the heat of compression to the air. Work was initiated in FY-1980 on this task, and preliminary results have indicated that this concept is competitive with other peak shaving concepts. The task was scheduled for completion at the end of the first quarter in FY-1981.

- Conceptual Design and Engineering Studies of Adiabatic CAES with Aquifer Storage
Principal Investigator - M. J. Hobson, Acres American, Inc.

This task consists of an engineering and economics study of the adiabatic CAES concept in which the air is stored in an aquifer. In this concept, the aquifer is used to store both compressed air and a part of the heat of compression. This task was initiated during the last quarter of FY-1980 and was scheduled for completion in FY-1981. This

34

<u>Title</u>	<u>Contractor</u>	<u>Funding Level</u>	<u>Status</u>
Conceptual Design/Economic Studies			
• Adiabatic CAES (Hard Rock Storage)	Acres American, Inc.	\$260,600*	Complete
(Aquifer Storage)	Acres American, Inc.	54,787*	Postponed
• CAES with FBC (CAES/FBC)	United Technologies Research Center	367,173*	Complete
• CAES with Coal Gasification (CAES/CG)	PNL	10,000	Complete
Component Evaluation and Development			
• Equipment Evaluation	ENTEC	63,000*	On Schedule
• Reliability Studies	PNL	10,000	On Schedule
• TES Development	PNL	30,000	On Schedule
	FluidDyne Eng. Inc.	160,000*	On Schedule
Second Generation Concepts Assessment and Support			
• New Concepts: Solar ACAES	TBD	-	Cancelled
• Economics of Second-Generation CAES Systems	PNL	30,000	On Schedule
• Concept Assessment	PNL	40,000	On Schedule

work was subsequently halted in late FY-1980 because of budget readjustments.

- Feasibility Study of CAES Augmentation by FBC
Principal Investigator - A. J. Giramonti, United Technologies Research Center

The objective of this task is to assess the feasibility of integrating coal-fired fluidized bed combustion (FBC) technology with CAES. This task was subcontracted during FY-1979, and the work originally planned was completed in FY-1980. This subcontract was subsequently extended to consider load following and part-load operation capability of the design. FY-1981 activities were limited to the wrap-up of this work, completion and distribution of the final report, and dissemination of the results.

- Feasibility of Combining CAES with Coal Gasification (CAES/CG)
Principal Investigator - W. C. Cliff, PNL (FY-1980)

The objective of this task is to establish the feasibility of the concept of integrating a coal gasification plant into a CAES cycle. The task included a reassessment of the results of a similar, EPRI-funded study which concluded that this concept was not particularly promising. The performance of this work was integrated into the Second-Generation Concepts Assessment and Support task, and the results are reported under that heading in Section 4.

3.5.2 Component Evaluation and Development

The overall objective of these tasks is to evaluate the technical limitations and reliability of engineered systems, equipment, and components identified for potential use in second-generation CAES plants. This information will be used to define uncertainties that may affect the early commercialization of CAES technology and to develop recommendations to DOE regarding additional developmental activities required to resolve these uncertainties.

- Equipment Evaluation
Principal Investigator - D. Chiang, ENTEC Research Associates

The purpose of this task is to evaluate the capability of commercially available systems, equipment, and components to meet the functional

requirements of CAES plants. Specific attention will be given to valves, turbines, compressors, flow controls, expansion joints, particulate removal equipment, and systems that may be required to meet environmental standards. Potential problems regarding availability and performance will be identified, and recommendations will be formulated regarding additional research and development required to remove the problems.

- CAES Systems Reliability Studies
Principal Investigator - R. W. Reilly, PNL

The reliability of CAES technology will strongly influence its potential for commercialization. The purpose of this task is to evaluate and quantify the reliability of individual subsystems and, ultimately, the overall system. Initially, the study will consider data requirements, methodology, and availability of the required data. This will be followed by the reliability evaluation of the system and its components.

- TES Development
Principal Investigators - K. R. Wheeler, PNL
D. G. DeCoursin, Fluidyne Engineering Corp.

The objective of the task is to develop technology required for the design, construction, and operation of commercial thermal energy storage systems (regenerators) for CAES plants. This task was initiated in FY-1981 and consists of two subtasks, both directed at identifying satisfactory TES materials that have the combined properties of long life, good fluid/thermal performance, and cost effectiveness. One subtask, being performed at Fluidyne, is directed at examining thermal ratcheting failure mechanisms. The other subtask at PNL is addressing thermal-chemical failure mechanisms.

3.5.3 Second-Generation Concepts Assessment and Support

The overall objective of these tasks is to support and integrate the results of all advanced CAES engineering and economics studies. These results will be used to develop recommendations to DOE on which of the advanced CAES concepts should continue into the program's development phase.

- Economics of Second-Generation CAES Systems
Principal Investigator - R. W. Reilly, PNL

This task is performed in support of the concepts assessment task and was initiated in FY-1980. It provides a standardized review of the economics of each of the second-generation CAES technologies. The cost estimates developed as a part of each CAES engineering and economic study will be reviewed for completeness and reasonableness. A final topical report which compares the economics of each of the technologies will be issued. These technologies will also be compared against the economics of one or more competing conventional technologies, including underground pumped hydro storage. Finally, a cost information data base will be generated from the data gathered through examination of these technologies.

- Concept Assessment
Principal Investigator - F. R. Zaloudek, PNL

This task will be directed towards acquiring, compiling, and integrating data on all projects related to CAES systems. This information will be used to develop recommendations to DOE on which of the second-generation CAES concepts should continue into the development/demonstration phase. Those recommendations will be made according to screening and selection criteria developed during CY-1980.

4.0 PROGRESS SUMMARIES

In this section detailed discussions are given of the individual projects that composed the Reservoir Stability Studies and Second-Generation CAES Concepts Studies during this reporting period. Topics discussed are organized according to:

- Project Objectives
- Project Tasks
- Technical Progress
- Technical Problems
- Publications

4.1 RESERVOIR STABILITY STUDIES

4.1.1a. Bubble Development and Water Coning in Porous
Media Reservoirs for CAES

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

OBJECTIVE

The objective of this portion of the CAES technology development program is to evaluate the thermohydraulic performance of porous media reservoirs under simulated CAES conditions. This involves the numerical analysis of mass and energy transport in the reservoir. The specific topics that have been addressed during the past year are bubble development and water coning. Several reservoir parameters that influence bubble development and water coning have been investigated under isothermal conditions. To perform the analysis a two-dimensional (cylindrical or areal), two-phase (air-water) numerical model was developed using finite difference solution methods for the equations describing fluid flow in the reservoir. The model includes capillary pressure, relative permeability, and can model the open wellbore in the computational grid.

Bubble development involves the injection of air into a fully saturated porous zone, thereby displacing the aquifer water. Experience in natural gas storage (Katz et al, 1979) and estimated for CAES (Katz and Lady, 1976) indicate that the time required for bubble development for a typical commercial site is on the order of years. The evaluation of various bubble development strategies may lead to reduced bubble development times. Also, such predictions will aid in planning of the overall site development schedule. For these reasons the capability to evaluate bubble development has been developed.

Water coning is illustrated in Figure 7. During a discharge cycle the depressurization around the wellbore causes a cone of water to rise towards the wellbore. The intrusion of water into the near-wellbore region could adversely affect reservoir operation. The water would reduce the flow area and the effective permeability to the flow of air. This effect could occur whether or not the reservoir is

FIGURE 7. Water Coning During Reservoir Extraction Cycle

being used for thermal energy storage. In reservoirs that are being charged with high-temperature air, geochemical reactions may occur due to the interaction of air and water. The potential problems increase with temperature. Such reactions would also increase the resistance to the flow of air. Since most of the reservoir pressure loss occurs in the convergent region near the wellbore, increasing the flow resistance in that area will require greater pressure losses to maintain a given air mass flow rate. Thus, the ability to predict the conditions for which water coning may occur is crucial to the development of appropriate

design guidelines for a porous media CAES facility. In this light, the development of a two-phase, two-dimensional numerical computer code was initiated.

TASKS

Task 1. Water Coning

Due to the perceived relative importance of the two topics, water coning was evaluated first. Since water coning is a response to the pressure distribution in the reservoir, the parameters that were evaluated were those that influence the pressure distribution. These parameters included the producing length, air mass flow rate, air storage zone thickness, permeability and the saturation functions.

Conditions of the Analysis

The water coning analysis is based upon a set of reference conditions applied to the reservoir geometry, material properties, and operating conditions. The values given to these parameters are given in Table 3. These values are consistent with the values used in previous analyses of compressed air energy storage in porous media reservoirs (Smith, Wiles, and Loscutoff, 1979). The analysis is also based on the weekly cycle described in the referenced reports. This cycle defines the times during the week when the reservoir is being charged or discharged and when the reservoir is closed. The analysis was performed by varying single parameters or groups of parameters about their reference values.

Results

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, cyclic duration in which those gradients exist. However, water coning will depend on site-specific conditions, particularly the fluid distributions following bubble development, and, therefore, should be included as part of site evaluation.

TABLE 3. Reference Conditions

Parameter	Reference Value
Geometry	
Reservoir Depth	520.0 m
Vertical Thickness (Air Zone)	30.0 m
(Water Zone)	20.0 m
Reservoir Diameter	120.0 m
Well Diameter	0.20 m
Producing Length	24.0 m
Properties	
Porosity	20%
Permeability (Horizontal)	500 md
(Vertical)	500 md
Wellbore Porosity	100%
Wellbore Permeability	$5.0 \cdot 10^9$ md
Operating Conditions	
Nominal Pressure	50 atm (5070 kPa)
Air Flow Rate (Injection)	6.66 kg/s
(Extraction)	8.79 kg/s
Percent of Air Cycled	12%
Temperature	300°K
Saturation Functions	
Relative Permeability (Porous Media)	
(air)	$k_r^g = (0.90-S)^2 \left\{ 2.34 - 1.37 (0.90-S)^2 \right\}$
(water)	$k_r^l = (S-0.20)^3 \left\{ 8.37 - 8.02 (S-0.20) \right\}$
Relative Permeability (Wellbore)	
(air)	$k_{r,w}^g = \left(\frac{1.0-S}{0.9995} \right)^2 \left\{ 2.0 - \left(\frac{1.0-S}{0.9995} \right)^2 \right\}$
(water)	$k_{r,w}^l = \left(\frac{S-0.0005}{0.9995} \right)^2 \left\{ 2.0 - \left(\frac{S-0.0005}{0.9995} \right)^2 \right\}$
Capillary Pressure (Porous Media)	
$p^C = \frac{0.05525}{S-0.15} - 0.065$	
Capillary Pressure (Wellbore)	
$p^C = 0.0$	

The parameters that were known to have an effect on the reservoir pressure response, and, therefore to water coning were evaluated with the following results:

- 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 one air extraction cycle.
- To avoid water coning in vertically thin reservoirs the necessary reduction of the producing length becomes a greater percentage of the total thickness and, as such, is responsible for an increase in the pressure loss across the reservoir.
- The pressure drop across the reservoir is proportional to the air mass flow rate so that higher flow rates will be associated with more severe water coning.
- In reservoirs having homogeneous permeability the water coning is more severe for large values of permeability provided that, as a basis for comparison, the pressure drop across the reservoir is the same for all cases.
- Even a slight reduction in vertical permeability can significantly reduce the severity of water coning.
- A stratified region 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. Perhaps the most important item to quantify regarding these functions would be the residual saturation.

Certain characteristics of water coning that were observed include:

- If water enters the bottom of the wellbore, the low flow resistance 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 saturation buildup in the sand immediately adjacent to the wellbore and to a lesser extent by the water content in the wellbore.
- Water coning may be described as having two modes. In one, mobile water may exist within the region affected by the sharp pressure gradients near the wellbore. In the second, the water movement is a response to the pressure differential across the entire reservoir. In this mode the air-water interface apparently moves much more slowly.

Task 2. Bubble Development

A generalized parametric study of bubble development has not been done. Instead, three specific problems have been addressed. These are:

1. Establish reasonable agreement with the Katz and Coats model (Katz and Coats, 1968)
2. Demonstrate capability to evaluate enhanced bubble growth rates using water extraction wells.
3. Compare the R-Z model with the areal model for single well air injection. Also determine the extent to which the fluids segregate to conform to gravitational-capillary equilibrium

Each of these areas is discussed below.

The Katz and Coats Model

Katz and Coats have provided a method for analytically calculating bubble growth rates for very simplified conditions. The method is based on a one-dimensional (radial) solution for the flow of water in porous media. A bulk compressibility of the rock and water is included. The method does not account for capillary pressure or relative permeabilities.

The bubble is assumed to exist at uniform pressure inside a sharp displacement front. Although the applicability of the model is limited, its accuracy has not, to our knowledge, been criticized.

Two cases were run with the computer model and the results were compared against solutions developed using the technique presented by Katz and Coats. General agreement was achieved although the simulation times were relatively short.

Water Extraction Wells

A very obvious limitation of the Katz and Coats model is the inability to simulate more than one well. We have speculated for some time that the bubble growth rate could be considerably enhanced by extracting water from wells outside the air bubble. For that matter, water could be extracted from wherever it exists, including those wells inside the bubble. The eventual use of such an approach is dependent on other issues that are beyond the necessity of our present consideration. This analysis demonstrates the ability to perform the computations and suggests the benefit to bubble growth.

In this analysis a computational grid was set up which was 1000 m on a side. A grid was defined to accommodate three water extraction wells. These were defined on a square pattern, 240 m on a side. This situation is depicted in Figure 8. Only the grid lines for the wells are shown. The source air pressure for these cases was 90 atm while the reservoir hydrostatic pressure was 50 atm.

Forty hours of air injection were simulated. Without the benefit of water extraction wells the code predicted that the mass of water displaced was 8.06×10^5 gm and that 1.08×10^5 gm of air had been injected based on a unit reservoir thickness of 1 cm. When the water extraction wells were included, the air injected and water displaced were approximately twice the values given above. The exact numbers are dependent on conditions whose description is beyond the scope of this summary. At any rate, the presence of the extraction wells could considerably influence the bubble development times.

FIGURE 8. Definition of Well Grid

R-Z Modeling

The initial analysis with the R-Z model was intended to provide a comparison between the vertically averaged saturations and the saturation distributions as predicted by the X-Y areal model. This comparison displays the importance of modeling the gravitational term.

A comparison of solutions from the X-Y areal model and the R-Z model requires some compromise due to the fundamental geometric difference. This involves the coincidence of computational grids, computational volumes, and treatment of any vertical effects which is possible in the R-Z model. Given the circumstances of the comparison; i.e., that unresolvable

differences occur between the X-Y areal model and the R-Z model, an exact agreement may not be possible. Reasonable agreement has been achieved. The displacement figures of Table 4 are provided for comparison.

The important point at issue in comparing the two model geometries is not whether the models are fundamentally in agreement, but is, instead, the significance of the vertical effects. In Figure 9 the vertically averaged saturation from the R-Z model are compared to results from the X-Y areal model. These results suggest that, at least during the initial stages, gross bubble development can be reasonably modelled without consideration of the vertical fluid distributions. This may not be true either later in the development process or for anisotropic conditions.

TABLE 4. Air Injection and Water Displacement After 35 Hours of Simulated Bubble Growth Using Different Model Geometries

<u>Model Geometry</u>	<u>Injected Air (gm)</u>	<u>Displaced Water (gm)</u>
R-Z	$1.94 \cdot 10^8$	$1.58 \cdot 10^9$
X-Y	$1.81 \cdot 10^8$	$1.30 \cdot 10^9$

The vertical saturation profiles given in Figure 10 suggest that gravity segregation is possibly not a very good assumption. This assumption would require that the vertical saturation distribution be characterized by three zones; a fully saturated zone at the bottom, a region containing only residual water (in this case a saturation of 0.20) at the top, and a transition zone (in this case approximately 10 m) separating the two. The transition zone is defined by the capillary pressure function. This necessary distribution clearly is not manifested here. However, for lower flow rates and conditions of greater vertical mobility, the gravity-capillary equilibrium assumption may be acceptable.

FIGURE 9. Saturation Profiles After 35 Hours of Air Injection

This analysis of bubble development has not addressed the main issue, i.e., the time required for bubble development. Instead, the analysis demonstrates the capability to perform bubble development calculations with reasonable accuracy. The first actual application of this model will involve predictions in support of the field test demonstration program.

REFERENCES

D. L. Katz and K. H. Coats, Underground Storage of Fluids, Ulrich's Books, Inc., Ann Arbor, MI, 1968.

FIGURE 10. Saturation Profiles from R-Z Model for Various Radial Nodes (m)

D. L. Katz, D. Cornell, R. Kobayashi, F. H. Poettman, J. A. Vary, J. R. Elenbaas and C. F. Weinaug, Handbook of Natural Gas Engineering, McGraw-Hill Book Company, New York, 1979, pp. 463-464.

D. L. Katz and E. R. Lady, Compressed Air Storage, University of Michigan, Ann Arbor, MI, May 1976.

G. C. Smith, L. E. Wiles and W. V. Loscutoff, 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, WA 99352, 1979.

L. E. Wiles, 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, WA 99352, October 1979.

L. E. Wiles, The Effects of Water on Compressed Air Energy Storage in Porous Rock Reservoirs. PNL-2869, Pacific Northwest Laboratory, Richland, WA, 99352, March 1979.

4.1.1b Porous Media Experimental Tasks

R. L. Erikson

Pacific Northwest Laboratory

OBJECTIVE

This paper is a summary of laboratory tests conducted between March 1980 and March 1981 on sandstone and well casing materials subjected to simulated CAES conditions. The objectives of this experimental program are: 1) to generate and interpret data that can be used to select reservoirs and develop operating criteria, and assess environmental issues; and 2) to develop equipment and procedures for site-specific field project support. Specific subtasks described herein cover well casing corrosion tests; sandstone permeability and mechanical stability tests with elevated-temperature dry air; similar tests with ground water; and the development of strategy for future experiments in the porous media flow facility currently undergoing acceptance testing.

TASK DESCRIPTIONS

Task 1. Equipment Development and Acceptance Testing

The major thrust is the development of the CAES porous media flow facility and the successful test acceptance of this system. This sophisticated flow system will enable the measurement of many physical properties of porous sandstone at the pressure and temperature of interest under dynamic air-flow conditions. Other rock properties of interest are thermal and chemical properties. A laboratory set-up at PNL consisting of a drop calorimeter, thermal conductivity apparatus, autoclave pressure vessels, and x-ray diffractometer will allow the determination of many of these properties.

Task 2. Aquifer Field Test Support

The purpose of this task is to characterize materials collected from the CAES field site and perform pertinent experiments on site

specific samples. The data obtained will be required for environmental purposes, lab-field data correlations, and long-term stability projections.

Task 3. Generic Porous Media Stability Experiments

Experimental studies conducted in simulated CAES conditions included tests to determine: 1) well casing corrosion, 2) permeability stability of sandstone, and 3) permeability/compressibility relationships in sandstone. The first two tests were conducted in autoclave pressure vessels and the third test in a flow loop system at Terra Tek, Inc.

The acceptance testing of the CAES porous media flow facility was initiated and experiments designed to investigate the following properties of reservoir rock: 1) permeability, 2) stress-strain behavior, 3) desaturation rates, and 4) cyclic fatigue. Each of these properties can be continuously monitored as a function of the following variables: 1) temperature, 2) time, 3) air humidity, 4) effective stress, and 5) pore pressure.

TECHNICAL PROGRESS

Task 1. Equipment Development and Acceptance Testing

The construction of the porous media flow facility was completed and acceptance testing initiated early in FY-1981. Basically, the system can be subdivided into four segments: 1) a heated, compressed air line, 2) a heated, steam line, 3) a pressurized hydraulic fluid line, and 4) a test cell enclosing the rock sample. The acceptance tests were designed to ensure proper operation of each of these subsystems. During FY-1981, the following acceptance tests were completed: 1) system leak and pressure tests, 2) air flow control system, 3) steam system, 4) electric valve control system, and 5) auxiliary trace heater system. The hydraulic system acceptance tests are currently in progress.

Other laboratory efforts that have involved the development of equipment needed for support of the experimental and field programs are:

- The purchase and installation of a heavy duty core driller necessary to prepare rock cores for the CAES porous media flow facility

- The repair and modifications of the thermal equipment by the manufacturer to correct malfunctions encountered during the first year of experimentation.
- The installation and testing of titanium autoclave pressure vessels needed to conduct rock/ground water compatibility tests on CAES field site samples.

Task 2. Aquifer Field Test Support

St. Peter sandstone and ground water samples from the CAES field site in Pittsfield, Illinois, were received from Dames and Moore. The 150 ft of core and ground water samples were examined, cataloged, and several laboratory tests were completed. The apparent porosity of eleven sandstone samples recovered from depths between 707 and 735 ft measured between 12 and 18%. The nitrogen gas permeability of 60 St. Peter sandstone samples were measured at room temperature. Average permeabilities parallel and perpendicular to the bedding were 576 and 695 millidarcies, respectively. There was considerable scatter in the data caused by the friable nature of this sandstone. However, the limited amount of laboratory data suggests the permeability of St. Peter sandstone is essentially isotropic.

Future experimentation includes physical/chemical compatibility studies of St. Peter sandstone and its native ground water under anticipated CAES conditions. The compatibility will be determined by exposing field samples of St. Peter sandstone and ground water in an autoclave supporting the pressure-temperature environment anticipated at the CAES field site. Two titanium autoclave pressure vessels needed for this experiment are currently being tested.

Task 3. Generic Porous Media Stability Experiments

An experimental study addressing the possible interactions of air and water on a reservoir sandstone under CAES environmental conditions was completed. In this study, Galesville sandstone cores were reacted in autoclave pressure vessels supporting one of four environments: 1) dry

air, 2) heated, air-water vapor, 3) heated, nitrogen-water vapor mixtures, and 4) heated, compressed, liquid water. The simulated CAES environments were maintained in autoclave pressure vessels by controlling the following independent variables: 1) temperature, 2) pressure, 3) time, 4) oxygen content, 5) carbon dioxide content, 6) nitrogen content, and 7) liquid volume. The dependent variables studied were: 1) apparent porosity, 2) gas permeability, 3) water permeability, and 4) friability. These variables were measured at ambient temperature and pressure before and after each sandstone sample was reacted in one of the CAES environments.

The experiments gave the following results:

- The Galesville sandstone exhibited excellent stability in dry air at all temperatures tested (50° to 300°C).
- Significant physical alterations occurred in sandstone samples exposed to liquid water above 150°C.
- 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, both permeability increases and decreases were observed.
- Sandstone may be a suitable storage media for heated humid air provided elevated temperature zones are relatively free of mobile liquid water.

Figure 11 illustrates changes in the gas permeability of sandstone samples as a function of temperature and humidity that were observed in this study.

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

Results of the corrosion study are given in Table 5 and Figure 12. The only significant corrosion product identified was hematite, an iron oxide. As expected, corrosion rates increased with temperature and

FIGURE 11. Percent Change in Gas Permeability with Temperature

TABLE 5. Corrosion Rates (mm/yr)*

Piping Casing	Temperature	
	175°C	300°C
A120	0.036 ± 0.009	0.070 ± 0.022
H40	0.056 ± 0.013	0.078 ± 0.015
H53B	0.064 ± 0.008	0.063 ± 0.001

*Test Conditions: 100% Humid Air (Salt Solution Reservoir), 12.1 MPa (120 atm) 336 Hr.

FIGURE 12. Corrosion Data for Carbon Steel A120 Well Casing Material

decreased with time due to 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 are not strongly adhered to the metal.

Permeability/compressibility tests for consolidated sandstones under simulated CAES operating reservoir conditions were conducted at Terra Tek, Inc. These tests were motivated by previous studies at Stanford, Texas A&M, and the University of California at Berkeley, where researchers have observed that the permeability of sandstones subjected to distilled water can decrease by 60 percent or more over the temperature range of 25 to 150°C. However, no systematic change in permeability has been observed for sandstones when dry gas is used as the working fluid. No data exist for humidified air, however, and it is uncertain whether the sandstone response to humidified air would mirror liquid-water or dry-gas results. Since the CAES porous media flow facility (offering controlled humidity, temperature, stress, and flow conditions) is not yet available, it is decided to investigate the cause(s) of permeability degradation in a liquid-water environment.

This laboratory study focused on one component of the reservoir stability question, the temperature sensitivity of sand and sandstone intrinsic permeabilities. Ottawa sand and Massillon sandstone samples were exposed to a hydrostatic confining pressure of 150 bars, a pore fluid pressure of 60 bars, and temperatures 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 a function of temperature and time. Potential permeability damage mechanisms were investigated including porosity reduction via internal and/or external particle plugging.

Important results are summarized in Figures 13, 14, and 15. Figures 13 and 14 illustrate the permeability degradation of Massillon sandstone and unwashed Ottawa sand as a function of temperature. Figure 15 illustrates a similar experiment for Massillon sandstone and unwashed Ottawa sand employing inline upstream filters.

It is concluded that apparatus contamination in the form of metal oxide or hydroxide colloids accounts for most of the permeability degradation with temperature observed in the early phases of this study. Elimination of aluminum and zinc sources and employment of small micron upstream filters seems to have essentially eliminated the contamination problem for this particular study. Under the relatively low effective

FIGURE 13. Permeability Ratio for Ottawa Sand at 25°C and 150°C

FIGURE 14. Permeability Ratio of Massillon Sandstone at 25°C and 150°C

FIGURE 15. Permeability Ratio Versus Temperature

stress and temperature conditions used in this study, temperature-induced creep compaction and thermal expansion of constituent minerals have negligible impact on porosity and thus presumably 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.

PUBLICATIONS

R. L. Erikson, J. A. Stottlemire, and R. P. Smith, An Experimental Study of the Response of the Galesville Sandstone to Simulated CAES Conditions, "PNL-3399, July 1980.

R. P. Elmore and J. A. Stottlemire, Corrosion of Well Casings in Compressed Air Energy Storage Environments, PNL-3429, October 1980.

J. A. Stottlemire and C. H. Cooley, "Temperature-Induced Permeability Alterations in Unconsolidated and Consolidated Aquifer Media," IECEC Conference, Seattle, WA, August 1980.

J. A. Stottlemire, C. H. Cooley, and G. J. Banik, "Temperature Sensitivity of Ottawa Sand and Massillon Sandstone Intrinsic Permeabilities," Proc. of 22nd Annual Rock Mechanics Symposium, Boston, MA, August 1981.

4.1.1c Assessment of Thermomechanical Properties of Caprock and Reservoir for Compressed Air Energy Storage in Porous Media

J. D. Blacic, P. D'Onfro, G. Bussod, and P. M. Halleck

Los Alamos National Laboratory

OBJECTIVE

Objectives of the program are 1) to assess the effects of temperature, effective pressure, and cyclic stress on elastic constants and compressive strength of a typical CAES porous reservoir rock; and 2) to determine the effects of dehydration and temperature on the tensile strength of a typical CAES caprock. The deliverables are a) identification of changes in properties and b) characterization of these changes, including identification of physical mechanisms if possible, for inclusion in models of porous media CAES systems.

TASKS

Task 1. Elastic Constants and Compressive Strength of Porous Reservoir Rock

Experiments are performed in which samples of a typical porous medium (Galesville sandstone, Illinois) are deformed in compression to determine Young's modulus, Poisson's ratio, and ultimate strength. These properties are determined at temperatures of 37, 120, and 204°C; confining pressures of 0.5, 20.3, and 41.4 MPa and gas pore pressures of 0 and 10.3 MPa. All samples are water saturated.

Task 2. Low Stress Cyclic Loading Effects on Elastic Constants and Compressive Strength of Porous Reservoir Rock

Experiments are performed on Galesville sandstone in which compressive stresses of 10 to 30% of the failure stress is applied repeatedly for 100, 1,000, or 10,000 cycles. Young's modulus and Poisson's ratio are measured and compared before and after cyclic loading to identify cyclic loading effects. Ultimate strength is determined after cycling and compared to results from Task 1. The same ranges of temperature and pressures as in Task 1 are used.

Task 3. Tensile Strength Properties of a Caprock

Indirect Brazil tests are used to determine the tensile strength of Kinderhook shale samples from the Pittsfield, Illinois field project. Samples are tested in the water saturated conditions at 23°C and 93°C to determine temperature effects. In order to evaluate possible effects of clay mineral dehydration on tensile strength, samples are also tested at 23° and 93°C after several days of drying. Samples are tested in orientations such that the fracture plane is either parallel or perpendicular to bedding in order to evaluate anisotropy of tensile strength.

TECHNICAL PROGRESS

Task 1. Elastic Constants and Compressive Strength of Porous Reservoir Rock

This task is complete.

Most details of Task 1 were reported last year. A brief summary of results is given below along with some details not previously covered. Elastic and strength properties of Galesville sandstone were experimentally determined at temperatures over the range 37 to 204°C and effective confining pressures of 0 to 32 MPa. Young's modulus increases from 30 to 60 GPa with increasing temperature and effective pressure. Poisson's ratio decreases from 0.3 to 0.1 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.

A summary of the ultimate compressive strength tests is shown in Figure 16 in the form of a shear stress versus effective normal stress plot for the temperature range 37 to 204°C. Combinations of shear stress and normal stress that plot above the experimentally determined strength envelopes are unstable, those below the envelopes are stable. Nonlinearity

FIGURE 16. Mohr Failure Envelopes of Galesville Sandstone for Three Temperatures. The shaded semicircle represents states of stress for an operating porous medium CAES reservoir.

of the envelopes compared to Berea sandstone is due to plastic deformation of the dolomite cement in Galesville sandstone. Expected operating ranges of stress for a porous medium CAES reservoir shown shaded in Figure 16 indicate a substantial safety factor. However, coefficients of sliding friction along fractures determined in our experiments (shown in Figure 17) 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.

Task 2. Low Stress Cyclic Loading Effects on Elastic Constants and Compressive Strength of Porous Reservoir Rock

This task is complete.

FIGURE 17. Coefficient of Sliding Friction on Fracture Planes vs. Effective Confining Pressure for Galesville Sandstone

Details of experiments to evaluate effects of cyclic stress on elastic constants and strength were reported previously. Results indicate that for up to 1,000 cycles there is generally no significant change in elastic constants of Galesville sandstone. However, at 10,000 cycles there are marked, but somewhat inconsistent, changes 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 this property.

GENERAL CONCLUSIONS FOR A POROUS RESERVOIR

- Increasing temperature, effective pressure, and cyclic stressing all have the effect of densifying the sandstone. This could result

in an increasing injection/retrieval impedance with time. However, this effect may be counterbalanced by:

- sliding motion along pre-existing joints, cracks, bedding planes, etc. which is likely to be enhanced by increasing temperature and pressure leading to a reduced reservoir impedance
- No phenomena have been identified in our experiments that would prevent successful operation of a porous CAES reservoir.

Task 3. Tensile Strength Properties of a Caprock

This task is complete.

Tensile strength of Kinderhook dolomitic shale was measured under dry and water saturated conditions at 23°C and 93°C. 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 are from a continuous core section, and in most cases alternate samples along the core were tested at 23°C and 93°C so as to reduce sample variability effects.

Tensile strength of Kinderhook shale is quite variable (Figures 18 and 19) 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 compared to 23°C. Since all tests were water saturated this weakening is probably not a result of clay contraction but to generation of pore pressures due to differential thermal expansion of the rock constituent minerals and water in pores. It is conceivable that this effect could cause total weakening at higher temperatures if pore pressures exceeding the local rock confining pressure occurred.

Figure 19 shows that samples tested parallel to bedding are only slightly weaker than those perpendicular to bedding (Figure 18). However,

FIGURE 18. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated. Fracture plane is perpendicular to bedding.

it should be kept in mind that our test samples are very small compared to reservoir scale. We would expect to see a substantially lower tensile strength along thicker coal seams and other stratigraphic breaks but these occur on a scale such that they are generally not included in our test samples.

When the 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 within 10 minutes of the beginning of drying. One would think that this cracking would weaken the samples in tension but, as shown in Figure 20, this appears to be more than offset by a strengthening of the rock matrix minerals. Average tensile strength parallel to bedding at 23°C is about

FIGURE 19. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Water Saturated. Fracture plane is parallel to bedding.

FIGURE 20. Tensile Strength Versus Core Depth for Kinderhook Shale at 23° and 93°C, Dry. Fracture plane is perpendicular to bedding.

three times higher in the dry samples compared to the 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 further increases tensile strength. The samples become brick-like. The large scatter in tensile strength of the dry samples compared to the water saturated samples is probably due to inhomogeneous cracking upon dehydration.

GENERAL CONCLUSIONS FOR A CAPROCK

- Tensile strength of a water saturated shale caprock may be reduced by a factor of two or greater if exposed to modestly elevated temperatures. The weakening mechanism should be positively identified so that implications and possible mitigating procedures can be evaluated.
- On a small scale, dehydration can increase the tensile strength of shale by a factor of three or more despite the occurrence of shrinkage cracking. The effect of dehydration on tensile strength of shale on a large scale should be evaluated. A way might be found to strengthen the injection hole region where it penetrates the caprock by careful drying of the borehole wall at low pressure before operation.
- Small scale (< 5 cm) anisotropy in tensile strength of a CAES caprock is probably not important. However, effects of possible large scale tensile strength anisotropy of a caprock should be evaluated.

PUBLICATIONS

J. D. Blacic, P. H. Halleck, P. D'Onfro, and R. E. Riecker, "Thermomechanical Properties of Galesville Sandstone," Amer. Geophy. Union Mono., in press.

4.1.1d Effects of Air Ventilation on Porous Rock

R. D. Allen

Pacific Northwest Laboratory

This is a compilation of research performed by the University of Wisconsin-Milwaukee for Pacific Northwest Laboratory under subcontract B-82289-AK.

OBJECTIVE

Laboratory studies of specimens prepared from various candidate CAES reservoir and associated caprock formations were conceived to achieve four program objectives:

- Evaluate the effects of cyclical air ventilation upon reservoir rocks and caprocks at various temperatures and pressures. These effects were to be determined by measurement of rock properties before and after exposure.
- Contribute to the development of CAES site-qualification criteria.
- Identify geological parameters which will require field monitoring.
- Assist in developing monitoring systems for operating installations.

TASKS

This project has been conducted in FY-1977 through FY-1980. The tasks necessary to fulfill project requirements are itemized and briefly explained below. Results achieved in FY-1977 through FY-1979 are also presented. Under "Technical Progress" the discussion stresses developments during FY-1980.

Task 1. Design and Construct Laboratory Equipment

Most aspects of design and construction were completed before FY-1980. The equipment allows cyclic reversible flow tests at elevated temperature on confined samples using dry, compressed air. Typical experimental

conditions are: pressure-550 kPa, temperature-120°C, and number of cycles-2000.

Task 2. Collect Specimens and Determine Detailed Local Geological Structures

Most field work took place before FY-1980. Sandstone specimens were taken from the Berea, Jordan, St. Peter, Mt. Simon, and Franconia formations. Carbonate specimens were taken from the Bedford, Salem, Platteville, and Knox formations. Sandy shales were taken from the Eau Claire and Mt. Simon formations.

Field work has been conducted in Wisconsin, Minnesota, Iowa, and Illinois. Outcrops in these states have been sampled and drill core samples have been obtained from Illinois and Indiana. In this study, only quartz sandstones have been considered in detail as potential storage media. Some carbonates with secondary porosity might be effective, but many are characterized by large variations in permeability and porosity and all are susceptible to dissolution.

Task 3. Ventilate Specimens Under Experimental Design Conditions

Before FY-1980 403 specimens were ventilated. The first experiments approaching in situ CAES conditions were performed in FY-1978. Parameters included: air temperature-110°C, confining pressure-up to 820 kPa, cycling-1000 cycles in four days, and mean air velocity through high permeability rock-16 cm/s.

In FY-1979 operations were concentrated on six sandstones, two shales and two carbonates. Replication and statistical analysis were stressed. Parametric ranges were: air temperature-120° to 200°C, confining pressure-550 to 5170 kPa, air pressure drop across specimens-up to 1100 kPa, and 2000 to 3000 cycles.

Task 4. Measure Properties and Correlate with Ventilation

The following mechanical and physical properties have been measured: Young's modulus, compressive strength, porosity, permeability, specific heat, thermal conductivity, and thermal expansion.

Early conclusions are itemized below:

- 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 which were also the purest quartz sandstones studied.
- Where Young's modulus and compressive strength changed significantly, the mean values increased and the variances decreased with ventilation.
- Permeability is changed significantly by ventilation. The net change is an increase, the rocks with smaller original permeability showing larger increases.
- Thermal properties are relatively unaffected by cyclic ventilation.

Task 5. Analyze Microstructure and Correlate with Ventilation

Microstructure involves size, shape, arrangement and orientation of grains, pores, and microfractures. Optical diffraction analysis was used to represent input microstructural orientation and spatial frequency data in polar coordinates. No significant changes in microstructure and in porosity were detected as a result of ventilation.

Task 6. Analyze and Interpret the Combined Data

The following conclusions were drawn from experiments through FY-1979.

- Moderately well cemented St. Peter sandstone, though 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.
- Although the results obtained should be useful in determining some of the possible effects of CAES on rock, confining pressure used during testing was much less than the lithostatic pressure expected in a CAES reservoir.

- To characterize the structure and lithology of the potential reservoir rock and associated caprock, subsurface drilling and core recovery are needed. Most specimens used in the cyclic ventilation study were from surface exposures.

Task 7. Study Regional Geology for Identification of Possible Storage Sites

In FY-1979 the potential for CAES in the Paleozoic sandstones of southeastern Minnesota was described as attractive based upon both field and laboratory studies.

TECHNICAL PROGRESS

This section addresses events in FY-1980 and general conclusions from the project.

Task 1. Design and Construct Laboratory Equipment

Equipment was designed and constructed to enable cyclic displacement of an air-water interface in core samples of reservoir rock. Air-water and dry air experiments were performed on St. Peter sandstone. No significant changes in properties were detected in either type of experiment.

Task 2. Collect Specimens and Determine Detailed Local Geological Structures

Core samples (10 cm diameter) of Mt. Simon sandstone were obtained from three locations within the Crescent City gas field which is located in Iroquois County, IL.

Task 3. Ventilate Specimens Under Experimental Design Conditions

Cyclic ventilation was performed on core samples of Mt. Simon sandstone and outcrop samples of St. Peter sandstone. Specimens ventilated with dry air totalled 112 whereas specimens cycled with the air-water interface totalled 53.

Task 4. Measure Properties and Correlate with Ventilation

Work performed in FY-1980 indicates that the critical variables of air movement affecting properties of susceptible reservoir rocks are

flow-rate and temperature. Of still greater importance is the make up of the rock itself. Based on several years of study, the best candidate for reservoir rock appears to be clean quartz-sandstone, medium- to coarse-grained, well-sorted, and moderately cemented with silica. The best example of such a rock from among those studied is the St. Peter sandstone.

The most sensitive dependent variable appears to be permeability. In some rocks the permeability increases with ventilation, and in others it decreases. In the Mt. Simon, the mean decrease was less than 2%. Porosity, compressive strength, and Young's modulus appear to show no adverse changes with ventilation. Thermal properties show no significant changes with ventilation.

Task 5. Analyze Microstructure and Correlate with Ventilation

Fabric analysis by optical correlation indicates no significant changes with cyclic ventilation; this conclusion is supported by microscopic examination. In the case of one-directional ventilation, optical diffraction analysis does indicate changes that could be explained by transport of fines.

Additional studies of the effects of cyclic displacement of the air-water interface in the St. Peter have yielded results entirely consistent with those obtained for dry-air ventilation of the St. Peter, that is, no significant changes in properties or fabric. This is an important conclusion, because it indicates that water did not affect the stability of rocks tested.

Task 6. Analyze and Interpret the Combined Data

Based on the parameters studied in the foregoing studies, the reservoir rock should be a clean quartz-sandstone. 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, particularly in the project's study area, tend to be cleaner (purer) 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 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.

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. Since 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 thermo-mechanical responses.

Jointing in the reservoir rock might increase 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.

Some Cambrian and Ordovician sandstones of the upper midwest include units that have the desirable physical characteristics for CAES and, in addition, are sufficiently deep, thick, and extensive.

Carbonate rocks, particularly with secondary porosity, might also be satisfactory reservoirs for a CAES system. Spatial variations in permeability and porosity and chemical susceptibility render these less desirable than the better quartz sandstones, but they might prove to be practical where sandstone is absent.

In considering any reservoir rock for CAES, the associated caprock's properties deserve equal attention. Also, interactions between the reservoir rock and the caprock must 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 have a profound effect on 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, both vertical and inclined, and accompanied by property-testing of the drill cores, would address these problems.

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 exploration targets.

Task 7. Study Regional Geology for Identification of Possible Storage Sites Promising Areas for CAES in Aquifer-Type Rocks

Based on studies conducted by personnel in this project, the following areas in the upper midwestern United States hold promise for CAES in aquifer-type rocks:

- Marshall states that a large area in the southern part of southeastern Minnesota has good potential for storage in Paleozoic sandstones. He suggests the following reservoir/caprock pairs: 1) Mt. Simon/Eau Claire, 2) middle Eau Claire greensand/upper Eau Claire, and 3) Galesville/Franconia.

- Gross has studied the area of eastern Iowa and southwestern Wisconsin and concludes that there are three possible reservoir/caprock pairs: 1) Mt. Simon/Eau Claire, 2) Galesville/Franconia, and 3) St. Peter/Glenwood and Maquoketa. Both Marshall and Gross conclude that suitable structures appear to be concentrated along the midcontinent gravity high, which extends from northwestern Wisconsin through northcentral Iowa to Kansas.
- Hopper states that 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.

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. Of course, acquisition of such sites might be accompanied by large legal, economic, and environmental burdens.

PUBLICATIONS

H. J. Pincus, Underground Compressed Air Energy Storage, Rock Mechanics and Geology Components, Annual Report - 10/1/79-9/30/80, report to Pacific Northwest Laboratory by University of Wisconsin-Milwaukee, Milwaukee, WI 53201, October 1980.

Theses

O. Gross, Compressed Air Energy Storage in Cambro-Ordovician Sandstones of Eastern Iowa and Southwestern Wisconsin. M.S. thesis, University of Wisconsin-Milwaukee, Milwaukee, WI, 1980.

A. Pujol-Rius, The Effects of Cycling an Air-Water Interface in St. Peter Sandstone. M.S. thesis, University of Wisconsin-Milwaukee, Milwaukee WI, 1980.

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

D. Meiri, Analysis of Compressed Air Aquifer Storage by Finite Element Method, Ph.D. thesis, University of Wisconsin-Milwaukee, Milwaukee, WI, 1979.

4.1.1e Field Studies of an Aquifer Reservoir

R. D. Allen

Pacific Northwest Laboratory

OBJECTIVE

Field studies of porous rock reservoirs were conceived to fulfill four program 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 and recovery, water production, and entrainment of mineral particulates.

TASKS

The program is divided into three broad phases: I. Field Test Plan and Preliminary Site Screening, II. Site Acquisition and Exploration, and III. Site Development and Operations. Within these phases nine discrete tasks are identified. Phase I embraces Tasks 1 through 3. Phase II consists of Tasks 4 and 5. The remaining tasks make up Phase III.

Task 1. Develop Aquifer Field Test Plan

A field test plan was developed to embrace all program activities, i.e., technical, scheduling, contractual and financial.

Task 2. Identify Necessary Site Characteristics

This task involved defining geological and depth requirements of the site.

Task 3. Perform Regional Site Screening and Select Candidate Sites

Task 3 involved a) screening of geologic data from all available sources, b) evaluating the top ranking sites and, c) recommending a site for further development.

Task 4. Acquire Testing and Development Rights

This task required the drafting of land leases to permit seismic exploration, confirmatory drilling, and subsequent site development. The last item includes building of access roads, erection of utility lines, installation of a surface facility, drilling of wells in defined locations for air injection and reservoir monitoring, instrumentation of wells, air injection/cycling, and final coring near the injection well. Leasing was scheduled to take place after suitable public relations activities to explain the program. A land acquisition firm provided direct contacts with the landowners.

Task 5. Qualify Test Site for Development

This task is initiated by drilling of a single well to measure the seismic velocity profile from the surface through at least the upper portion of the reservoir rock. Shallow high resolution seismic reflection surveys were then used to locate potential small structural traps, e.g., second order domes or closed anticlines. Confirmatory holes were used to a) log the stratigraphy, b) develop structure contour maps of a key horizon, c) obtain cores for laboratory qualification of caprock and reservoir rock physical properties, and d) obtain ground water samples for analysis.

Task 6. Develop Site by Drilling, Instrumentation, and Installation of Surface Plant

The injection/monitoring well geometry is determined by the configuration of the structural trap chosen. The injection/withdrawal well will be monitored at various radial and vertical coordinates by thermistors and thermocouple psychrometers in closed-instrument wells; and piezometers in packer-isolated wells at various depths. Compressed air tracer tests may be performed in the closed-instrument wells to follow CAES reservoir development. The surface plant will include compressor/receiver, pressure regulator, heater, flow meter, hygrometer, thermistors, circuit control valves, outlet muffler, and bypass test loop.

Task 7. Conduct CAES Field Tests

Injection of cool air will occur for up to six months to develop the original air bubble. Air cycling at ambient temperatures will be followed by cycling at incrementally higher temperatures from 50°C (122°F) to 200°C (392°F). Physical characteristics of reservoir performance and air injection/withdrawal will be monitored.

Task 8. Conduct Pre- and Post-Test Coring and Laboratory Analysis

Pre- and post-test cores of reservoir rock and caprock will be compared with respect to mineralogy and microstructure, rock mechanical properties, permeability and porosity, thermal properties, and residual water content and composition. The threshold pressure of the caprock from near the injection wellbore will be compared with the original value.

Task 9. Analyze Field and Laboratory Data

Changes in reservoir and caprock physical, chemical, mineralogical, and biological properties (if relevant) will be evaluated. Results will be compared to numerical modeling and laboratory predictions. System characteristics and performance with time will be evaluated. Overall results will be extrapolated to predict full scale system performance. Design and stability criteria will be modified to incorporate field experimental conclusions.

Task 10. Decommission Facility and Restore Site

All items of equipment, structures, foundations, pipelines, and utility lines and connections will be removed. All wells will be grouted in accordance with the rules and regulations of the State of Illinois, relating to the abandonment of oil and gas wells. All damages caused by construction, operation, ingress, and egress will be repaired or compensated. The land will be restored, as nearly as practicable, to its original condition.

TECHNICAL PROGRESS

Task 1. Aquifer Field Test Plan

This task was completed in FY-1980. The field plan includes program management, site-selection procedures, test plan development, field set up and operation, activities for FY-1980 through 1982, and projected expenditures. The test plan will evolve during the program requiring periodic updating.

Task 2. Site Characteristics

This task was completed in FY-1980. The site criteria adopted include:

- Reservoir depth - ca. 200 m (656 ft)
- Reservoir rock - high purity, moderately cemented quartz sandstone
- Reservoir thickness - > 5 m (16.4 ft)
- Reservoir radius - ca. 100 m (328 ft)
- Reservoir permeability - > 300 md
- Reservoir porosity - at least 10%
- Reservoir pore volume - up to 10^6 m^3 ($1.307 \times 10^6 \text{ yd}^3$)
- Caprock lithology - impermeable carbonate or shale
- Caprock thickness - > 6 m (19.7 ft)
- Caprock threshold pressure - > 1380 kPa (200 psi)
- Structure - second order dome or "closed" anticline with slope less than 15°
- Vertical closure - > 5 m (16.4 ft)

Task 3. Site Selection

Eleven candidate sites were identified in the Illinois Basin. These were chosen for screening on the basis of stratigraphy, structure, accessibility, and favorable lithology. The following criteria were used to rank candidate sites: 1) available detailed exploration data; 2) absence of petroleum higher in the structure; 3) reservoir bed not too deep for economical field experiment; 4) reservoir bed not too shallow to retain air at suitable pressure; 5) no known structural deficiency 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 emerged as the most favorable structure for detailed exploration.

The Pittsfield dome is a doubly plunging anticline extending about 25 km (17 mi) WNW of Pittsfield. A suitable caprock sequence consists of the Joachim dolomite (10 m thick), the Platin 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/Jochaim contact is 197 m (645 ft) below ground surface. Two second order closures were described about 3.2 and 8.1 km (2 and 5 mi) WNW of Pittsfield. These were tentatively identified from structure contour mapping of the uppermost Silurian as shown in Figure 21. Within the St. Peter, these closures are potential reservoirs for injection, storage, and withdrawal of compressed air.

Task 4. Testing and Development Rights

The basic land acquisition instrument in use is the "Option and Air Storage Easement and Lease". This instrument includes every potential activity, i.e., multiyear option, seismic exploration, drilling exploration, surface plant development, and air injection and storage. The contents of this document were developed by an Illinois law firm specializing in oil and gas leases, Pacific Northwest Laboratory, and Coates Field Service, Inc. In addition, an "Underground Air Storage Easement" and a limited exploratory drilling permit were prepared for "special situations".

FIGURE 21. Structure Contours and Seismic Traverses near Pittsfield, Illinois

Forty parcels of land, averaging about 150 acres each, have been leased. Detailed site characterization indicates that the NE 1/4 of Section 21 is one favorable area for reservoir development. No additional leases are required for this project to proceed.

Task 5. Qualify Test Site

Structural site characterization proceeded in three stages: 1) initial drilling, 2) seismic surveying, and 3) confirmatory drilling. The first hole was drilled about midway between the apparent closure centers to supply the following: 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: vertical - 695 m and horizontal - 576 md. Average porosity was 19.8%. 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 1380 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 was conducted along eight east-west and north-south trending lines as shown in Figure 21. 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 $9 \text{ m} \pm 2 \text{ m}$ ($29.5 \text{ ft} \pm 6.6 \text{ ft}$) for closure. Both are within preselected specifications. The second small anticline, 8.1 km (5 mi) WNW of Pittsfield, was not as well defined.

A second deep borehole was drilled to begin confirming the better defined 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. 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 is a diagnostic key bed which was used for the following reasons: 1) few existing wells penetrate the St. Peter; 2) although more wells penetrate the Silurian than the Ordovician Maquoketa, 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 data from lithologic and gamma logging of these 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.

The program concluded with the boring of two deep holes into the upper region of the better defined anticlinal structure. These were necessary 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 solids. Dominant cations were Ca^{++} , Mg^{++} , K^+ and Na^+ .

Dominant anions were Cl^- , $\text{SO}_4^{=}$, and HCO_3^- . Significant quantities of boron, silica, strontium, and ammonia were found. The pH was 8.07.

The combined interpretation of drilling and seismic reflection results has identified the structure shown in Figure 22. Nearly 15.2 m (50 ft) of closure is indicated within an area of about 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 about 0.017 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 22. Structure Identified Near Pittsfield, Illinois

Task 6. Develop Site and Operate Test

PNL's request for proposal B82313-A-L, "Field Evaluation of Compressed Air Energy Storage Within an Aquifer" caused response by an adequate number of qualified bidders. On technical merit, PB-KBB, Inc., of Houston, Texas, was selected to conduct Phase III. Site development now under way includes land leasing, injection well permitting, development of surface plant layout and road access, and arrangement for utility connections. The injection/withdrawal well is to be bored, cased, and instrumented before June, 1981, subject to application approval by the Illinois Environmental Protection Agency. Numerical modeling will use geologic and geometric parameters specific for the injection location to provide quantitative inputs to field design decisions. The final design of the compressor plant, monitoring well field and instrumentation, and ancillary equipment is scheduled for completion in August, 1981. Injection of the air bubble and air cycling experiments are scheduled for 1982.

PUBLICATIONS

R. D. Allen and P. J. Gutknecht, Porous Media Experience Applicable to Field Evaluation for Compressed Air Energy Storage. PNL-3294, Pacific Northwest Laboratory, 1980.

R. D. Allen, J. S. Trapp, and T. E. Jensen, "Site Characterization for Injection of Compressed Air into an Aquifer," 22nd U.S. Symposium on Rock Mechanics, June 29-July 2, 1981, Cambridge, MA.

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

L. D. Kannberg, T. J. Doherty and R. D. Allen, "Aquifer Field Test for Compressed Air Energy Storage," 16th Intersociety Energy Conversion Engineering Conference, August 9-14, 1981, Atlanta, GA.

N. Rudd and R. D. Allen, "Field Studies of Porous Rock Reservoirs," Proceedings of Mechanical, Magnetic, and Underground Energy Storage 1980 Annual Contractors' Review, CONF-801128, Washington, DC, 1980.

4.1.2a Numerical Modeling of Compensated Compressed

Air Energy Storage Systems

T. Brandshaug and A. F. Fossum

Re/Spec Inc.

OBJECTIVE

The objective of this program is to develop and use numerical models to evaluate the behavior of compensated CAES caverns in hard rock and to establish a methodology for the development of stability criteria.

TASKS

The program is divided into the following five tasks:

Task 1. Parametric Operational Thermoelastic Stress Analyses for CAES Caverns

This task involves finite element calculations of the thermoelastic stress states in the rock mass around caverns of different shapes and spacings for ranges of in situ stress, cyclic internal cavern pressures, and cyclic wall temperatures. The predicted temperature, stress, strain, and potential failure zones could be interpreted by designers to provide crude estimates of potential necessary support measures.

Task 2. Air Leakage

The goal of this task is to develop an air leakage model that would permit locally ubiquitous jointing and air leakage. The model should include lithostatic pressure, lateral stress, hydrostatic cavern operating pressures, and rock mass conductivity.

Task 3. Complementary Support

The objective of this task is to obtain a survey and evaluation of the design, construction, and operating procedures for underground storage caverns in Scandinavia. This information should be used to complement the numerical analyses results in arriving at a rational set of guidelines for the design of CAES caverns.

Task 4. Special Topics

The goal of this task is to predict the effectiveness of remedial support activities related to cavern stability by numerical modeling.

Task 5. Numerical Modeling of the PEPCO Site

The purpose of this task is to evaluate the Acres American design of PEPCO with the Re/Spec CAES analysis methodology and identify areas where the Acres design differs significantly from that developed from Re/Spec stability criteria methods. Data for the analysis should be provided by the Re/Spec laboratory efforts.

TECHNICAL PROGRESS

Task 1. Parametric Operational Thermoelastic Stress Analyses for CAES Caverns

A numerical CAES simulation model was developed previously by Re/Spec that is capable of modeling: 1) the material characterization of the rock, including the intact and jointed rock mass behavior within both the elastic and inelastic regimes; 2) the geometrical construction sequence of the CAES cavern; 3) the cyclic variation in temperature and pressure within the cavern and the associated rock response; and 4) the motion of air or water within the rock mass. This model consists of discrete, but quasi-statistically coupled, submodels of particular phenomenological events.

Numerical simulations and parametric analyses were conducted for the construction and operation of hypothetical CAES caverns with the use of these numerical procedures. Excavation stress modeling results were incorporated into empirical guides for excavation stability that take into account rock classifications based on rock mass strength, in situ stress, and maximum compressive stress concentrations along a cavern periphery. Transient and quasi-steady heat transfer simulations were made for the cyclic heating and cooling of CAES caverns corresponding to the emptying and filling of hot air and cold water during the daily

charge and discharge operations. Thermoelastic and failure analyses of intact and jointed rock were made making use of the temperature fields calculated in the heat transfer simulations.

The air and water temperatures assumed in the thermal analyses were 40°C and 10°C, respectively. It was found that after 50 operational cycles, the rock temperatures approached a steady oscillatory behavior within the first meter into the cavern walls. Since both the roof and the floor were maintained at constant temperatures of 40°C and 10°C, respectively, the temperature gradienty extended much farther into the rock at these two locations than into the walls. Figure 23 shows the temperature isotherms around a CAES cavern for different operational cycles. Relatively high thermal gradients exist in the rock all around the cavern. The thermal gradients in the roof and the floor diminish as operation continues; however, the gradient in the walls does not change substantially from the initial stage of operation.

The oscillatory behavior of the temperatures in the cavern walls leads to oscillatory behavior of the stresses as well. Figure 24 shows three types of cyclic behavior that can result, namely tension-tension, tension-compression, and compression-compression cycling. It was found

FIGURE 23. Temperature Isotherms (°C) Around a CAES Cavern for Different Operational Cycles

FIGURE 24. Principal Stress Trajectories Around a CAES Cavern for Different Operational Cycles

that for multiple caverns, extraction ratios could be found for which the tension-tension, and tension-compression cycling could be eliminated.

In the failure analyses performed for the operation phase, it was found that multiple caverns could be located in a competent igneous rock at 750 m without failure even after substantial strength reductions caused by fatigue or thermal shock were simulated. However for the cases considered, no tensile stresses had developed.

Task 2. Air Leakage

An air leakage model was developed and used to simulate an air tightness test of the Flygmotor CAES cavern system near Trollhatten, Sweden. Quantitatively, the results for air leakage were somewhat greater than actually occurred during the tests. However, coefficients of lateral earth stress could not be obtained and had to be assumed based on typical measured values in hard rock at a depth of about 100 m. Also two values of permeabilities were available. The empirical permeability/

stress relationship was derived with a bias towards the greater values of permeability. Qualitatively, air leakage simulations made with the use of stress-dependent permeability relationships, showed that the coefficient of lateral earth stress had only minor influence on the volume of air leakage. However, the location of leakage in the cavern is strongly dependent on the in situ stress ratio, with the higher value giving rise to a greater loss of air through the cavern walls.

Task 3. Complementary Support

A literature survey was made to accumulate knowledge that is currently available in underground excavation practice including a bulk of detailed precedent information, case history results, rock mass quality considerations, and support requirements based on precedent experience. In addition, attempts were made to gather as much information as possible on underground air storage caverns in Scandinavia including the world's first two air surge chambers. This information included methods for site selection and characterization, including geological data, selection of depth, orientation and cross section of caverns, methods and details of excavation and rock reinforcement, operating conditions, and testing procedures for liquid or gas leakage.

It was found that, based on information supplied by Re/Spec's subcontractor, Hagconsult AB of Stockholm, the Norwegians and Swedes have accumulated a vast amount of excavation experience dating back to the turn of the century. Stability and design criteria for underground openings have evolved through trial and error procedures over many years. Although empirically derived, these criteria have been used successfully in recent years in the design of numerous underground power plants.

Although most of this experience related to the excavation of underground openings under ambient conditions, the Norwegians have also been successful in building and operating compressed air surge chambers with operating pressures to 4 MPa. The only analysis of air leakage prior to construction was an observation of water permeability tests at the site. Thus, in light of their success, the Norwegians concluded that site investigations furnished a satisfactory basis for air leakage evaluations.

Although the Norwegians have experienced relatively low air leakage rates from their compressed air chambers, the Swedes have found that gas tightening procedures were necessary for the storage of LPG. Nonetheless, this experience tells us that the excavation of large caverns and the storage of compressed gas in these caverns seems to be within the state-of-the-art.

Task 4. Special Topics

It was found in the simulations of reinforcement measures that artificial support such as rock bolts provided little or no increase in structural stiffness or strength. This is not to say that rock bolting does not provide support. However the nature of the support is different than implied above. Rock bolts are used primarily to support blocks or pieces of rock occurring from intersecting joints, etc.

Generally speaking, there is adequate information available to enable a designer to design an underground opening with the size, shape, and depth required of a CAES cavern with regard to its excavation and construction, based on a combination of numerical modeling and precedent considerations.

The design methodology used in this study for the excavation phase of a CAES cavern can provide a guide in the evaluation of support requirements for caverns of different shapes when excavated in a rock mass with relatively well quantified rock properties and geotechnical characteristics. However, since the empirical information used in this design methodology often includes different types of rock masses in the same classification, different support could be called for in a site specific situation. Thus results obtained by this method should not be viewed as end results but as an indication that more or less consideration should be given to support measures. The empirical guides have generally been conservative.

Little precedent information is available on compressed air or gas cavern with features similar to those envisioned for CAES caverns and there is no data available for the thermal/mechanical cycling of

rock masses. Scoping calculations similar to those of this program are necessary to identify regions of high stress or zones of potential failure. Designs can then be modified to reduce potential problems. For example, the results of this program indicate that induced cyclic tensile stresses can be eliminated by choosing an adequate extraction ratio.

Since experience is non-existent or limited on the behavior of large rock masses subjected to the operating conditions of CAES caverns, it is recommended that numerical methods be used in combination with in situ tests to permit the development of a design methodology.

Task 5. Numerical Modeling of the PEPCO Site

The Acres American design of the PEPCO caverns was analyzed numerically with the Re/Spec CAES simulation models. Elastic stresses were determined for an array of four caverns following initial excavation. This information was then related to case history data for determination of artificial support requirements. Figure 25 illustrates the suggested support requirements based on case history studies. Figure 25 suggests that the cavern walls do not need any form of artificial support, while the roof will need light support.

The failure analysis for the pre-operational phase of the caverns was performed with a Mohr-Coulomb failure criterion with strength values obtained from tests on Sykesville gneiss. Figure 26 shows rock failure limited to a small region in the cavern roof and floor (outer caverns).

Thermoelastic operational analyses resulted in no tensile stresses along the cavern walls. Thus the cavern walls are subjected to cyclic compression-compression stress states. This type of stress state is the most favorable type at cyclic stress states from the standpoint of fatigue failure.

FIGURE 25. Support Requirements for the PEPCO Caverns as a Function of Rock Quality

Generally speaking, the PEPCO analysis strongly indicate that cavern stability can be maintained with minimal artificial support requirements both before and during CAES operations.

TECHNICAL PROBLEMS

No major technical problems have occurred that might have affected costs, schedule, or overall program objectives.

FIGURE 26. Failure Zones Around the PEPCO Caverns After Initial Excavation

PUBLICATIONS

P. F. Gnirk, T. Brandshaug, G. D. Callahan, and J. L. Ratigan, "Numerical Studies of Compensated CAES Caverns in Hard Rock," Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, U.S. Department of Energy, Division of Energy Storage Systems, Washington, D.C., August 1979, pp. 106-117.

P. F. Gnirk and A. F. Fossum, "On the Formulation of Stability and Design Criteria for Compressed Air Energy Storage in Hard Rock Caverns," Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, Boston, MA, August 5-10, 1979, v. 1, pp. 429-440.

T. Brandshaug, "Thermomechanical Assessment of Compensated CAES Caverns in Hard Rock," Proceedings of the 21st U.S. Symposium on Rock Mechanics, Rolla, MO, May 28-30, 1980, pp. 163-174.

M. L. Klasi, "On the Optimum Design of Rock Mechanics Parametric Studies with Numerical Models," Proceedings of the 21st U.S. Symposium on Rock Mechanics, Rolla, MO, May 28-30, 1980, pp. 566-569.

P. F. Gnirk and A. F. Fossum, "Synopsis of Stability and Design Criteria for CAES and UPHS in Hard Rock Caverns," ROCKSTORE 80 -- Subsurface Space, International Symposium for Environmental Protection, Low-Cost Storage and Energy Savings, Stockholm, June 22-27, 1980, pp. 615-622.

T. Brandshaug and A. F. Fossum, "Numerical Studies of CAES Caverns in Hard Rock," Proceedings of the 1980 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, U.S. Department of Energy, Division of Energy Storage Systems, Washington, D.C. November 10-13, 1980, pp. 207-212.

4.1.2b Laboratory Testing of Hard Rock Specimens Subjected to Loadings and Environmental Conditions Appropriate to a Compressed Air Energy Storage Cavern

A. F. Fossum
Re/Spec Inc.

OBJECTIVE

The program objective is to formulate preliminary design and stability criteria for compressed air energy storage (CAES) caverns based on laboratory investigations of the response of rock specimens to loading conditions typifying those of an operating CAES cavern. The design and stability criteria should relate to the unknowns which could affect the technical and economic feasibility of CAES caverns so that their long lifetime suitability can be assured and encouragement given to early commercialization of the CAES concept.

TASKS

The program was divided into the following five tasks:

Task 1. Determination of Significant Rock Properties

Gather information regarding the proposed operating conditions for CAES installations and for existing caverns of similar size and shape to permit an assessment of what rock properties are important and over what range of temperature and pressure they need to be known. Perform a literature search to determine the availability of the requisite rock properties at the appropriate environmental conditions. Evaluate techniques available from composite material mechanics for evaluating thermal properties from a knowledge of the thermal properties of a rock's constituent minerals and their volume percent.

Task 2. Procurement of Specimens

Select and procure for testing rock specimens of several typical CAES host rock types.

Task 3. Selection of Specific Procedures for Rock Characterization

Provide a geological description including the mineralogical composition of all selected rocks.

Task 4. Laboratory Testing

Conduct tests on rock specimens at room and elevated temperatures with dry and saturated moisture conditions. These tests should include indirect tension tests, unconfined compression tests, triaxial compression tests, anisotropic triaxial compression tests, mechanically cycled fatigue tests, thermally cycled fatigue tests and thermal conductivity tests. The tests should be designed 1) to determine the amount of strength and stiffness reduction caused by the non-ambient conditions associated with CAES, 2) to determine if the methods for estimating the shear strength-normal strength relationship are adequate over pressure ranges appropriate to CAES, 3) to determine if the methods for estimating thermal conductivity are adequate, and 4) to establish the amount and type of testing needed to define the properties of the rock adequately for CAES application.

Task 5. Establish Stability and Design Criteria

Scrutinize the results of this program and other PNL sponsored programs to arrive at a set of guidelines to be used by designers of CAES caverns.

TECHNICAL PROGRESS

Task 1. Determination of Significant Rock Properties

Information collected in this task revealed that the operating conditions in a CAES cavern will likely include 1) maximum air pressures of 7 to 7.5 MPa, because of turbine machinery limitations and pressure losses during the generation cycle, requiring a facility depth of 715 to 765 m, 2) air temperatures on the order of 40°C to 100°C, and 3) water temperatures from near freezing 0°C⁺ to 20°C. For design purpose, the useful life of a compensated CAES cavern system is designated as 30 years, or approximately 11,000 temperature cycles.

The significant rock properties include physical, hydrological, and thermomechanical properties. An evaluation was made of the existence of material properties data from the literature that assesses the availability of the requisite rock properties at the appropriate environmental conditions.

The greatest inadequacies in physical, hydrological, and mechanical properties data exist in the areas of laboratory and in situ values for non-intact rock testing at non-ambient conditions. Thermal properties data at non-ambient conditions is somewhat more adequate. Although data exist, some types of data for intact rock at ambient and non-ambient conditions are also marginal to somewhat inadequate.

It was found that satisfactory results could be obtained from composite material mechanics for estimates of upper and lower bounds of a rock's thermal conductivity but that less satisfactory results could be expected for prediction of thermal expansion coefficients.

Task 2. Procurement of Specimens

Based on information collected in Task 1 and on discussions with PNL personnel, several typical CAES host rock types were selected from the igneous intrusive, metamorphic, and sedimentary rock classes.

From the three general rock classifications, igneous intrusive, metamorphic, and sedimentary, the following specific rocks were selected:

<u>General Classification</u>	<u>Specific Rock</u>	<u>Source Location</u>
• Igneous - Intrusive	Milbank Granite	Hunter Quarry, Milbank, SD
• Metamorphic - Nonfoliated	Sioux Quartzite	Concrete Materials Company Quarry Sioux Falls, SD
- Foliated	Sykesville Gneiss	PEPCO Sykesville, MD
• Sedimentary - Chemical	Oneota Dolomite	Vetter Stone Co, Kasota, MN

Of the four rocks selected, three were obtained in large quantities from rock quarries. Only the Sykesville Gneiss was obtained at depth from drill core.

It was assumed that outcrop samplings of quarry samplings would be sufficiently representative of candidate formations for CAES demonstration. The major concern with quarry rock was the possibility that the weathering processes, may have disturbed the rock structure. To address this concern Re/Spec personnel visited the quarries to examine the exposures. It was found in some locations that removal of cement by leaching was evident but restricted to the walls of joints and cracks in the rock where surface water had apparently seeped through and been channelized. This phenomenon was observed primarily at the surface. The volume of weathered rock was small relative to the total volume of rock exposed.

Task 3. Selection of Specific Procedures for Rock Characterization

Physical characteristics of the specific rock formation were determined together with petrographic and chemical analyses of the rock specimens.

In addition detailed geologic descriptions have been made of each rock type.

Task 4. Laboratory Scale Testing of Rock Specimens

The testing program revealed that the influence of moisture on the shear strength of the rocks tested was statistically insignificant. However, the tensile strength decreased by about 15 to 20 percent.

Temperatures of the order of 100°C had negligible effect on the strength properties of all rocks tested. However, it was found that when a rock was heated and then quenched in water, a significant reduction was observed in the compressive strength. Most of the damage occurs in the first cycle. No discernable difference existed between the compressive strength of rock specimens cycled between 10°C and 50°C and those cycled between 10°C and 150°C. After the first cycle in which the compressive strength dropped an average of 18 percent for all rock types tested, no subsequent damage was noticeable upon further cycling.

However, the friction angle as determined from a Mohr's diagram, was unaffected by this thermal cycling. Figure 27 shows the Mohr failure envelope for Milbank Granite after one thermal cycle between 10°C and 50°C together with the failure envelope obtained at ambient conditions. Figure 28 shows similar results for Oneota Dolomite. Note that because the friction angle is unaffected by this cycling, the actual presentage of shear strength reduction decreases with increasing confining pressure.

Mechanical fatigue testing showed that for loading that alternates between tension and compression over 50 percent of the tensile strength could be lost within 11,000 cycles corresponding to a CAES cavern life of approximately 30 years. The damage occurs in the tensile portion of the cycle. Figure 29 shows cyclic stress-strain curves for Milbank Granite cycled between ± 62 percent of its tensile strength. Damage from microcracking can be seen by the change in modulus in the tensile region of the stress-strain plot of cycle 2500. Figure 30 shows how the

FIGURE 27. Mohr Failure Envelopes for Milbank Granite

FIGURE 28. Mohr Failure Envelopes for Oneota Dolomite

modulus decays with cycles, and Figure 31 is an S (strength) - N (cycles) plot for Milbank Granite cycled in the tension-compression mode. Fatigue strengths were much higher in the tension-tension and compression-compression modes for all rock types tested.

Planes of foliation in a rock mass have a pronounced affect on ultimate strength reminiscent of jointed rock behavior as shown in Figure 32. When the direction of the major principal stress is oriented at 30 to 50° from the foliation plane, the strength can be reduced by as much as 50% as compared to that for orientation of 0 to 90°.

FIGURE 29. Cyclic Stress-Strain Curves for Milbank Granite

FIGURE 30. Modulus Decay Curve for Milbank Granite

FIGURE 31. Tension-Compression S-N Curve for Milbank Granite

Task 5. Formulation of Stability and Design Criteria

With regard to CAES, igneous intrusive rock masses are considered generally to be the most favorable rock type if joint, faults, or folds have not seriously impaired the integrity of the rock mass. They can be found in masses sufficiently large to accommodate a CAES system. The intact rock is often homogeneous and isotropic. The petrography, particularly the interlocking crystalline texture, imparts generally high strength and favorable elastic, thermal, and weathering properties to the rock. Porosity and permeability are generally low. Finally, these rocks normally occur at sufficient depth to be of interest to CAES.

Metamorphic rock is considered generally to be the second most favorable rock type for CAES. These rocks are the product of the action of heat, stress, or heated fluids on other rocks, igneous or sedimentary.

FIGURE 32. Variation of Compressive Strength of Sykesville Gneiss with Foliation Angle

When they occur in sufficiently large masses, nonfoliated rocks such as quartzites may be suitable for caverns as igneous intrusives. These rocks, particularly the quartzites, are usually homogeneous and isotropic and have good strength characteristics.

Cleavage and schistosity are terms frequently used to describe the tendency of rocks to separate parallel to planes of foliation, cleavage, sometimes called rock cleavage to distinguish it from mineral cleavage, is the ability of rocks to break along parallel surfaces of secondary origin. This property is controlled by platy minerals that have been aligned by pressures in the earth's crust. Schistosity is a term applied to the variety of rock cleavage found in rocks that are sufficiently

recrystallized to be called schist or gneiss. Joints, partings, fissures, and fractures may be closed at shallower depths in foliated rocks that in igneous intrusive rocks.

From the standpoint of stability of a CAES cavern, the major difficulty may arise from the foliation itself. Foliation planes can cause the strength, elasticity, and thermal properties of the rock to be anisotropic and rather variable. Additionally, weathering of such rocks may be accelerated along planes of foliation and by the presence of easily altered metamorphic minerals.

Sedimentary rocks are generally considered less favorable than igneous or metamorphic rocks for CAES for several reasons. One, they are generally, though not always, bedded and may be interbedded with other less competent rock types also. Two, their strength is considerably lower than for igneous rocks (except for some dolomites and limestones). Three, their porosity and permeability are much greater (particularly for elastic rocks) than for igneous rocks and may present insurmountable air and water leakage problem. And finally, weathering and solution characteristics are much poorer than for igneous rocks.

Strength reductions can be expected in the tensile and compressive strength of rock masses subjected to a CAES cavern environment. The loss of tensile strength is not a major concern since this strength is generally quite low to begin with. The loss of compressive strength caused by thermal shock, although of the order of 20 percent, is tempered by the fact that the frictional coefficient remains relatively constant. Thus the percentage loss of failure strength of the rock decreases with increasing mean stress. Most of the damage will be caused in the first few cycles.

Over the confining pressure and temperature ranges of interest to CAES application, the failure envelopes can reasonably be assumed to be linear. Because the friction coefficient was not influenced by the non-ambient conditions, reasonable estimates could be made in the future

of the failure envelopes with relatively easy to obtain indirect tension and unconfined uniaxial compression tests. Strength reduction factors could be obtained routinely for site specific rocks from these tests. A reasonable assumption to make after the failure envelope has been established is to truncate the tensile portion of the envelope to zero. This is advisable since an already low tensile strength will be reduced by mechanical fatigue and thermal shock.

This program has demonstrated that although the compressive and tensile strengths are adversely influenced by a CAES cavern environment, the reduced failure strength of initially intact hard rocks is sufficiently high to indicate that a CAES plant could be operated satisfactorily. It has also been demonstrated that foliated and/or jointed rock masses require special attention and assessment of strength requirements and strength values become quite site specific.

TECHNICAL PROBLEMS

No technical problems have occurred that might have affected the overall program objectives.

PUBLICATIONS

P. F. Gnirk and A. F. Fossum, "On the Formulation of Stability and Design Criteria for Compressed Air Energy Storage in Hard Rock Caverns," Proceedings of the 14th Intersociety Energy Conversion Engineering Conference, Boston, MA, August 5-10, 1979, v. 1, pp. 429-440.

A. F. Fossum, "Laboratory Testing of Hard Rock Specimens for Compensated CAES Caverns," Proceedings of the 1979 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, U.S. Department of Energy, Division of Energy Storage Systems, Washington, DC, August 1979, pp. 119-127.

P. F. Gnirk and A. F. Fossum, "Synopsis of Stability and Design Criteria for CAES and UPHS in Hard Rock Caverns," ROCKSTORE 80 -- Subsurface Space, International Symposium for Environmental Protection, Low-Cost Storage and Energy Savings, Stockholm, June 23-27, 1980, pp. 615-622.

A. F. Fossum, "Laboratory Studies of Hard Rock for CAES," Proceedings of the 1980 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, U.S. Department of Energy, Division of Energy Storage Systems, Washington, DC, November 10-13, 1980, pp. 214-219.

4.1.2c Analytical Model for CAES Reservoirs

D. Rowe

Rowe and Associates

OBJECTIVE

The objective of this task is to develop a computer program to calculate hydrodynamics in hydraulically compensated CAES reservoirs with particular emphasis on champagne effect related phenomena.

TASKS

For FY-1980 and 1981, the specific tasks were to:

1. investigate the possibility of champagne-effect induced blowout,
2. provide analytical support to Potomac Electric Power Company (PEPCO) and Acres American in their preliminary design of a CAES facility, and
3. interface with Rensselaer Polytechnic Institute (RPI) on their experimental studies of the champagne effect.

These objectives have been met.

TECHNICAL PROGRESS

Highlights of specific technical progress are as follows:

Code Review and Result Presentations

Details of physical and numerical modeling employed in the computer program were presented and critically reviewed at a review group meeting. Analytical results were presented at the DOE Contractors' Review and to interested parties from PEPCO, Acres American, RPI, and Electric Power Research Institute.

Blowout Investigation

Sensitivity calculations were performed for the CAES facility designed by Acres American for PEPCO. Results indicated that blowout

is unlikely for a properly designed facility and parameters were identified that can act to mitigate the champagne effect.

Computer Program Documentation

Computer program development has been completed and documentation is in progress with completion expected in June 1981. The program provides a one-dimensional, isothermal simulation capability for the entire CAES facility including air pipe, cavern, U-bend, compensation pipe, and reservoir. The dynamics of air, water, and dissolved air are obtained by the solution of transient continuity and momentum equations for the phases. Constitutive relationships are included in a general form to facilitate the investigation of parameter sensitivities.

CURRENT ACTIVITIES

Work in progress includes computer program documentation and the analytical investigation of experiments conducted at RPI.

4.1.3a Laboratory Tests of Salt Specimens Subjected to Loadings
and Environmental Conditions Appropriate to a
Compressed Air Energy Storage Reservoir

R. L. Thoms

Louisiana State University

OBJECTIVE

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

TASKS

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

Task 1. Cyclic Thermal and Mechanical Testing of Salt

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

Task 2. In Situ Slant Borehole Pressure Cycling

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

Task 3. In-Situ Permeability Measurements

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

Task 4. Development of Stability Criteria

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

Task 5. Reporting

Monthly reports and a final report will include data and findings of the test program along with stability criteria development for CAES salt reservoirs. The final report, in draft form, is due September 30, 1981.

TECHNICAL PROGRESS

Task 1. Cyclic Thermal and Mechanical Testing of Salt

Specimens of rock salt for laboratory tests were obtained from the following sources: Avery Island, Jefferson Island, West Hackberry, Bayou Choctaw, Bryan Mound, Vacherie, and Rayburn's domes of the U.S. Gulf Coastal region. In addition, salt was obtained from the Red Lake deposit of northwestern Arizona and from the Huntorf dome in West Germany. Salt specimens were not obtained from the bedded deposits of the U.S. due to involved costs and time limitations; however, the opportunity exists to obtain specimens from these sources.

Laboratory tests currently being performed include the following: 1) Brazilian, 2) uniaxial, 3) triaxial compression, 4) triaxial extension, and 5) permeability. Tests have been underway on salt from four different sources, i.e., Jefferson Island, Bayou Choctaw, West Hackberry, and Bryan Mound.

The Brazilian test series was completed in November 1980, and the results were reported in the 1980 Annual Contractors' Review Meeting (November 10-13, 1980). Specimens from Cote Blanche dome also will be included in this series by September 1981.

Other tests in the series generally proceed with time from static to cyclic loading and then to cyclic loads at elevated temperatures. Figure 33 depicts results from a typical test. It can be noted that deformation accelerates with the onset of cyclic loads. However, for this case, the stress environment also is more severe for the cyclic load stage since coupled lateral and axial stresses are applied 180 degrees out of phase as compared to the static phase.

Laboratory tests at constant elevated temperatures have been initiated, but attempts to synchronize cyclic thermal loads with applied cyclic stress conditions have been temporarily abandoned. Thermal "inertia"

FIGURE 33. Status Triaxial Compression of Bryan Mound Dome Salt.

of the triaxial test cells was so large that cooling the apparatus to track cyclic applied stresses proved impractical. Thus, tests are underway which employ mean values of temperature anticipated in walls of CAES reservoirs in salt. Further, the natural background temperature of a salt formation can be anticipated to strongly dominate temperature around CAES reservoirs since air with relatively small heat capacity is injected into the center of the reservoir away from the walls. Effects of cyclic thermal loads will be studied in the in situ tests in the Cote Blanche salt mine as described later in this report.

Permeability tests have been performed in the laboratory on specimens collected mainly from the Jefferson Island (JI) salt dome. Results indicated a strong dependence on the history of the salt specimens which included location within the mine. For example, salt specimens collected at mine locations where localized floor heave was present tended to display relatively large values of permeability. Permeability generally decreased with increasing confining pressure for triaxial specimens, and also decreased immeasurably small values after only two or three cyclic load applications.

Task 2. In Situ Slant Borehole Pressure Cycling

Figure 34 depicts results obtained in August 1980, for a cyclic pressure test of a slant borehole in the Jefferson Island (JI) salt mine.

FIGURE 34. Typical Data for Cyclic Pressurization of Boreholes in Salt Mine

Time proceeds from right to left in this Figure. Monitored acoustic emissions (AE) and diametrical hole displacements were in phase with applied pressures for this test.

The JI test site was lost because of flooding on November 20, 1980. Thus a new site was sought in another mine.

Domtar, Ltd., operators of the Cote Blanche mine in south Louisiana kindly made available a test site in that mine. Twelve test holes have been drilled and an instrument shed has been assembled at the site. Major units of instrumentation have been transported underground and checked out.

Background seismic "noise" due to mining operations has been monitored, and one slant hole has been prepared for testing. On April 14 a preliminary "air tightness" check was performed on this hole in which pressures were brought up to 250 psi (1.7 mPa) and held for one or two minutes. A seal on the "wellhead" failed and thus planned cyclic testing was postponed to a later field trip. Only a minor modification of the seal design is necessary to "fix" the slant hole for further tests. Additional holes will be prepared for tests by mid-May, 1981.

Task 3. In Situ Permeability Measurements

An in situ permeability test was developed for radial transient flow of gas from holes in rock salt. The test procedure incorporates a numerical solution of the corresponding quasi-linear equation and a portable "packer" to seal off test sections of holes drilled for salt mining. The test method is particularly suited for rock salt which is anticipated to have very low permeability. The analytical portion of the test method has been completed, and the "packer" has undergone initial testing in the Cote Blanche Mine. Further development of the "packer", which leaked during initial trials, is planned. Information has been received from Sandia Corporation on packer design which will be incorporated into the LSU instrument.

Task 4. Development of Stability Criteria

No activity in development of quantitative criteria.

Task 5. Reporting

Monthly reports are submitted regularly.

TECHNICAL PROBLEMS

Flooding of the JI mine on November 20, 1980, caused a slippage in the in situ test schedule of approximately 5 months. However, full recovery of all study objectives now is anticipated with work at the Cote Blanche mine site.

PUBLICATIONS

R. L. Thoms, M. Nathany, R. Gehle, "Low-Frequency Cyclic Loading Effects on Rock Salt," Proceedings Rockstore 80, M. Bergman, Ed., V2, p. 755, Stockholm, June 1980.

R. L. Thoms, "Laboratory Studies of Rock Salt," Proceedings Mechanical, Magnetic and Underground Energy Storage 1980 Annual Contractors' Review CONF-801128, Washington, D.C., November 10-13, 1980, p. 199.

G. S. Gipson and R. L. Thoms, "On the Transport of Gaseous Matter Through Permeable Media Between Cylindrical Cavities," Inter. Jour. of Engr. Science, in press.

R. L. Thoms, "Permeability of Rock Salt for Compressed Air Energy Storage," abstract of presentation to Fall Meeting of Solution Mining Research Institute (SMRI), Minneapolis, MN, Oct. 1980.

4.1.3b Numerical Modeling of Behavior of Caverns in Salt for Compressed Air Energy Storage

S. Serata and J. F. McNamara
Serata Geomechanics Inc.

OBJECTIVE

The program objective was to develop and numerically analyze the critical design parameters affecting the long-term stability of CAES operating caverns in salt. The computer codes used for the numerical computations were REM, a proprietary structural finite element code based on the constitutive model developed at Serata Geomechanics, Inc. (SGI), and *HEAT*, a heat transfer finite element code developed by Professor R. L. Taylor, Department of Civil Engineering, University of California (Berkeley). In particular, for FY-1980, the problems associated with elevated temperature and air penetration effects were addressed.

SUMMARY OF PREVIOUS WORK

The results of previous work conducted at SGI can be summarized as follows:

- Critical design parameters warranting numerical treatment and evaluation were found to be:
 - 1) cavern depth
 - 2) cavern air pressure
 - 3) in situ lateral stress
 - 4) salt octahedral shear strength
 - 5) general salt material properties
 - 6) cavern length to diameter ratio
 - 7) cavern separation to diameter ratio
 - 8) cavern temperature
 - 9) cavern boundary air penetration

- A literature survey was conducted and the SGI constitutive model was found to be flexible enough to incorporate the large amount of laboratory and field data gathered.
- The results of cyclic laboratory testing indicated that cyclic loading will increase the strength of salt when the salt is in the viscoplastic state.
- For parametric numerical studies involving 1) to 7) above, CAES operation was found to be highly compatible with long-term structural stability of the caverns.

TASKS FY-1980

Task 1. Model Modification and Testing

The objective of this section of the work was to incorporate the effects of temperature on salt behavior into the numerical model. This capability could then be exploited parametrically to determine acceptable operating temperature range for CAES applications.

Task 2. PNL Selected Test Case

This task consisted of a specified benchmark type problem suggested by PNL designed to provide baseline checking of *HEAT* and REM.

Task 3. Single Cavern Axisymmetric Analysis

The goal of this task was to establish, through REM parametric analysis, acceptable ranges of the critical parameters for stable, continuous long-term CAES operation.

Task 4. LSU Borehole Analysis

In order to provide a more realistic link between the computer computations and actual field conditions, computer simulation of test boreholes being monitored in the Jefferson Island mine were conducted.

TECHNICAL PROGRESS

Task 1. Model Modification and Testing

Model modifications were made reflecting the temperature effects on salt behavior summarized in the literature review of FY-1979 work. All model and code changes were rigorously tested and verified as correct. The modifications made are:

- 1) REM and *HEAT* were interfaced to allow accessibility of temperature distribution data produced in *HEAT* to REM.
- 2) A linear thermal expansion term was included in the volumetric part of the constitutive model in REM.
- 3) The viscoplastic creep rate equation was modified to incorporate temperature effects.
- 4) Octahedral shear strength was modified to include temperature dependence.

Task 2. PNL Selected Test Case

Task 2 work indicated that the modifications made in Task 1 enabled the combined REM/*HEAT* code to analyze a wide variety of phenomena including both thermal conduction and convection, cyclic temperature and pressure thermomechanical loading, sequential excavation simulation and non-linear temperature-dependent viscoplastic analysis. Specific results demonstrated that thermal cycling will only occur within the first 10 ft of a CAES cavern boundary and will primarily cause cycling of the vertical and tangential stress there. The pressure cycling, in contrast, could affect the stress conditions as far as 1-2 diameters away for a 300-ft diameter cavern.

Task 3. Single Cavern Axisymmetric Analysis

The results of the large body of work compiled in this section can be summarized as follows:

- In situ lateral stress is the most dominant parameter governing long-term cavern behavior. Stability is greatly reduced as the in situ lateral stress approaches the theoretical limit.

- Given that other parameters maintain moderate values, CAES caverns are structurally stable in the long term for temperatures to 200°F.
- Air penetration and boundary deterioration primarily affect local stability of CAES caverns.
- At cavern length-to-width ratios of less than 8, supporting effects of the roof and the floor greatly reduce radial strain.

The main simulations for this section are summarized in Figure 35 where L/D = cavern length to diameter ratio, T = °F, P_i = cavern pressure, γ_c = critical strain for air penetration initiation, ΔP_L = % theoretical excess lateral stress, B.C. = base condition run from which each parameter

FIGURE 35. Simulation Run Summary for Axisymmetric Case -- Maximum Boundary Displacement Versus Time. B.C. = Base Condition; C.C. = Control Case

was varied, and C.C. = control case run in which no temperature or air penetration effects were considered.

Task 4. LSU Borehole Analysis

Data describing the mine and borehole geometry was obtained from Professor Robert Thoms at LSU. Simulations were made to determine the global stress conditions surrounding the borehole and appropriate tensor transformations were made to rotate the global stress so as to facilitate plane strain analysis in the plane normal to the boreholes. Due to the high confining stress in the vicinity of the test holes, only slight hole closure was evidenced in the analysis.

TECHNICAL PROBLEMS

No major technical difficulties arose in the course of the project and the FY-1980 report was submitted in December 1980.

4.1.4 Compressed Air Energy Storage Environmental Control Concerns

M. A. Beckwith
Pacific Northwest Laboratory

OBJECTIVE

The objectives of this project are to identify potential environmental and regulatory problems associated with the implementation of CAES technology, to assess the nature and magnitude of potential problems, to identify systems or strategies required to prevent or control adverse impacts, and to develop sufficient information and experience for decision making purposes regarding this developing technology. This project, while a complementary part of the CAES Technology Development Program at PNL is funded by the Environmental Control Technology (ECT) Branch of the Environmental and Safety Engineering Division with the Office of Environmental Compliance and Overview of the Department of Energy. This funding arrangement arose primarily because of the different missions of the respective DOE offices responsible for technology development and environmental compliance.

TASKS

Initially the program was divided into several discrete tasks corresponding to various environmental and regulatory issue areas. A program plan was developed and published in June 1980 (PNL-3431, 1980).

As work proceeded on the various tasks, it became apparent that assessment of the various environmental issue areas based solely on currently available information (as outlined in the program plan) would not significantly advance the state of knowledge concerning the environmental implications of CAES technology. Actual field data and field experience were clearly required to adequately assess the environmental impacts and

necessary control technology associated with CAES. Therefore the project was realigned to more clearly reflect the laboratory and field test phases of the technology development program. By supporting initiation of the field tests through preparation of necessary permits and supporting information, interfacing with appropriate regulatory bodies while at the same time assessing from an environmental perspective the data developed in laboratory and engineering studies, meaningful environmental/regulatory information and experience could be developed in a cost-effective manner.

TECHNICAL PROGRESS

As much information regarding environmental impacts and control technology as was available was collected; preliminary assessments of various environmental issue areas were made resulting primarily in recommendations for further required research activities. Regulatory requirements for the planned Shallow Aquifer Field Test were assessed and collection of the supporting environmental information begun.

TECHNICAL PROBLEMS

Technical problems were largely eliminated by redirection and reorganization of the project to better reflect technology development and engineering research activities. Future technical problems will be presented primarily by regulatory uncertainties and incomplete understanding of the subsurface environment.

PUBLICATIONS

M. A. Beckwith and D. W. Boehm, Compressed Air Energy Storage (CAES) Environmental Control Concerns and Program Plan, PNL-3431, Pacific Northwest Laboratory, Richland, WA, June 1980.

4.2 SECOND-GENERATION CONCEPTS STUDIES

4.2.1a Engineering Study of Adiabatic CAES

M. J. Hobson

Acres American Incorporated

OBJECTIVE

The objective of the study was to develop a conceptual engineering design of an adiabatic CAES system using water-compensated hard rock caverns for compressed air storage. Adiabatic CAES is a cycle variation which eliminates all hydrocarbon based fuel input within the CAES plant. It incorporates a thermal energy storage (TES) to cool and store the heat generated during the air compression mode for subsequent reheating of the compressed air during the power production mode. The conceptual design was based upon the preliminary engineering design of a 924 MW conventional CAES plant located in the state of Maryland prepared by Acres American in a project funded by the Department of Energy (DOE), Electric Power Research Institute (EPRI), and Potomac Electric Power Company (PEPCO).

TASKS

Task 1. The Thermal Energy Store

The objective of this task was to develop an underground TES regenerator to facilitate the heat exchange from the compression mode to the expansion mode of the CAES system. Activities in this task included:

- Review of state-of-the-art TES technologies to determine the most appropriate heat storage system for adiabatic CAES with regard to thermal performance, cost, and near-term availability of components.
- Review of potential heat storage media and the selection of promising materials based on cost, and thermophysical properties.
- Evaluation of possible TES configurations and selection of the most practical component arrangement.

- Determination of TES sizes and evaluation of thermal performance of selected TES materials with the aid of computer models.

Acres' efforts were assisted by Massachusetts Institute of Technology/ Energy Laboratory (Boston, Massachusetts) and Central Electricity Generating Board (London, England).

Task 2. Turbomachinery

The objective of this task was to develop a turbomachinery system based on equipment available from the Dresser Clark product lines.

Activities in the task included:

- Evaluation and selection of axial and centrifugal compressors
- Evaluation and selection of high and low pressure turbines
- Development of the turbomachinery arrangement
- Review of general compressor and turbine performance and conditions.

Task 3. Cycle Arrangement

The objective of this task was to develop the most efficient cycle arrangement compatible with available turbomachinery capable of providing the desired electric power output. Activities in this task included:

- Review of recent studies on cycle configurations
- Preliminary assessment of cycle performance using the Acres CAES computer model to screen promising adiabatic CAES cycles
- Identification of the most effective cycle based on the findings of Tasks 1 and 2, and determination of performance of design and off-design conditions.

Task 4. Conceptual Design

The objective of this task was to develop a conceptual design of the adiabatic CAES plant based on the selected system configuration. Activities in this task included:

- Development of a plant arrangement that satisfied operational requirements and environmental constraints.

- Development of the turbomachinery layout
- Development of the underground TES system and air storage facilities.

Task 5. Capital and Levelized Energy Costs

The objective of this task was to estimate on a conceptual basis the capital and levelized energy costs for the life of the facility using electric utility costing methods. Activities in this task included:

- Estimation of plant capital cost in terms of direct cost, interest during construction, and contingency
- Estimation of operating cost in terms of operating and maintenance labor, maintenance supply, and equipment replacement costs
- Estimation and evaluation of levelized energy cost for the life of the facility in accordance with the requirements and guidelines of the EPRI Technical Assessment Guide, Report No. PS-866-SR.

Task 6. Final Project Report

The work efforts of Tasks 1 through 5 were reported in the final project report.

TECHNICAL PROGRESS

The draft final report was submitted in November 1980, review comments were received and incorporated into the text, and the final report was submitted in March 1981. Major conclusions of the adiabatic CAES program are summarized in the following paragraphs.

Technical Feasibility

The plant configuration developed in this conceptual design study does not appear to include any design problems which would prohibit plant construction, however, a number of design areas require more detailed investigation before detailed engineering can proceed.

A number of uncertainties exist with thermal energy storage material properties and behavior under the operating conditions of adiabatic CAES. Unknown are such items as cyclic life, and particulate generation rate and size distribution for the various storage materials. Pebble bed containment vessel wall stresses due to thermal expansion are unknown, but do not appear to be severe or uncontrollable. Prediction of the exact behavior of such large quantities of materials in single containments is somewhat uncertain as comparably sized systems that operate under similar thermal conditions have never been built. Performance prediction is, however, largely a function of how well air distribution within the bed can be predicted, and therefore depends upon construction features which ensure as-designed conditions. Part-load and partial-cycling TES system behavior was not investigated to any depth in this study. Although no significant deviations are expected, behavior under such conditions must be defined to clarify operating procedures and limitations.

Design of the high temperature air shafts received considerable attention during this study. The arrangement of the pipe to accommodate startup expansion is, of course, critical to successful containment of the stored air. The design approach selected should be adequate, and, although unusual in construction, appears well within the capability of construction technology.

The availability of suitable valves was investigated by both Acres and Dresser Clark and does not appear to be a problem at this stage. The large piping required in the low pressure plant sections will involve custom fabrication, but adequate facilities are available.

The availability of turbomachinery based upon commercially offered designs appears good. Some modification to standard product designs would be required to achieve the temperature limits proposed in this study (870°F max), but no insuperable problems are anticipated. The use of temperatures above those proposed would require, however, extensive compressor redesign or development of new designs. The design configuration

developed in this study does include a high horsepower gearbox in the centrifugal compressor train, which is a state-of-the-art component that would require design evaluation. Other compressor arrangements are possible which could eliminate this gearbox.

Plant operating characteristics need further evaluation and definition, particularly in light of utility system needs. The adiabatic plant design does not appear quite as flexible as combustion turbines or fuel-fired CAES, but does appear capable of supplying peaking power in a load following mode. More detailed evaluation of TES system behavior should include definition of any restrictions on partial load operation that may exist.

The unusually large number of turbomachinery components for the conceptual design (see Figure 36), raising some concerns regarding system reliability, is the direct result of the study requirement to use commercially available designs and a limited effort towards optimized machinery selection. Actual machinery for an adiabatic CAES plant would likely involve fewer rotating components, with some development of new designs, regardless of whether the turbomachinery is supplied by Dresser, Sulzer/BBC or any other manufacturer. Reduction of the number of machines would benefit reliability, should benefit plant cost and physical layout, appears well within technological limits, and may be performed by the manufacturers themselves if a market is shown to exist.

The general conclusion of this conceptual design study is that no significant barriers are foreseen to technical feasibility, but that plant reliability, TES material properties, and system behavior need further study before technical feasibility is certain.

Economic Feasibility

The levelized energy (production) cost evaluation showed that adiabatic CAES is marginally competitive with oil-fired CAES (see Table 6).

FIGURE 36. Air System Flow Diagram

**TABLE 6. Comparison of Oil-Fired CAES, Adiabatic CAES, and Combustion Turbines
1990 Levelized Busbar Cost (mills/kWh)**

Capacity Factor (percent)	Oil-Fired CAES ^(a) (10-hr storage)	Adiabatic CAES ^(b)				Combustion Turbine ^(c)
		Iron Oxide Fill (8.3-hr storage)	Iron Oxide Fill (10-hr storage)	Denstone Fill (10-hr storage)	Cast Iron Fill (10-hr storage)	
10	369.9	368.3	378.2	410.6	492.3	446.4
15	297.6	269.4	276.0	297.6	351.8	409.6
20	261.4	219.9	224.9	241.1	281.7	391.2
25	238.6	-----	194.2	207.2	239.7	380.0

^(a) 924 MW output, 30-year life, water compensated hard rock air caverns

^(b) 800 MW output, 30-year life, water compensated hard rock air caverns

^(c) 50 MW output, 30-year life, 300 \$/kW capital cost (1990), 2.0 mills/kWh variable O&M, 140 mills/kW-hr fixed O&M, 12,000 Btu/kWh heat rate (1980 dollars)

The economic evaluation concluded that the cost and durability of the heat storage materials for the TES are critical to the viability of the adiabatic concept. Expensive heat storage materials that are likely to last longer (such as white cast iron balls) place adiabatic CAES at an economic disadvantage compared to oil-fired CAES. On the other hand, relatively inexpensive heat storage materials such as iron oxide pebbles give adiabatic CAES a cost advantage over the oil-fired concept, but the longevity and reliability of these cheaper materials are more in doubt. If several replacements of TES materials are required over the life of the plant, then the economic advantage of adiabatic CAES with low cost TES materials could possibly be lost.

Consideration of factors other than those incorporated in the levelized cost analysis approach indicates that adiabatic CAES could likely only complement the fuel-fired design as an air storage alternative. The operating characteristics of the fuel-fired design (less compressing load, greater generation capability) make it more compatible with the limited availability of charging power in many utilities, but the independence from petroleum based fuels in the adiabatic design may become increasingly attractive.

Recommendations

Acres recommends that further development of the adiabatic CAES cycle be pursued through:

- 1) an intensive testing program to determine feasibility of low cost heat storage materials
- 2) development of pebble bed design models to permit optimal design of TES beds with regard to bed configuration, thermal and mechanical stress conditions, and thermal performance.
- 3) review of the general turbomachinery approach selected for this study design by an independent turbomachinery specialist, with particular attention given to the high temperature compressors, the problem of blading erosion/separator efficiency requirements, and system reliability.

If the above proves materials properties are acceptable, the program should continue with:

- 1) preliminary design of a demonstration plant based upon commercially available equipment in association with an interested utility, and
- 2) development of more advanced high efficiency axial compressors capable of discharge temperatures in the range of 1000 to 1200°F or higher.

TECHNICAL PROBLEMS

All study activity complete.

PUBLICATIONS

Conceptual Design and Engineering Studies of Adiabatic CAES with Thermal Energy Storage, prepared for Battelle Pacific Northwest Laboratory by Acres American, Incorporated, under Subcontract B-82284-A-E, March 1981.

4.2.1b Coal-Fired Fluid Bed Combustion Augmented Compressed
Air Energy Storage Systems

R. D. Lessard and A. J. Giramonti
United Technologies Research Center

OBJECTIVE

The objective of the program was to provide a technical and economic assessment of compressed air energy storage (CAES) concepts which use coal-fired fluid bed combustors (FBC) instead of oil-fired conventional combustors.

TASKS

To achieve the stated program objective, a six-task analytical and preconceptual design program was performed. The last task was completed during the current reporting period.

Task 1. Technology Assessment

Provide information about coal-fired atmospheric fluid bed combustion (AFBC) and pressurized fluid bed combustion (PFBC) technology pertinent to application in a CAES power plant system.

Task 2. Systems Analysis

Identify a preferred coal-fired FBC/CAES power plant system configuration.

Task 3. Preconceptual Power Plant Design

Transform the preferred FBC/CAES system configuration into a preconceptual power plant design.

Task 4. Application of Thermal Energy Storage

Explore the application of thermal energy storage (TES) to FBC/CAES systems.

Task 5. Part-Load and Load Following Operation

Investigate the performance of possible approaches to achieving FBC/CAES system part-load and load following operation.

Task 6. Evaluation of System Load-Following Capability

Evaluate both the steady-state, part-load and transient performance of the integrated FBC/CAES system.

TECHNICAL PROGRESS

Task 1. Technology Assessment

An assessment of the technology revealed that although there are still several challenges to overcome, there is strong evidence an FBC could be successfully coupled with the turbomachinery of a CAES power plant.

Task 2. Systems Analysis

A parametric performance and cost evaluation of a wide spectrum of FBC/CAES power plant system configurations provided an indication that an open-bed PFBC would provide the most attractive and logical near-term application of an FBC in a CAES power plant system.

Task 3. Preconceptual Power Plant Design

The key design point operating characteristics of the power plant are summarized in Table 7. The levelized busbar cost was estimated to be 117.9 mills/kWh.

Task 4. Application of Thermal Energy Storage

Two coal-fired CAES system concepts incorporating thermal energy storage (TES) were investigated; a PFBC/CAES/TES system recovering the heat of compression and a CAES/TES system integrated with a steam system. The PFBC/CAES/TES system was estimated to have a round trip heat rate of 12589 Btu/kWh while the CAES/TES/steam system was estimated to have a round trip heat rate of 10870 Btu/kWh.

TABLE 7. Key PFBC/CAES Power Plant Operating Characteristics

Power, MW (4 units)	
Turbine	876.4
Compressor	799.6
Heat Rate, Btu/kWh	
Generator	4,538
Compressor	9,095
Round Trip	13,633
Storage Pressure, atm	71.2
PFBC Bed Conditions	
Temperature, °F	1,562
Pressure, atm	15.0
Annual Utilization, hr/yr	2,190
Capacity Factor	0.25

Task 5. Part-Load and Load Following Operation

A preliminary investigation of the PFBC/CAES system revealed that one approach to achieving power plant part-load operation is to vary the turbine output by concurrently and proportionately changing coal and air flows during CAES power generation and varying compressor input during CAES cavern charging. Another approach to achieving part-load operation is to continuously operate the PFBC and turbines at design output and varying compressor input. The round trip heat rate of the cycling PFBC/CAES system was estimated to be approximately half that of the continuous firing system and the levelized annual cost approximately 7% lower.

Task 6. Evaluation of System Load-Following Capability

The open-bed PFBC/CAES power plant system would achieve part-load operation by concurrently and proportionately varying the mass flow of

both the air and coal to the PFBC to produce a varying thermal output. Operation in this manner will also: 1) produce a constant bed temperature, and therefore, a constant low-pressure turbine inlet temperature because the air and fuel flows remain proportional; 2) provide a bed pressure that is directly proportional to the flow through the bed because the low-pressure turbine nozzle area is fixed resulting in choked flow; and 3) yield a constant superficial velocity in the bed over the entire load range because the flow rates are proportional to pressure and the bed temperature remains constant.

An investigation was initiated to examine key PFBC operating parameters, including combustion efficiency, freeboard and cyclone combustion, sulfur retention, fluidization, elutriation, and solids handling all at 100%, 50%, and 25% design load.

The combustion efficiency is expected to be at least 98.5% over the operational range of 25% to 100% load at the design bed temperature and fluidizing velocity. Higher efficiencies could be achieved by increasing the number of solids feed points. Because of the high combustion efficiency, little combustion is expected in the freeboard or cyclones. Combustion conditions do not, therefore, represent a limitation to steady-state, part-load operation. No experimental data on sulfur retention directly related to the expected conditions in the combustor exist, and model predictions differ significantly. However, no difficulties are envisioned in designing a solids injection system capable of supplying the range of dolomite required (Ca/S ratio of 1.5 at 100% to possibly 2.8 at 25% load) to meet the specified goal of 85% sulfur retention.

An analysis of fluidization conditions expected throughout the 25% to 100% load range indicates that satisfactory fluidization could be maintained for both steady-state and transient operation. An estimate of the solids loading of the combustion gas at the cyclone entry revealed an increase from 4075 ppm at steady-state, 25% load to 5033 ppm at steady-state, 100% load. This increase results partly from the increased solids

fuel rate and partly because of the higher proportion of fuel material due to the denser fluidizing gas. However, because the gas velocities in the cyclones remain nearly constant over the load range, resulting in nearly constant efficiency, and because the dust elutriated at high loads is coarser than at low loads, the increase in dust loading in the cleansed gas will be less than at the cyclone inlet. Consequently, elutriation should not pose a problem as long as the detailed design of the solids handling equipment takes into account the momentary high particulate loadings in the combustion gas expected on turnup after prolonged part-load, steady-state operation.

To determine the ability of the system to respond to load changes, transient simulations were made using a UTRC computational model. Other than the PFBC, the major factors affecting CAES system response are the heat exchanger thermal mass and the volumetric lag associated with changing pressure in the PFBC containment vessel. The effect of these factors on the bed temperature response to a 10% change in both air flow and fuel rate is shown in Figure 37.

FIGURE 37. PFBC/CAES Bed Temperature Response

Because it is necessary to hold bed temperature relatively constant to avoid damage to the refractory material in the bed, it appears that coordination of fuel rate and air flow will be an important factor in system design. To identify the required response of the fuel feed mechanism, a number of different air flow rate changes (which approximates power level change) were examined. At a 15%-per-minute change in throttle valve restriction, the required rate of change in fuel flow is slightly greater than 18%-per-minute. This is shown in Figure 38 which presents the fuel rate required to maintain constant bed temperature as the throttle valve restriction is changed from 25% to 100% load in 5 minutes. While commercial equipment can respond at 18%-per-minute or slightly faster, it is generally not sized for much more than 10% over the design feed rate. As shown in Figure 38, a feed rate of 20% in excess of design will be needed to maintain constant bed temperature for the specified transient. Assuming that fuel rate can respond as shown in Figure 38, Figure 39 shows the resultant change in output power. Because

FIGURE 38. Fuel Rate Requirement

FIGURE 39. Power Response

of volumetric and thermal lags, it takes slightly more than 5 minutes to reach 100%. The change in air temperature out of the cold side of the heat exchanger is shown in Figure 40. Because of the high cold-side film coefficient, heat exchanger metal temperature will closely follow this profile. Thus, the heat exchanger will have to be designed to withstand a 250 R (140 K) temperature change in approximately 7 minutes.

It is apparent that output changes on the order of 15%-per-minute over a large range are feasible with current state-of-the-art equipment. For smaller excursions (on the order of 25%) rates of change of 25%-per-minute may be feasible. Because of these rapid response rates, the desirability of the system should be greatly enhanced.

FIGURE 40. Recuperator Temperature Response

TECHNICAL PROBLEMS

None, the program has been completed.

PUBLICATIONS

A. J. Giramonti, R. D. Lessard, D. Merrick, and M. J. Hobson, Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System -

Volume I - Executive Summary

Volume II - Introduction and Technology Assessment

Volume III - Preconceptual Design

UTRC Report No. R80-954490-20, United Technologies Research Center, June 1980.

R. D. Lessard, W. A. Blecher, and D. Merrick, Technical and Economic Assessment of Fluidized Bed Augmented Compressed Air Energy Storage System - System Load Following Capability, UTRC Report No. R80-954490-29, United Technologies Research Center, January 1981.

R. D. Lessard and W. A. Blecher, "CAES/FBC Studies," Proceedings of Mechanical, Magnetic, and Underground Energy Storage 1980 Annual Contractors' Review, Washington, D.C., November 10-13, 1980.

4.2.2a Line by Line Assessment of Principal Subsystems, Equipment Items and Components of Compressed Air Energy Storage Systems

D. L. Chiang and C. K. Jee
ENTEC Research Associates

OBJECTIVE

There are major technical and manufacturing barriers preventing wide-spread industry adoption of ACAES technology. This study was initiated to identify more clearly these issues and recommend possible courses of action to be taken. Specifically, this report addresses the following salient issues:

- Are the uppermost operating requirements of ACAES systems within industry technical and manufacturing state of the art?
- What is the lead time required to upgrade/redesign currently available equipment for ACAES application?
- What influencing factors will synchronize industry's developmental efforts with Battelle's commercialization time frame for ACAES applications?
- What R&D activities, if any, should DOE take to stimulate the early commercialization of this application?

TASKS

Task 1. Equipment, Subsystems and Component Definition

To ensure that all key equipment, subsystems, and components are identified, a review of four second generation CAES concepts were conducted. They include:

1. CAES/FBC (coal-fired fluidized bed combustor). A detailed engineering and economic study of this concept was recently completed by United Technologies Research Center and reported in UTRC R80-954490-20, volumes 1-3.

2. CAES/CG (coal gasification). This concept was evaluated by United Technologies Research Center under sponsorship of Electric Power Research Institute (EPRI) and presented in EPRI EM-1077.
3. ACAES/Hardrock (adiabatic CAES using hardrock air storage reservoir). Presently undergoing detailed study by Acres American, Inc. (M. Hobson, principal investigator).
4. Hybrid CAES (thermal energy storage used to reduce oil consumption). Under detailed study by United Engineers and Constructors (UE&C) under EPRI sponsorship (A. J. Karalis, principal investigator).

Task 2. Vendor Surveys for Availability Determination

A thorough examination was performed to determine each vendor's capability to design as well as their capacity to manufacture CAES equipment in a timely manner. To effectively determine commercial availability, each vendor's capability was surveyed and examined by the following:

- Analyze vendor catalogs - This analysis consisted of reviewing the catalogs and determining the general state-of-the-art of equipment manufacturing as well as obtaining a preliminary idea of current performance standards of "off-the-shelf" items.
- Conduct direct contact survey - A telephone survey was conducted among a select group of manufacturers to identify more precisely equipment manufacturers' capabilities to supply CAES-related hardware.
- Conduct a limited field/on-site survey - Further verification of information to ensure accuracy necessitated a limited number of on-site or personal visits with the suppliers to obtain the proper information. This survey was conducted on an "as needed" basis and contingent on PNL approval.

Task 3. Problem Area and Equipment Constraints Identification

A major segment of this task was devoted to identifying potential constraints to CAES equipment availability.

Task 4. Survey of Current R&D on CAES Related Equipment, Subsystems and Components

CAES equipment R&D was conducted in parallel with other energy projects requiring similar types of equipment (e.g., coal gasification and liquefaction, underground coal conversion, oil shale, etc.). A data base on equipment constraints was suspected to exist in these projects and cross-reference checks or additional data were obtained by conducting the R&D survey.

TECHNICAL PROGRESS

Task 1. Equipment, Subsystem and Component Definition

The studies of the four CAES technologies were reviewed. Although the processes are distinctly different, there was considerable component commonality. The components this study focused on include:

- Turbomachinery (design, manufacturing or operating shortfalls which may limit the early commercialization of ACAES application).
- High pressure, temperature, and large diameter alloy valves, control valves, pipes, and fittings.
- High efficiency filtration equipment to minimize potential damages to the turbomachinery.
- Power transmission gears (current design and manufacturing limits).
- Methods to contain thermal expansion of the well casing.
- Major subsystems of a cyclic coal gasification/CAES system.
- Concrete pressure vessel for the A-5 hybrid advanced compressed air storage system.

Task 2 and Task 3. Vendor Survey for Availability Determination; and Problem Areas and Equipment Constraints Identification

1. Turbomachinery Availability

Responses from turbomachinery manufacturers on the state of commercial readiness were far from being uniform. However, several key issues are apparent. They include:

- No manufacturers have turbomachinery trains operating under similar conditions to ACAES/FBC and adiabatic CAES systems; but most turbomachinery manufacturers surveyed are confident that compressors, expanders, and gears can be manufactured to the operating requirement of CAES/FBC and adiabatic CAES applications.
- The estimated developmental/scale-up time frame ranges from two to five years from the date of order. A detailed technical investigation, analysis, and in some cases, a prototype developmental program will be required to upgrade/modify current designs for CAES application.
- Strong market indications (either firm orders which will allow the company to write off developmental cost on the first machine, or strong economic indications that CAES is financially attractive to utilities) will be necessary to stimulate a more active interest on the part of manufacturers to direct resources to upgrading their components for CAES applications.
- From the perspective of depth of technical research required, adiabatic CAES technical issues are more readily identifiable with possible solutions than the ACAES/FBC. In the case of CAES/FBC the potential "showstopper" is the development required for the gas turbine LT100 and the associated coal-fired fluidized-bed system.

2. Commercial Readiness of the Valve Industry

A survey of the valve industry's capabilities to supply large diameter (48" to 96"), high pressure and temperature valves indicated that the valve industry is currently capable of supplying valves in quantity up to 60" diameter for the pressure and temperature ranges required for adiabatic compressed air energy storage (ACAES) systems. Sizes up to 120" diameter have been supplied to refineries for fluid catalytic cracking service; however, the continuing functional ability of these larger diameter valves requires considerable scheduled maintenance for reliable service. All manufacturers surveyed were confident that

60" diameter and larger valves meeting ACAES operation requirements can be met, but it will take a minimum of two years of design modification and testing before a fully functional valve can be manufactured.

3. Commercial Readiness of the Piping and Expansion Joint Industries

- Pipes operating under ACAES conditions are readily available; however, large diameter pipes (greater than 90") will need to be designed and manufactured under ASME pressure vessel code Section VIII, Division I, rather than piping codes specified under ANSI B31.3. The code variance will not affect pipe availability although it will have an impact on its cost.
- Thermal expansion of the well casing is routinely handled by the oil/gas industry when the wells operate at temperatures less than 650°F. Temperatures greater than 650°F will require significant amounts of developmental work in both cement material and cementing practices.
- Above-ground piping stresses due to thermal expansion can be contained by the proper application of currently available expansion joints and the use of expansion loops.

4. Technical Feasibility of a Cyclic Coal Gasification/CAES System

An integrated coal gasification/CAES system was recently conceived as an attractive alternative for generating utility peak-load power. A number of gasification/CAES system concepts have been investigated by several power equipment manufacturers and architectural-engineering firms and a feasibility analysis was performed. The results of the analysis indicated the following:

- It is unlikely that an integrated coal gasification/CAES plant can be operated in a daily cyclic operation such that the coal gasification plant will be shut down and maintain a "hot" standby condition. This is made based on the projected longer response time and potential operating problems resulting from frequent shut down and start up. These operational problems may include the thermal stress on material,

formation of undesirable liquid products, and excess corrosion and embrittlements in a coal gasifier environment.

- It is technically feasible to operate the coal gasification process at partial load (approximately 50%) without adversely affecting the performance of a process. However, the feasibility of such operation hinges on further economic advantages and possible use of fuel gas during off-peak periods.

5. Assessment of Concrete Pressure Vessel for an Advanced Compressed Air Storage Plant

An assessment of the prestressed concrete thermal energy storage (TES) pressure vessel used in a conceptual design of an A-5 hybrid advanced compressed air storage (ACAS) plant reveals that no major problems exist regarding the availability of the concrete and the construction as well as the operation of the vessel. Methods and techniques have been developed, material standards have been established, and logistic problems have been resolved as a result of experience in the nuclear power industry. Reactor containment vessels of nuclear power plants are similar to the TES prestressed concrete pressure vessels and the following factors apply:

- Size of structure - the overall size of a reactor containment vessel is approximately 210 feet high by 150 feet in diameter. The wall thickness of the vessel is 4.5 feet for the side walls and 3.5 feet for the dome, which has a radius of 70 feet. Thus, the inside diameter of the vessel is approximately 140 feet and the volume is approximately 2,600,000 cubic feet.
- Structural characteristics - the vessel is designed and constructed to withstand a light aircraft impact, an earthquake of a magnitude of 6 (Richter Scale) and a reactor accident resulting from equipment failures, loss of coolant (LOCA), and other malfunctions.
- Construction - procedures and material standards have been well defined and documented by the U.S. Nuclear Regulatory Commission. At various stages of constructing the containment vessel, tests are

conducted to assure safety and integrity. Vendors have experienced no problems conforming to the stringent standards and supplying the material.

Task 4. Survey of Current R&D on CAES Related Equipment, Subsystems, and Components

Significant progress was made in gathering and analyzing data for this task. The initial finding is that the Coal Conversion Division at DOE is also concerned with the state of industrial readiness to supply advanced state-of-the-art equipment in a timely manner; however, the operating requirements of some components are less severe than ACAES requirements such that direct analogies are not readily apparent.

TECHNICAL PROBLEMS

No major technical problems occurred that had a significant effect on costs, schedule, or overall project objectives.

PUBLICATIONS

An interim draft report was submitted to Pacific Northwest Laboratory on March 16, 1981.

4.2.2b Adiabatic CAES Development, Thermal/Chemical Screening Tests

K. R. Wheeler

Pacific Northwest Laboratory

OBJECTIVE

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

TECHNICAL PROGRESS

Material Selection

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

Thermal/Chemical Test System

A conceptual design study by Acres American detailed the low pressure (TES 1) and the high pressure (TES 2) storage bed operating conditions. Analysis showed that condensation of water probably would not occur in TES 1. TES 2, however, has a return air temperature low enough to experience condensation under almost all conditions. Water condensation combined with certain industrial air impurities causes a highly corrosive environment for TES materials. It is calculated that the bed operating condition of 1215 psia and 569°F was potential for producing acid

environment. A higher operating temperature of 830°F will promote rapid oxidation of susceptible materials.

A laboratory materials test system featuring a high temperature-high pressure autoclave will subject an approximate 0.1 ft³ volume of each material for an arbitrary but significant time to simulated critical bed conditions. Figure 41 is a schematic of the autoclave system showing capability for moist, contaminated gas to flow through a test column at selected temperature and pressure. Additionally, a pressurized bellows will mechanically load the column to simulate overburden pressure.

FIGURE 41. Simulated TES Material Environment Reaction Column

Simulated TES materials exposure conditions for performance evaluation are:

- Autoclave air pressure: 1215 psia
- Temperature: 569°F (wet surface), 830°F (dry surface)
- Test duration: 30 days
- Air quality: Typical of PEPCO site
- Material stress: Autoclave pressure plus simulated overburden pressure.

Materials Evaluation

All materials are pre-test characterized by structural examination, weight, mechanical and failure properties, and chemical composition.

Following exposure, the materials will again be examined and measured for changes in their mechanical, physical, and structural properties resulting from interaction with the harsh environment. Strength changes, fracture mode, and evidence of surface reaction and structural penetration by acid will be of special interest. Analysis of the autoclave effluent will possibly give evidence of bed decomposition.

Test Status

Samples of taconite (iron ore), Denstone, granite chips, and white cast iron were obtained and characterized. As expected, white cast iron is the strongest and hardest of the materials. Internal stress cracks, however, from cooling during the casting process may be penetration points for corrosion. Cast iron is probably not a serious contender by reason of economy and availability. Denstone is slightly stronger and stiffer than taconite and appears to be more dense. Denstone is significantly more costly than the iron ore and more difficult to obtain in quantity. Granite has several attractive features (cost and availability) but microcracks in some specimens might allow penetration of moisture.

The test system is undergoing final operational checks. Iron ore will be the first material for evaluation in early May.

4.2.3a Conceptual Design/Economic Assessments

F. R. Zaloudek and R. W. Reilly
Pacific Northwest Laboratory

OBJECTIVE

This task is directed towards acquiring, compiling, integrating, and assessing data on all projects related to second-generation CAES concepts. Its objective is to develop recommendations to DOE on which of the second-generation concepts studied should be considered for future research and development activities and to define the nature of these activities.

TECHNICAL PROGRESS

An assessment was made of the relative merits of the adiabatic CAES, hybrid CAES, CAES/PFBC and CAES/CG concepts. This assessment was based on information provided in conceptual design studies performed by Acres American, Inc., United Engineers and Constructors, and United Technologies Research Center. This assessment covered considerations of technological readiness, relative economic benefits, and operational viability of each concept. Only the cycling CAES/PFBC and CAES/CG concepts were included in this study; the continuous combustion versions of these concepts will be considered later. Based on the results of this assessment, recommendations were developed regarding component development activities that should be undertaken pursuant to the goals of the Second-Generation CAES Studies.

SUMMARY OF RESULTS

The results and conclusions of this study are summarized as follows:

- The hybrid CAES and adiabatic CAES concepts appear nearest to technological readiness of the second-generation CAES concepts considered. The only major problem remaining before the design of

a demonstration plant can be undertaken is the identification and characterization of TES materials. This could be accomplished in 2 to 3 years. Other engineering development requirements identified could be addressed during design and construction. The CAES/PFBC concept could possibly be brought to the point where design of a plant could commence in the late 1980s. However, the problems identified are numerous and complex and would require the availability of significant R&D funds. The CAES/CG concept was judged not to be technologically viable in the foreseeable future.

- Both hybrid and adiabatic CAES designs appear to have no significant operationally related problems that would preclude utility acceptance of the basic technology involved. Either the hybrid or adiabatic designs may be perceived by a utility as a superior concept depending on their forecasted fuel availability. The more favorable charging ratio of the hybrid concept may be the deciding factor that would induce a utility to select this concept over the adiabatic concept. The CAES/PFBC design appears to possess attractive performance characteristics and almost no dependence on petroleum fuels. However, its operational flexibility, convenience, and plant availability appears to be less than the hybrid and ACAES designs. Also of importance is the relatively unfamiliarity of U.S. utilities with PFBC technology. This could provide complications in organizing utility participation in a demonstration of this concept. The cycling coal gasifier technology does not appear sufficiently advanced to consider the CAES/CG concept operationally viable.
- It appears that adiabatic CAES has the greatest potential for low cost energy of the second-generation concepts examined. Under base case conditions, the levelized power costs of adiabatic CAES concepts are significantly lower than the other second-generation concepts except at the very high capacity factors ($> .22$) and high charging power costs (25 mills) where all power costs tend to converge. The

levelized power costs for the hybrid concept appear to generally follow the CAES/FBC and CAES/CG except at low capacity factors and low power costs where they improve somewhat. Comparisons of adiabatic CAES with two non-storage peaking/intermediate technologies (combustion turbine and advanced combined cycle) revealed that it enjoys a significant power cost advantage when low cost (10 mill) charging power is available. With high cost charging power, adiabatic CAES loses some of its power cost advantage to the conventional CAES and combined concept plant designs. Similar comparisons with UPH revealed that a 2000 MW UPH design had power cost advantages over adiabatic CAES under all conditions examined. However, when very approximate adjustments were made to UPH power costs to place them on the same unit size basis as the CAES studies, it was found that UPH could lose most of its power cost advantage, and the only differences observed were well within the error band of the calculations. More information on the costs of smaller UPH plants is required before definite conclusions can be drawn regarding the relative cost advantages of these two concepts.

SUMMARY OF CONCLUSIONS

This assessment of second-generation CAES technology led to the following conclusions:

- The adiabatic CAES appears to be the most attractive concept for early demonstration. It is operationally viable, economically attractive, and close to technological readiness. Design of a demonstration plant could proceed in 2 to 3 years if research regarding TES system performance is undertaken in a timely manner.
- The hybrid CAES concept is also a candidate for early demonstration. It is similarly operationally viable and close to technological readiness. However, it is not as economically attractive as ACAES. It has a more favorable charging ratio than ACAES which may make it more attractive to some utilities.

- The CAES/PFBC concept has numerous and complex problems and unknowns that would require a major developmental program to adequately address. Such major development activities generally lie beyond the scope of CAES studies. Perhaps later, when PFBC technology becomes more advanced under sponsorship of other federal government and private programs, this concept may become more attractive.
- The CAES/CG concept with cycling gasifier appears unsuitable for demonstration in the foreseeable future.

RECOMMENDATION SUMMARY

The following recommendations were made to DOE with respect to the specific Second-Generation CAES technologies considered here:

- Research should be undertaken to identify suitable TES materials and define their performance in CAES TES units. This research will benefit both adiabatic and hybrid designs and will bring them both equally well to the status of technological readiness.
- Consider both adiabatic CAES and hybrid CAES as candidates for demonstration. The availability of two concepts for demonstration would allow a prospective cooperating utility some latitude in selecting a system that would fit best into its set of circumstances.
- Defer immediate consideration of CAES/PFBC as a candidate for demonstration. When significant advancement of PFBC technology as a result of other federal and private research and development activities has been accomplished, renewed attention should be given to this concept.

4.2.3b Economic Assessment

R. W. Reilly

Pacific Northwest Laboratory

OBJECTIVE

Economic assessment is an ongoing support function within the CAES Technology Program. Its objective is to define the economic potential of CAES, with emphasis given to assessment of second-generation CAES technologies. The major product is an assessment as to which second-generation CAES technologies have the greatest potential for cost-effective energy storage.

TASKS

During the last year the major tasks have been:

Task 1. Economic Screening Studies for Advanced CAES Designs

- CAES coupled to thermal energy storage
- Solar-coupled CAES
- Direct steam-fired CAES

Task 2. Evaluation and Comparison of the Results of DOE/Utility/EPRI Compressed Air Energy Storage Design Studies

- Development of a general analytical approach and a set of acceptable economic parameters to be used in CAES economic analyses
- Review of the independent CAES design study final reports
- Normalization of the cost/design estimates in these reports to widely applicable standards
- Estimation of busbar costs.

Task 3. Investigation into the Feasibility of a CAES Reliability Study

- Review of reliability assessment methods
- Determining the availability of reliability data for above ground equipment

- Determining the availability of reliability data for hard rock caverns, solution-mined salt deposits, and well-aquifer systems
- Recommendations for future CAES reliability studies.

Task 4. Support to the Utility Applications Program

- Providing general economic information, including the cost of energy from alternative generation modes
- Reviewing capital cost estimates and making comparisons against other CAES cost estimates to determine if they are realistic estimates.

TECHNICAL PROGRESS

Task 1. Economic Screening Studies for Advanced CAES Designs

Economic screening studies were made for three different types of advanced CAES technologies.

The first investigation compared the economic performance of six CAES configurations, two conventional, two hybrid, and two adiabatic designs. The technical information was taken from three independent studies of CAES coupled to thermal energy storage devices. The results suggest that CAES/TES is economically competitive with conventional CAES and oil-fired turbomachinery for peaking and intermediate use. And, under the condition of inexpensive charging energy, CAES/TES exhibits considerable economic advantage over these other technologies. The results of this analysis were presented at the 15th Intersociety Energy Conversion Engineering Conference in Seattle.

A second screening analysis was performed for a solar/CAES hybrid, wherein a solar central receiver is used for heat topping in an adiabatic CAES plant. The results indicate that (at a 20% capacity factor) the solar/CAES hybrid can supply electricity more cheaply than a solar-thermal plant, and that under conditions of high compression energy cost, a solar plant can be attractive relative to an adiabatic CAES plant. The results were submitted to the program office in an informal report, and served as the basis for a successful proposal for a more in-depth study.

A third brief economic analysis was made for a coal/steam electric design that utilizes both CAES and TES storage devices. The plant is configured so that the steam turbine is directly shafted to the compressor, thus eliminating generator, motor, and transmission line losses. The heat of compression is used for feedwater preheating, and a TES unit, charged by a continuously operating steam generator, is used for reheating the compressed air before power generation. The results indicate that the direct-coupled steam CAES plant is economically attractive as an intermediate load generation device as compared to a cycling steam plant or an oil-fired combined cycle plant. The degree of interdependency between components, however, may lead to expensive control equipment and decreased reliability. The results were submitted to the program office in an informal report, and will be presented at the 16th Intersociety Energy Conversion Engineering Conference in Atlanta.

Task 2. Evaluation and Comparison of the Results of DOE/Utility/EPRI
Compressed Air Energy Storage Design Studies

The final reports from six major U.S. CAES design studies are now available; this task compares the economic performance of those designs. The CAES technologies represented in the studies are conventional CAES (2), adiabatic CAES/TES, hybrid CAES/TES, CAES coupled to fluidized bed combustors, and CAES coupled to coal gasification units. The economic comparison is composed of two parts: 1) development of comparable capital cost estimates for the technologies, and 2) estimation of the cost of producing (storing) electricity from these technologies.

During the capital cost normalization process, the basic engineering designs developed by the A&E firms were not altered, so as to minimize the introduction of error. Rather, balance-of-plant items (such as land cost, switchyard size, and cooling systems) were standardized, ensuring that the economic comparisons reflect differences in the technologies, rather than differences in ancillary systems.

The major components of the normalization process are outlined below:

- All cost estimates were converted to midyear 1979 price levels.
- All labor and supply costs were normalized to a site on the northeast coast of the United States.
- All turbomachinery cost estimates were normalized to single-plant cost estimates (i.e., assumptions of mass production were eliminated).
- All turbomachinery was assumed housed in turbomachinery buildings, rather than weatherized for external deployment.
- Switchyards were normalized to breaker-and-a-half designs; one line was assumed intercepted for 220 MW_e plants, two lines for 800 to 1000 MW_e plants.
- All cooling cost estimates were normalized (on a \$/kW_t-rejected basis) to wet cooling using mechanical draft wet cooling towers.
- All optional cost items unique to a particular design were eliminated.
- The hybrid cost estimate was adjusted to include two TES filter systems and a TES bypass.

Indirect costs were applied to the normalized direct cost estimates on a consistent basis. Fifteen percent of direct cost was allowed for design and construction management. Contingency was applied on a variable basis to reflect relative uncertainty: 15% of direct cost was allowed for turbomachinery, cavern construction, thermal energy storage devices, fluidized bed combustors, and coal gasification units; 5% was allowed for the remainder of the capital cost estimate, including land, switchyard, and balance-of-plant items.

The economic performance of the normalized plant designs was compared using the levelizing methodology presented in the EPRI Technical Assessment Guide (1979). Life-cycle busbar costs were estimated for a set of base-case economic assumptions, and then some of these assumptions were varied to investigate the relative busbar costs under alternative

scenarios. All busbar estimates were made over a range of capacity factors (.075 - .250). Two compression energy costs (10 mills/kWh and 25 mills/kWh) were selected to investigate the effect of variation in charging cost.

The base case represents a situation where fuel oil costs escalate at only a moderate rate (8%/yr) with respect to coal (7%) and compression energy (7%) costs. The results in Figure 42 indicate that, in general, adiabatic CAES generates lowest cost power at the low charging energy cost, whereas conventional CAES is least expensive at high charging energy costs. The other CAES concepts (hybrid, CAES/FBC, and CAES/CG) become competitive only at the high capacity factors for the high compression energy cost situation.

In Figure 43 conventional and adiabatic CAES are compared against oil-burning peaking (combustion turbine) and intermediate load (combined

FIGURE 42. Comparison of the CAES Technologies under Base-Case Conditions

FIGURE 43. Comparison of Conventional and Adiabatic CAES Against Alternative Peaking/Intermediate Load Technologies

cycle) technologies. At the low compression energy cost, the CAES technologies are distinctly less expensive than the oil-fired units. At the high compression energy cost, CAES technologies are more economic than the combustion turbine, but the oil-fired combined cycle plant generates less costly energy than either of the CAES technologies.

In Figure 44, the two CAES units are compared against a 1000 MW_e underground pumped hydro storage plant. The capital cost estimate for UPHS was provided by Acres American. Since the UPHS plant has an expected lifetime of 50 years, the levelized costs of both conventional and adiabatic CAES were recalculated based upon the same lifetime.

FIGURE 44. Comparative Economic Performance of CAES and UPHS under Base-Case Conditions. All storage units are sized for 10 hours storage. Plant lifetime is assumed to be 50 years. The CAES turbomachinery and TES fill (adiabatic CAES) are assumed to be replaced at 25 years.

The turbomachinery for both plants and the TES fill were assumed to be replaced after 25 years of operation. At 10 mills/kWh charging cost, UPHS is slightly more economic than adiabatic CAES, and considerably more economic than conventional CAES. At the higher 25 mills/kWh charging cost, UPHS has a greater advantage over adiabatic CAES (due to its lower EER), but conventional CAES has become more competitive, even becoming the least expensive of the three at low capacity factors.

If we assume all of the original base-case parameters, but escalate fuel oil prices at 10% per year (3% over coal and compression energy), then adiabatic CAES is the most cost effective under all circumstances investigated (see Figure 45). At the low compression energy cost, adiabatic

FIGURE 45. Comparison of CAES Technologies under a High Fuel Oil Price Escalation Assumption. (10% vs. 7% for Coal and Compression Energy).

CAES is considerably more economic than the other CAES technologies and the oil-fired generation plants. At the higher compression energy cost, coal gasification and fluidized bed combustion approach the economic performance of adiabatic CAES. The relationship between adiabatic CAES and UPHS remains unchanged from the base case, since neither of them burn fuel oil.

The cost of capital and fixed charge rate employed in the analysis thus far are those suggested by EPRI in the Technical Assessment Guide (1979) for analysis of future generation technologies. These rates

represent a typical financial structure for a private utility. The effect of a municipal utility financing structure on the economic performance of the CAES technologies is investigated in Figure 46. The assumed cost of capital is 8% and the fixed charge rate is 12%; all other assumptions are the same as in the base case. Such an assumption favors the more highly capital intensive technologies, and this effect is evident in the curves. At the low compression energy cost adiabatic CAES exhibits considerable advantage over its closest competitors; at the higher compression energy cost, adiabatic CAES maintains a small advantage over its competitors, except below about 12% capacity factor, where the oil-fired combined cycle plant is least expensive.

FIGURE 46. Comparison of the Economic Performance of CAES Technologies under Municipal Financing (Cost of Capital = 8%; Fixed Charge Rate = 12%)

The results of this task will be presented at the 16th Intersociety Energy Conversion Engineering Conference in August 1981.

Task 3. Investigation into the Feasibility of a CAES Reliability Study

The CAES reliability feasibility study is still in progress. Activities to date include a review of reliability assessment methodologies, definition of a recommended modeling approach, and initial investigations into the availability of reliability data for above-ground generating equipment and for below-ground storage. This task will be completed by the end of fiscal year 1981.

Task 4. Support to the Utility Applications Program

General economic assessment support has been provided to the program office and to utilities considering CAES under this task. In general this effort has consisted of reviewing capital cost estimates for CAES plants, comparing these estimates to the normalized estimates derived under Task 2, and supplying other information (such as the cost of energy from alternative generation technologies). There will be no formal report on this task.

TECHNICAL PROBLEMS

There have been no technical problems encountered in the economic assessment support function. Delays in the publication of several of the independent CAES design studies have caused the output of Task 2 to be delayed beyond its original target date.

PUBLICATIONS

R. W. Reilly, "The Economics of Compressed Air Energy Storage with Thermal Energy Storage," presented at the 15th Intersociety Energy Conversion Engineering Conference, August 18-22, 1980, Seattle, Washington.

DISTRIBUTION

<u>No of Copies</u>		<u>No of Copies</u>	
	<u>OFFSITE</u>	228	DOE Technical Information Center
	Acres American, Inc. Attn: D. Willett Liberty Bank Building Main at Court Buffalo, NY 14202	5	US Department of Energy Attn: S. Strauch Office of Energy Systems Res. (CS-66) Forrestal Building (Room 1G-080) 1000 Independence Ave., S.W. Washington, DC 20585
	Acres American, Inc. Attn: M. J. Hobson The Clark Building Suite 329 Columbia, MD 21044		US Department of Energy Attn: J. H. Swisher Office of Energy Systems Res. (CS-66) Forrestal Building (Room 1G-080) 1000 Independence Ave., S.W. Washington, DC 20585
	Bechtel National Inc. Attn: W. Stevens (50/20/B37) Res & Eng. PO Box 3965 San Francisco, CA 94119		US Department of Energy Attn: J. Gahimer Office of Energy Systems Res. (CS-66) Forrestal Building (Room 1G-080) 1000 Independence Ave., S.W. Washington, DC 20585
	Black and Veatch Attn: D. R. Bervig 1500 Meadow Lake Parkway PO Box 8405 Kansas City, MO 64114		US Department of Energy Attn: A. A. Churm Chicago Patent Group Chicago Operations Office 9800 South Cass Avenue Argonne, IL 60439
	Central Illinois Public Service Co. Attn: A. H. Warnke Vice President Power Supply 607 East Adams Street Springfield, IL 62701		US Department of Energy Attn: CP Demos Chicago Operations Office 9800 S. Cass Avenue Argonne, IL 60439
	Commonwealth Edison Co. Attn: T. J. Maiman Sta. Mech. Engr. Dept. Mgr. 36 FN West PO Box 767 Chicago, IL 60690	5	US Department of Energy Attn: B. Gallagher Office of Energy Systems Res. (CS-66) Forrestal Building (Room 1G-080) 1000 Independence Ave., S.W. Washington, DC 20585
	Commonwealth Edison Co. Attn: D. E. DeViney 1319 South First Avenue Maywood, IL 60153		

No of
Copies

US Department of Energy
Attn: J. Mathur
Division of Environmental
Safety and Engineering
MS-E201, Germantown
Washington, DC 20545

US Department of Energy
Library
Mail Station G-043
Washington, DC 20585

US Department of Energy
Library, Attn: R. F. Kimberlin
Room 1223
Washington, DC 20585

US Department of Energy
Attn: L. J. Rogers
Division of Generation and
Storage Applications
Office of Electric Energy Sys.
12 & Pennsylvania, M/S 3344
Washington, DC 20585

Electric Power Research Instit.
Attn: R. B. Schainker
PO Box 10412
3412 Hillview Avenue
Palo Alto, CA 94304

Electric Power Research Instit.
Attn: A. Ferreira
c/o NEPLAN
174 Brush Hill Avenue
West Springfield, MA 01089

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

No of
Copies

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

Lawrence Berkeley Laboratory
Attn: Library
University of California
Bldg 50, Room 134
Berkeley, CA 94720

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

Lawrence Livermore Laboratory
Attn: T. Barlow
PO Box 808
Livermore, CA 94550

Los Alamos Scientific Laboratory
Attn: Jim Blacic
G-6-LASL-Stop 978
PO Box 1663
Los Alamos, NM 87545

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

Marchwood Engineering Labs
Attn: I. Glendenning
Head of Long-Term Studies
Southampton, England

Massachusetts Institute of Tech.
Attn: J. L. Nash-Webber
Energy Lab
Cambridge, MA 02139

No of
Copies

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

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

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

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

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

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

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

Sandia Laboratories
Attn: Tech. Library Div. 3141
Albuquerque, NM 87185

Sandia Laboratories
Attn: H. M. Dodd
Organization 5743
Albuquerque, NM 87115

No of
Copies

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

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

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

Soyland Power Cooperative, Inc.
Attn: Royal B. Newman
PO Box A1606
Decatur, IL 62525

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

Tennessee Valley Authority
Attn: Gerald Phillips
1150 Chestnut, Tower 2
Chattanooga, TN 37401

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

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

No of
Copies

No of
Copies

United Technologies Research
Center

Attn: R. D. Lessard
Silver Lane
East Hartford, CT 06108

University of California
Attn: T. L. Brekke
Department of Civil Engineering
1847 Yosemite Road
Berkeley, CA 94707

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

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

University of Wisconsin
Attn: H. J. Pincus
Dept. of Geological Sciences
Sabin Hall and Greene Museum
PO Box 413
Milwaukee, WI 53201

Westinghouse Electric Corp.
Attn: W. F. Kobett
CAES Project Manager
Combustion Turbine Sys. Div.
Long Range Develop-Lab 100
PO Box 251
Concordville, PA 19331

Westinghouse Electric Corp.
Attn: D. Ayers
Manager, Fluid Systems Laboratory
1291 Cumberland Avenue
West Lafayette, IL 47906

ONSITE

2 DOE Richland Operations Office

D. K. Jones
H. E. Ransom

33 Pacific Northwest Laboratory

R. D. Allen
T. J. Doherty
J. R. Eliason
R. L. Erikson
L. D. Kannberg (15)
J. E. Minor
R. Raymond
R. W. Reilly
J. A. Stottlemire
A. M. Sutey
L. E. Wiles
F. R. Zaloudek
Technical Information (5)
Publishing Coordination (2)