**Pacific Northwest Laboratory
Annual Report for 1978
to the DOE Division of
Energy Storage Systems**

**Compressed Air Energy Storage
Technology Program**

June 1979

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PACIFIC NORTHWEST LABORATORY
ANNUAL REPORT FOR 1978
TO THE
DOE DIVISION OF ENERGY
STORAGE SYSTEMS

COMPRESSED AIR ENERGY STORAGE
TECHNOLOGY PROGRAM

by
W.V. Loscutoff
Staff Members and Subcontractors
of Pacific Northwest Laboratory

June 1979

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON 99352

PREFACE

The 1978 Annual Report from the Pacific Northwest Laboratory (PNL) to the DOE Division of Energy Storage Systems is the first report covering a full year's work since PNL became the lead laboratory for DOE's Compressed Air Energy Storage Technology Program. The report describes all of the major research conducted during the calendar year 1978 and includes work that was initiated prior to the reporting period. It also includes preliminary reports on several new projects initiated during 1978.

The two parts of the report are oriented toward particular segments of the CAES program. Part I reports on research performed to establish design and stability criteria for CAES reservoirs. Part II reports progress on research performed on advanced CAES concepts. The report consists of project reports authored by research engineers and scientists from PNL, Argonne, Massachusetts Institute of Technology, University of Wisconsin, Louisiana State University, and several companies representing the industry. 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. The contributing staff has responded to numerous requests from DOE during the year for planning and for special assistance.

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, to the editors who edited the individual project reports, and to Sue Arey who assembled, typed and assisted in editing the annual report.

W.V. Loscutoff
Project Manager
Compressed Air Energy Storage

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COMPRESSED AIR ENERGY STORAGE TECHNOLOGY PROGRAM

FOREWORD

Compressed air energy storage (CAES) is a technique for supplying electric power to meet peak load requirements of electric utility systems. It incorporates a modified state-of-the-art gas turbine and an underground reservoir---an aquifer, a salt cavity, or a mined hard rock cavern. The compressor and turbine sections of the gas turbine would be alternately coupled to a motor/generator for operation during different time periods. During nighttime and weekend off-peak periods, low-cost power would be used to compress air which would be stored in the underground cavern. During the subsequent daytime peak-load periods, the compressed air would be withdrawn from storage, mixed with fuel, burned, and expanded through the turbines to generate peak power. This concept reduces the consumption of premium fuels by more than 60 percent for conventional CAES systems. Some advanced CAES concepts do not require any premium fuels at all.

Studies have shown that the CAES concept is technically feasible and, under certain conditions, may be economically viable. CAES systems offer several advantages over conventional systems used by utilities for meeting peak load requirements. Replacement of current gas turbines by CAES plants could result in annual savings of more than 100,000,000 barrels of oil. The net annual oil saving would be greater in the future. CAES 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 compared to the conventional peaking plant.

The development of CAES technology is a recognized objective of the DOE Division of Energy Storage Systems. The specific objectives are to develop the technology on reservoirs in order to accelerate the commercialization of the concept and to develop advanced CAES concepts

that will eliminate dependence of the concept on petroleum fuels for operation. The program has two major program elements--Reservoir Stability Studies and Advanced Concepts Studies. The Reservoir Stability Studies are aimed at development of stability and design criteria for CAES reservoirs. The Advanced Concepts Studies are directed at developments of CAES plants that will require little or no petroleum fuels for operation. This program is a multi-year activity sponsored by the Division of Energy Storage Systems.

The CAES Technology Program was initiated in 1975 and has developed into a fairly comprehensive program in 1978. The scope of the program includes the following:

- technical and economic feasibility of CAES
- conceptual (site specific) designs of CAES plants
- preliminary evaluation of technical and economic feasibility of no-oil CAES concepts
- preliminary analysis of two-stage (thermal storage and air storage) concepts
- preliminary design and stability criteria for reservoirs
- parametric analysis of flow characteristics and thermal development of aquifer reservoirs
- preliminary analysis of CAES equipment development needs
- numerical analysis of the behavior of CAES reservoirs
- laboratory studies of the behavior of CAES reservoirs
- feasibility studies of advanced concepts
 - coal-fired fluidized-bed combustion with CAES
 - coal gasification with CAES
 - thermal energy storage with CAES
 - advanced CAES cycles
- field studies of CAES reservoirs.

The above activities complement and support the needs of the joint DOE/EPRI CAES Development Program currently under way with three participating utilities.

The 1978 Annual Report presents progress on the work funded by the Division of Energy Storage Systems with support from the Division of Electrical Energy Systems. The report is in two parts, corresponding to the two program elements: Reservoir Stability Studies and Advanced Concept Studies. In each part, articles describe progress made during the calendar year 1978 on individual projects.

PART I - RESERVOIR STABILITY CRITERIA

RESERVOIR STABILITY CRITERIA

W.V. Loscutoff - PNL

1.0 INTRODUCTION

1.1 OBJECTIVE

The primary objective of the Reservoir Stability Studies program is to establish design and stability criteria for underground CAES reservoirs. Comprehensive and reliable criteria of this kind are necessary for the commercialization of CAES technology by the utility industry.

1.2 BACKGROUND

Among the unknowns which affect the technical and economic viability of compressed air energy storage are those related to the response of an underground reservoir to pressure and temperature fluctuations that will be encountered in the daily charge and discharge operations. The thermo-mechanical effects and stresses generated by the pressure and temperature fluctuations could conceivably cause chemical and mechanical damage to porous aquifer structures and cavern walls. Certain conditions might lead to surface deterioration which could contribute to plugging of aquifer pores or contribute to particle carryover to the turbines. Fracturing could occur in aquifers or caverns leading to leakage or other damage. In mined caverns, spalling and further disintegration of the walls could lead to successive caving, blowouts, and, eventually, to total collapse and surface subsidence. The possibility of such problems is often mentioned in the literature, but virtually no data are available to predict the conditions under which problems might be expected, the actions required to prevent their occurrence, or the consequences of any failures which might occur. There are only a few criteria that are available to define stability of air storage reservoirs subjected to daily thermal and pressure fluctuations over a period of 30 years. This presents a barrier to immediate and economically feasible implementation of the concept. To eliminate this barrier to commercialization of the CAES concept, a number of studies have been established within the CAES Technology Program.

1.3 SCOPE

The Reservoir Stability Studies are divided into three areas of activity according to the three major types of reservoirs, aquifers, hard rock caverns and salt cavities, that may be used with a CAES plant. Four phases of activity are either in effect or planned for each type of reservoir. These phases are aimed at stepwise development of reservoir design and stability criteria as follows:

Phase 1. Preliminary criteria based on state-of-the-art surveys.

Phase 2. Supplementary criteria based on numerical studies.

Phase 3. Supplementary criteria based on laboratory studies.

Phase 4. Final criteria based on field studies.

The program outline is shown in Figure 1.1. This approach was dictated by the need to provide critical technical information to the utilities involved in the DOE/EPRI demonstration program. Each of the phases are subdivided into specific tasks. This section reports on the progress achieved in these tasks during 1978. The reservoir stability studies within PNL have been summarized here by the staff members performing the effort. The studies carried out by agents under subcontract to PNL were summarized by L. D. Kannberg for this report. Certain portions of the summaries appear verbatim from reports submitted by the subcontractor.

FIGURE 1.1. CAES Reservoir Stability Program Outline

2.0 FLUID FLOW AND THERMAL ANALYSIS FOR CAES IN POROUS ROCK RESERVOIRS

L.E. Wiles and L.D. Kannberg - PNL

The purpose of analysis of the hydrodynamic and thermodynamic response to mass cycling in CAES porous rock reservoirs is to provide design guidelines for the efficient and stable operation of the air storage reservoir. The performance of the reservoir depends on reservoir material properties, reservoir geometry, and operating conditions. The influence of many of the important parameters was investigated at PNL in FY-1977. That analysis made use of a computer code based on one-dimensional, radial transport of mass and energy in a dry porous rock reservoir.⁽¹⁾

The capability of the code was extended in FY-1978 to permit the analysis of the effects of water on reservoir performance. Potential problems or areas of concern related to the presence of water in the reservoir that could be evaluated with a one-dimensional model were identified. These include deliverability, thermal energy recovery, working fluid recovery and storage volume. It was the objective of this study to quantify the magnitudes of these effects. This was done by evaluating the influence of injection temperature, injection humidity and residual water content on reservoir performance.

While the performance of the bulk of the reservoir and the influence of individual parameters can be reasonably characterized by the one-dimensional modeling, the delineation of the influences of the vertical boundaries, potential stratification of permeability, and gravity effects requires two-dimensional modeling. Code development and analysis to this end was also done at PNL in FY-1978.

A description of the two-dimensional code is discussed in this section. The study on the effects of water on one-dimensional reservoir performance was presented at the 1978 Mechanical Energy Storage Contractors Meeting and have been published in the proceedings of that meeting.⁽²⁾ Hence it will not be presented here. The reader is asked to refer to the reference for details of that study.

2.1 TWO-DIMENSIONAL ANALYSIS OF DRY RESERVOIRS

2.1.1 Theoretical Development

2.1.1.1 Basic Assumptions

In general, the hydrodynamic and thermodynamic behavior of a CAES porous rock reservoir can be characterized by a set of conservation equations that describe the flow of an air-vapor mixture and liquid water through a rigid porous material. A number of assumptions must be made such that the resultant set of equations does not include terms irrelevant to CAES in porous rock reservoirs. These assumptions are:

- The air-vapor mixture is homogeneous and behaves as an ideal gas.
- The rock porosity, density, and heat capacity are constant.
- The rock is immobile.
- Binary diffusion in the air-vapor mixture is negligible.
- Inertial effects are negligible.
- The air-vapor mixture, liquid, and rock are in thermal equilibrium.
- Kinetic energy is negligible.
- Viscous dissipation of energy is negligible.

2.1.1.2 Reduced Equations

Additional assumptions were made to facilitate the study of this problem. These include:

- The transport of mass and energy occurs in the radial and vertical directions.
- The reservoir and the air are dry.
- Darcy's law applies.

With these assumptions the governing equations reduce to the following:

Conservation of mass

$$\phi \frac{\partial \rho_a}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left(\rho_a r \frac{k_r}{\mu} \frac{\partial P}{\partial r} \right) - \frac{\partial}{\partial z} \left\{ \rho_a \frac{k_z}{\mu_a} \left(\frac{\partial P}{\partial z} - \rho_a g \right) \right\} = 0 \quad (2-1)$$

Conservation of energy

$$\phi \frac{\partial T}{\partial t} = \frac{1}{(1-\phi)\rho_s C_s} \left[-\phi \frac{\partial}{\partial t} (\rho_a u_a) + \frac{1}{r} \frac{\partial}{\partial r} (\rho_a h_a r \frac{k_r}{\mu_a} \frac{\partial P}{\partial r}) \right. \\ \left. + \frac{\partial}{\partial z} \left\{ \rho_a h_a \left(\frac{k_z}{\mu_a} \frac{\partial P}{\partial z} - \rho_a g \right) \right\} + \frac{1}{r} \frac{\partial}{\partial r} (Kr \frac{\partial T}{\partial r}) + \frac{\partial}{\partial z} (K \frac{\partial T}{\partial z}) \right] \quad (2-2)$$

Details of the solution method are beyond the scope of this discussion. Those details will be provided in a topical report to be issued in FY-1979.

2.1.1.3 Boundary Conditions

The geometry adapted to this two-dimensional (2-D) analysis is shown in Figure 2.1. The radial boundary conditions are similar to those specified for the one-dimensional analysis. At the well boundary, however, pressures are specified that were computed by the one-dimensional dry model of FY-1977 to provide approximately constant mass flow rates.

FIGURE 2.1. Geometry of the 2-D Reservoir Model

The code will be modified at a later date to include computation of heat transfer and fluid dynamics in the wellbore. This modification will permit more realistic simulation of two-dimensional reservoir storage dynamics than use of the one-dimensional code boundary condition computations.

The boundaries between the porous zone and the cap rock and basement rock are closed to mass transfer. Heat is lost to these regions by conduction.

2.1.2 Analysis of Vertical Effects

The intent of this analysis is to quantify the influence of vertical boundaries, stratification of permeability, and gravity on the performance of a dry reservoir.

The reference conditions given in Table 2.1 were used in this analysis. Those conditions apply to the storage zone. Additional parameters are given in Table 2.2. Material properties such as permeability and thermal conductivity were assumed to be isotropic. The weekly charge and discharge cycle as described in Reference 2, was applied. The overburden was assumed to be a thermal insulator. The geothermal gradient was taken as $0.02^{\circ}\text{F}/\text{ft}$ ($0.036^{\circ}\text{C}/\text{m}$).

2.1.2.1 Analysis of the Reference Reservoir

The analysis of the reference reservoir permits an evaluation of the influence of the vertical boundaries and gravity on the performance of the reservoir. This analysis can also be used to judge the usefulness of the one-dimensional modeling.

Temperature profiles are shown in Figure 2.2 for a homogeneous, dry reservoir. This result was obtained after completion of the final charging cycle of the first week of simulated reservoir operation. The temperature profiles indicate that very little thermal energy is lost to the cap rock or basement rock. Since there is no convection in the cap rock or basement rock, then the model dictates that thermal energy transport depends entirely on conduction, which is extremely slow. The

TABLE 2.1. Reservoir Parameters

Parameter	Reference Value
Geometry	
Reservoir Diameter	400 ft (122 m)
Well Diameter	7 in (18 cm)
Properties	
Porosity	20%
Permeability	500 md
Rock Thermal Conductivity	$1.25 \frac{\text{Btu}}{\text{hr-ft-}^{\circ}\text{F}}$ ($2.16 \frac{\text{W}}{\text{m-}^{\circ}\text{C}}$)
Rock Thermal Capacity ($\rho_s C_s$)	$3.91 \frac{\text{Btu}}{\text{ft}^3\text{-}^{\circ}\text{F}}$ ($2.62 \frac{\text{MJ}}{\text{m}^3\text{-}^{\circ}\text{C}}$)
Operating Conditions	
Nominal Pressure	50 atm (5070 kPa)
Mass Flow Rate	
Injection	$0.119 \frac{\text{lbm}}{\text{sec-ft}}$ ($0.177 \frac{\text{kg}}{\text{s-m}}$)
Extraction	$0.158 \frac{\text{lbm}}{\text{sec-ft}}$ ($0.235 \frac{\text{kg}}{\text{s-m}}$)
Initial Reservoir Temperature	100°F (38°C)

TABLE 2.2. Additional Reference Conditions Applied to the 2-D Analysis

<u>Parameter</u>	<u>Reference Value</u>
Geometry	
Cap Rock Thickness	37.5 ft (11 m)
Storage Zone Thickness	100 ft (30 m)
Basement Rock Thickness	50 ft (15 m)
Properties (Basement Rock and Cap Rock)	
Permeability	0
Porosity	0
Operating Conditions	
Injection Temperature	450°F (232°C)
Well Pressures	Computed by code development in FY-1977 to approximate flow rates given in Table 2.1.

FIGURE 2.2. Temperature Profiles in the Homogeneous Reservoir

result also indicates that buoyancy effects are not significant in the homogeneous reservoir. Heating of the rock occurs somewhat uniformly in the radial direction. Thus, there are no significant vertical temperature differentials to create a noticeable buoyancy component.

The thermal development and pressure cycling in the bulk of the reservoir agrees with that predicted by the one-dimensional model. Thus, the one-dimensional model can be used to characterize the performance of the bulk of a homogeneous reservoir with equal accuracy but at a much lower cost.

2.1.2.2 Stratified Permeability

A horizontal layer (i.e., a cylindrical disc) having a permeability of 50 md was defined to exist between zones having permeabilities of 500 md. The layer was 15 ft (4.6 m) thick and was centered halfway between the cap rock and basement rock.

In Figure 2.3 vertical temperature profiles are shown after completion of the final charging cycle of the first week of simulated reservoir operation. The results show that thermal development of the low-permeability zone is significantly diminished. However, comparison of Figures 2.2 and 2.3 show that thermal development of the 500-md zones, the cap rock, and basement rock is not noticeably affected by the presence of the low-permeability layer.

2.1.3 Conclusions and Recommendations for Further Study

A two-dimensional model was developed to analyze the performance of dry, nonhomogeneous reservoirs. Initial analyses were performed to evaluate vertical heat losses and gravitational effects, both of which appear to be small. Also, the results show that the one-dimensional model developed at PNL in FY-1977 is an equally valid tool for describing the performance of the bulk of a homogeneous reservoir.

The capability to analyze nonhomogeneous reservoirs and other vertical transport effects has been demonstrated. Continued code

FIGURE 2.3. Temperature Profiles in the Stratified Reservoir

development is in progress which improves the efficiency of the calculations. A parametric evaluation of possible nonhomogeneous reservoir structures will follow successful completion of that effort.

In addition, temperature and pressure profiles computed by the two-dimensional code are necessary for evaluation of the potential for failure of reservoir integrity due to thermomechanical stress behavior. Thus, data from the code will be used as input to the stress analysis.

2.2 REFERENCES

1. G.C. Smith, J.A. Stottlemire, L.E. Wiles, W.V. Loscutoff, H.J. Pincus, FY-1977 Progress Report: Stability and Design Criteria Studies for Compressed Air Energy Storage Reservoirs. PNL-2443, Battelle, Pacific Northwest Laboratory, Richland, WA 99352, March 1978.

2. L.E. Wiles, "Fluid Flow and Thermal Analysis for CAES in Porous Rock Reservoirs." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors Review Meeting. CONF-781046, Luray Virginia, October 1978.

3.0 STRUCTURAL ANALYSIS IN POROUS MEDIA

J.R. Friley - PNL

The objective of the numerical structural analysis investigation was to determine the stress and strain level of a generic porous rock reservoir as a result of the pressure and temperature loads incurred. Structural response of the various rock masses involved is an item which needs attention when the selection of a porous rock site is to be made. Potential areas of concern in this regard involve cap rock crack development and fatigue stress damage of both porous and non-porous rock masses. Excessive crack formation (or enlargement of existing cracks) in the site cap rock will allow air leakage and hence tend to degrade site performance. Fatigue stress levels, if excessive will tend to promote crack growth and/or produce contaminants in the form of sand particles or "fines". This later structural effect will be an important consideration in assessing the likelihood of pore plugging and the performance of turbomachinery components.

3.1 BACKGROUND

Unlike man-made materials, rock is seldom a uniform and continuous medium. Rock properties are likely to vary from one location to another even within a particular site. In addition, joints or faults within the rock masses will influence the reservoir response to CAES structural loadings. The results of the analyses to be presented here are of a generic site and reflect those site dependent anomalies. Hence, the structural model's applicability should be interpreted with this in mind.

The theory upon which this structural modeling was based assumed that the thermal and flow characteristics of porous CAES reservoirs were completely independent of the structural response. A discussion of thermal/flow modeling precedes this discussion (Section 2.0). Structural analysis to be presented in this section made use of rock temperatures and pore pressures obtained from that modeling.

A porous elastic material subjected to pore pressure loading is somewhat of a novelty in the general field of structural analysis. The bulk of the work in this field deals with ground water flow and seepage problems. In these instances, typical conditions are such that flow and structural equations are coupled and must therefore be solved simultaneously. These conditions prevail when the stiffness (bulk modulus) of the flowing medium is appreciable when compared to the stiffness of the porous material. For the analysis at hand, the flowing medium is a gas and hence decoupling the two phases seems appropriate.

The analysis procedure on which the modeling is based makes use of a poroelastic formulation. A more detailed description of the method is given in Reference 1. Using indicial notation, the elastic stress strain equations in this formulation are:

$$\epsilon_o = \frac{1-2\nu}{E} (1-\beta)P + \alpha(T-T_o) \quad (3-1a)$$

$$\sigma_{ij} = (Pf) \delta_{ij} + E_{ijkl} [\epsilon_{kl} - \epsilon_o \delta_{kl}] \quad (3-1b)$$

The equilibrium condition is

$$[\sigma_{ij} - (Pf)\delta_{ij}]_{,j} = 0 \quad (3-2)$$

Here, $(,j)$ denotes partial differentiation with respect to the j^{th} coordinate direction.

The above formulation is an initial strain formulation and as such, standard finite element procedures are applicable.⁽²⁾ These equations were implemented by using a modified version of the computer code AXISOL.⁽³⁾ For the treatment of elastic material containing a pore pressure, the thermoelastic portion of that code was modified to consider the initial strain due to pore elastic as well as thermoelastic effects. In addition, normal stress terms were modified by a factor of (pf) as indicated by Equations 3-1 and 3-2. The implementation of these two

steps allows treatment of pore pressure effects as an analog of a thermoelastic formulation. Cap rock and base rock masses of course utilized the conventional thermoelastic formulation.

Some insight can be gained regarding the relative structural effects of temperature and pore pressure loading in the porous zone by comparing the relative magnitudes of the two initial strain components of Equation 3-1b. Material values thought to be similar to those encountered in a porous medium are shown in Table 3.1. Using these values, a pressure of 600 psi causes an initial strain similar to that of a 10°F temperature change. Normal operating conditions used in this study had pressure values of approximately 690 psi and temperatures of several hundred degrees fahrenheit in the wellbore vicinity. For this reason, it is believed that nonuniform thermal loading will probably have greater structural influence than pore pressure loading.

TABLE 3.1. Structural Analysis Material Properties

	<u>Cap Rock and Base Rock</u>	<u>Porous Rock</u>
E (psi)	4.65×10^6	4.35×10^6
ν	0.25	0.25
$\alpha \frac{\text{in}}{\text{in}^\circ\text{F}}$	5.6×10^{-6}	5.6×10^{-6}
f	_____	20%

The structural model used in this investigation is shown in Figure 3.1b. The generic site was assumed to be axisymmetric and was chosen to be compatible in geometry and depth to the model used for the determination of temperatures and pore pressure. Site depth was assumed to be 562 ft (measured from the top face of the cap rock). Overburden loading was simulated by imposing a vertical load corresponding to 1 psi per foot of depth.

Boundary conditions for the model consisted of radial restraints at the outer boundary and vertical restraints at the lower boundary. These boundary conditions and the overburden loading represented the in situ stress condition of the site model. These assumed boundary conditions may not faithfully represent in situ conditions of an actual site since conditions vary considerably from one location to another. In situ lateral stresses in particular may vary considerably from those modeled here.

FIGURE 3.1a. Generic Site Physical Model

The main course of structural loading is due to temperature and pressure loading of the compressed air. Hot compressed air is forced down the wellbore and out into the porous zone. This flow will consist of daily and weekly cycling as described in the flow model discussion. In the caprock vicinity, temperature distributions will exist in which the central region next to the wellbore is nearly isothermal with the compressed air. Here flow will be primarily radial. In the porous zone, rock temperatures adjacent to the wellbore will also be similar to the air temperature and will again diminish with radius. Because of the combined effects of conduction and transport in the porous zone, however, radial temperature gradients will probably be smaller than those of the cap rock. Because of these characteristics of the porous and cap rock masses, isotherms will probably take the general shape shown in Figure 3.1a.

FIGURE 3.1b. Generic Site Finite Elemental Model

Because of the large thermal mass of the rock, the radius of the thermal influence will no doubt increase gradually. The daily and weekly cycling of air temperature during the charge/discharge cycling will have greatest effect on the rock close to the wellbore.

During initial site development, the hot inner portions of the cap and porous rock masses will tend to expand radially and induce tensile hoop stresses in the cooler adjacent material. This characteristic behavior can be anticipated for the cap rock, the porous rock and the base rock. Axial expansion of the relatively thick porous layer will tend to push upward on the cap rock and induce flexural loading. This flexural loading will induce tensile stresses on the top face of the cap rock and compressive stresses on the bottom. The amount of flexural loading will depend on:

- the radius of the high-temperature central region in the porous zone
- the amount of curvature in the caprock mass
- the relative stiffnesses of the porous and caprock materials
- the reaction due to overburden stiffness

The overburden stiffness and cap rock curvature were neglected in this study. It is believed that the effects of these two assumptions cause conservative estimates of the flexural stress level on the top surface of the cap rock.

The response just described was related to the nominal or average response. Response due to the cyclic nature of the loading will no doubt be concentrated much closer to the wellbore. It can be anticipated that fluctuations in temperature will be of such a limited spatial expanse in the porous zone that cyclic flexural stresses in the cap rock due to cyclic axial expansion of the localized porous zone will be minimal. Potentially significant cyclic hoop stress levels and axial stress levels in both the porous and cap rock masses may be anticipated, however.

3.2 DESCRIPTION OF ANALYSES PERFORMED

The analyses performed can be grouped into three categories:

- analyses to assess elastic stresses
- analyses to assess fatigue stresses due to load cycling
- analyses to study postulated cracking behavior of the cap rock with subsequent redistribution of stresses.

In each of these categories, temperature and pressure data taken from the thermal flow modeling described elsewhere in this report were utilized. Data sets corresponding to the ends of weeks 1, 26, and 53 were used. Temperature contour plots for each of these data sets are shown in Figures 3.2 through 3.4. Here, the general growth of the thermal effects can be seen. In addition, the increased heat transfer due to transport in the porous zone (as opposed to pure conduction in the cap rock) can be seen. Pore pressures for these cases were nearly constant throughout the porous zone ($690 \text{ psig} \pm 10 \text{ psi}$).

Principal stresses were computed for each element in the finite element mesh. From these principal stresses, maximum normal (tensile) and shear stresses were determined. Contour plots of these stresses are shown in Figures 3.5 through 3.15. Tensile stress trends in the cap rock change considerably from the week-1 case to the week-53 case. Tensile stresses for week 1 are apparently caused by circumferential expansion of the hot inner rock stretching the cooler outer rock. As time goes on, however, the size of the hot porous zone increases and pushes up on the cap rock, adding a tensile flexural stress component on the top surface and a compressive component on the bottom.

No net tensile stress was noticed in the porous rock mass. This no doubt is due to

- relatively small radial thermal gradients involved
- the compressive effect of the in situ and pore pressure loadings.

Tensile stresses in the base rock are noticeable in Figures 3.5 through 3.7. The most likely cause of this is thermal expansion of the localized heated rock at the base of the model. This expansion in

FIGURE 3.2. Temperature Distribution (°F) After One Week of Simulation

FIGURE 3.3. Temperature Distribution (°F) After 26 Weeks of Simulation

FIGURE 3.4. Temperature Distribution (°F) After 53 Weeks of Simulation

FIGURE 3.5. Tensile Stress Levels (psi) After One Week of Simulation

FIGURE 3.6. Tensile Stress Levels (psi) After 26 Weeks of Simulation

FIGURE 3.7. Tensile Stress Levels (psi) After 53 Weeks of Simulation

FIGURE 3.8. Shear Stress Levels (psi) After One Week of Simulation

FIGURE 3.9. Shear Stress Levels (psi) After 26 Weeks of Simulation

FIGURE 3.10. Shear Stress Levels (psi) After 53 Weeks of Simulation

FIGURE 3.11. Cap Rock Cyclic Stresses One Foot Above Cap Rock/Porous Media Interface

FIGURE 3.12. Porous Media Cyclic Stresses Due to 24 H Charge Discharge Cycle Elevation Near the Middle of Aquifer

FIGURE 3.13. Week-One Crack Pattern (300-psi Tensile Strength)

FIGURE 3.14. Week-26 Crack Pattern (300-psi Tensile Strength)

FIGURE 3.15. Week-53 Crack Pattern (300-psi Tensile Strength)

conjunction with the lack of radial restraint along the model base no doubt accounts for the tensile stress level shown.

Fatigue stress evaluations of the model under study were also performed for loading conditions at the ends of weeks 1, 26, and 53 in the site simulation. For this study, the daily cycling stress (not the weekly) was assumed. While weekly stress cycling is no doubt greater in magnitude than daily, it was felt that the greater frequency of daily cycling made it more appropriate for investigation.

By using temperature and pressure differences at the extreme points of the charge/discharge cycle, fatigue loading data was computed and applied to the model. An assessment of fatigue stress severity was then made by observing shear stresses resulting for this load differential. Fatigue stress values for points located in the cap rock and porous rock regions are plotted in Figures 3.11 and 3.12 as a function of reservoir age. As can be seen from these figures, fatigue stress

- tends to diminish (but not vanish) with reservoir age
- tends to diminish with distance from the wellbore
- tends to be greater in the porous zone than in the caprock region.

Analyses described thus far were based upon the assumption that material behavior was elastic. The rather large tensile stresses in the caprock region tend to indicate that this assumption might be a questionable one especially in localized regions. If cracking does occur, then the question of stress redistribution becomes potentially significant; i.e., will stresses redistribute to cause additional cracking or will the cracking be self arresting?

The problem of crack propagation is one which must be addressed incrementally since localized cracking will alter stiffness characteristics for future behavior. The method employed was applied to study cracking of the cap and base rock masses during the first year of site simulation. The tensile stress failure threshold utilized in this investigation was 300 psi and is thought to be representative of shale behavior. This value was taken from Reference 4.

Orthotropic material behavior was assumed for treating elements fractured by tensile stresses. Loading conditions corresponding to the end of the first week were applied and the resulting principal stresses were computed. Material stiffness (Young's modulus) in elements showing large tensile stresses was neglected in the direction of maximum tensile stress. Using these new material characteristics, initial loads were reapplied and stresses were recomputed. Material stiffnesses were then modified for elements showing tensile stress levels at a somewhat lower level than during the first iteration. This process was continued for the same load case, using decreasing tensile stress thresholds until the actual (300 psi) threshold was reached. The cracked region computed in this fashion is shown in Figure 3.13.

Using modified material properties arrived at as described above, temperature and pressure values corresponding to the 26th simulation week were applied. Further cracking was simulated by using tensile thresholds in excess of 300 psi and iterating down to 300 psi. A final load step corresponding to the 53rd simulation week was then applied and modeled in a similar fashion. Regions which demonstrated cracking behavior for these two weeks are shown in Figures 3.14 and 3.15.

3.3 CONCLUSIONS

In this investigation, primary concern was focused on tensile and fatigue stress responses of the generic reservoir modeled. The resulting stress levels indicated:

- Tensile stresses existed only in the cap and base rock masses. These were caused by radial expansion at the hot inner portion next to the wellbore and, in the case of the cap rock, flexure resulting from vertical expansion at the hot porous zone.
- Fatigue shear stresses were greater in the porous zone in the wellbore vicinity. These stresses tended to decrease with reservoir age and with distance from the wellbore.

These conclusions must be interpreted in view of the assumptions made for the structural modeling. The tensile stresses developed in the cap rock due to flexure are no doubt greatly sensitive to these assumptions. The amount of flexure would no doubt decrease markedly if

- the cap rock had a slight curvature
- overburden stiffness was significant.

The other source of tensile stresses in the cap rock dealt with radial expansion of the hot central region and the subsequent stretching of the cooler surrounding rock. This tensile mode is probably much less sensitive to cap rock geometry and can probably be anticipated for most site geometries.

Fatigue stresses in both the cap and porous rock forms resulted primarily from thermal cycling of a very small region of rock in the vicinity of the wellbore. For this region, it is felt that the fatigue stress predictions are regionally insensitive to model geometry and boundary conditions. The behavior of the porous and cap rock forms to this level of fatigue stress will have to be determined from fatigue testing.

3.4 REFERENCES

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4.0 AIR/WATER/ROCK INTERACTIONS IN POROUS MEDIA

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4.1 INTRODUCTION

Sandstone aquifers are being suggested as potentially suitable reservoir media for the storage of compressed air at temperatures ranging from 50°C to 300°C. In this elevated-temperature compressed air energy storage (CAES) concept, the thermal energy of compression is retained, stored, and utilized to minimize the requirements for prime fuel during the production phase of the CAES cycle.

One unknown associated with the elevated temperature CAES scheme is the physical and chemical response of porous media to elevated temperatures, pressures, humidities, and oxidation potentials. Therefore, a laboratory-scale experimental program has been initiated at Pacific Northwest Laboratory and includes the following: 1) air-water-rock interactions in autoclaves; 2) thermomechanical property testing in triaxial load cells; 3) thermal conductivity, specific heat capacity, and linear thermal expansion coefficient measurements; and 4) physical and chemical property testing in a prototype multiphase fluid flow facility. Only the results of autoclave tests using the Galesville sandstone are discussed in this report.

Autoclaves are an expedient means for obtaining preliminary data. However, the following four limitations should be noted: 1) the rock sample cannot be confined under a simulated lithostatic load; 2) there is no controlled advective transport of liquids or gases through the interior of the rock cores; 3) the fluid-solid volume ratios are very high; 4) the sample size is such that only a small incremental volume of the reservoir can be simulated at any one time; and 5) the environment within the autoclaves cannot be adequately controlled. Fabrication of a prototype flow facility should eliminate the first three of these limitations.

4.2 EXPERIMENTAL STRATEGY

The main objectives of the experiments were: 1) identify independent variables that have significant impact on the response of the rock, 2) identify those independent variables that have relatively small influence and therefore can be held constant in future experiments, and 3) identify trends in the data pertaining to CAES reservoir design and/or operating criteria. A Plackett-Burman experimental design⁽¹⁾ was selected to systematically investigate the linear response characteristics of the dependent variables to various combinations of the maximum and minimum magnitudes of the independent variables. The variables and their ranges are listed in Table 4.1.

TABLE 4.1. Range of Independent Variables

<u>Independent Variable</u>	<u>Minimum Value</u>	<u>Maximum Value</u>
Pressure (bars)	60	120
Temperature (°C)	50	300
Time (months)	0.5	2.0
Oxygen content (%)	0.0	21.0
Carbon dioxide content (%)	0.0	0.1
Stirring frequency (per day)	0	8
Liquid saturated environment	No	Yes
Air and vapor saturated environment	No	Yes

*Dependent Variables - Gas permeability, Liquid permeability, Friability

4.3 SAMPLE DESCRIPTION

Samples of Galesville sandstone were obtained from the Media natural gas storage reservoir in Illinois. The 10-cm-diameter well cores were recovered from a depth of 685 m. The sandstone is white to grayish-white and has an estimated mean grain size of 0.5 mm. Petrographic examination reveals that the subangular clasts are equant to subequant in form and are almost entirely quartz with minor amounts of plagioclase and kaolinite. The cementing material is also predominantly crystalline quartz. Table 4.2 presents an approximate mineralogical breakdown. The rock as a whole is moderately well sorted and exhibits cyclic parallel bedding of thin, coarse-grained layers and thicker, fine-grained layers.

Figure 4.1 is a micrograph of a typical Galesville sample. Figure 4.2 presents the pretest gas and liquid permeabilities for the Galesville samples used in this preliminary set of autoclave experiments.

TABLE 4.2. Galesville Mineralogy

Quartz	98 percent
Feldspar (plagioclase)	1
Clay (Kaolinite)	< 1
Carbonates	< 1
Other	< 1

10X

SAMPLE - D

100X

FIGURE 4.1. Micrograph of Galesville Sandstone

FIGURE 4.2. Pre-Test Permeabilities for Galesville Sandstone Samples

4.4 PETROPHYSICAL PROPERTY ALTERATIONS

Table 4.3 illustrates the percent change in permeability and "friability" for various combinations of the independent variable magnitudes. Figure 4.3 presents gas permeability data in a series of three dimensional plots. For example, in Figure 4.3a, the changes in gas permeability are shown in the circles as either increasing ($\uparrow$) a specified percentage over the pretest level or decreasing ($\downarrow$) a certain percentage. The independent variables are temperature, time, and relative humidity. The sandstone cores were reacted in a totally dry air environment (D), an air and water vapor environment (V), or a liquid water environment (L). Figure 4.4 is a plot of gas permeability changes as a function of temperature.

TABLE 4.3. Test Matrix for Screening Experiments

Trial	Pressure (bars)	Temperature (°C)	Time (mnths)	Oxygen (%)	CO ₂ (%)	Stirring (Yes-No)	Liquid (Yes-No)	Vapor (Yes-No)	Permeability (% Change)		Friability Index (% Change)
									Gas	Liquid	
1	120	300	0.5	21	0.1	Y	N	N	↓03	00	↑ 27
2	120	50	2.0	21	0.1	N	N	N	↓02	↓04	↑ 41
3	60*	300	2.0	21	0.0	N	N	Y	↑31	↑78	↑222
4	120	300	2.0	0	0.0	N	Y	N	↑65	↑73	↑474
5	120	300	0.5	0	0.0	Y	N	Y	↑76	↑38	↑185
6	120	50	0.5	0	0.1	N	Y	Y	↓17	↑37	↑ 29
7	60	50	0.5	21	0.0	Y	Y	N	↓03	↓08	↑ 43
8	60	50	2.0	0	0.1	Y	N	Y	↓18	↑31	↑ 26
9	60*	300	0.5	21	0.1	N	Y	Y	↑96	↓36	↑171
10	120	50	2.0	21	0.0	Y	Y	Y	↓11	↑51	↑ 61
11	60*	300	2.0	0	0.1	Y	Y	N	↑12	↑28	↑480
12	60	50	0.5	0	0.0	N	N	N	↑02	↓04	↑ 31

*Actual pressure increased to prevent flashing

FIGURE 4.3a. Percent Changes in Gas Permeability for Various Combinations of Temperature, Time, and Humidity

FIGURE 4.3b. Percent Changes in Gas Permeability for Various Combinations of Temperature, Oxygen, and Humidity

FIGURE 4.4. Gas Permeability Variations Versus Temperature

Observations concerning gas permeability alterations are as follows:

- Temperature and humidity are the dominant independent variables.
- The length of the experiment has a moderate effect.
- Pressure, oxygen content, carbon dioxide content and autoclave stirring frequency have negligible effects and can be held constant in future Galesville experiments.
- The mean net air permeability change was approximately 28 ± 10 percent, but may be unrealistically high because of the lack of confining stress during the experiments and, in some cases, severe erosion of the core's cylindrical face.
- The sandstone cores demonstrate good stability with respect to air permeabilities if one or both of the following conditions are met: 1) temperatures below 150°C, and/or 2) negligible humidity.
- The observed increases in porosity and permeability might be due to solution of quartz and carbonate cement, since alterations are only observed when the core is subjected to liquid and/or vapor phase water.
- An increase in permeability, if it occurs in the field, might be beneficial to CAES operations. If the increase is associated with matrix disaggregation, however, particle plugging and formation consolidation might be of concern.
- Sample inhomogeneity is the main contributor to the data scatter.
- Statistically meaningful conclusions are not possible without additional data.

Figure 4.5 presents the percent change in liquid water permeability for the same experimental conditions listed in Table 4.3. The primary observations concerning liquid permeability alterations are:

- Humidity, time, and temperature are the dominant independent variables.
- A more rapid response is observed for vapor-dominated tests than for liquid-dominated ones.

FIGURE 4.5a. Percent Change in Liquid Permeability for Various Combinations of Temperature, Time, and Relative Humidity

FIGURE 4.5b. Percent Change in Liquid Permeability for Various Combinations of Temperature, Oxygen Content, and Relative Humidity

- Oxygen content, carbon dioxide content, pressure, and stirring frequency effects are negligible.
- The mean increase in liquid permeability was approximately 32 ± 10 percent.
- Statistically meaningful conclusions are not possible without additional data.

Friability refers to the potential for the grains in the sandstone to disaggregate. It is somewhat analogous to grain-to-grain contact strength. Measurements were made with a modified modulus of rupture apparatus common to soil physics applications. This point-load strength is arbitrarily termed the Friability Index in this study. Numerical values are listed in Table 4.3. Figure 4.6 is a set of three dimensional representations of this data. A plot of friability as a function of temperature is shown in Figure 4.7. The disaggregation experienced by

FIGURE 4.6a. Percent Change in Friability Index for Various Combinations of Temperature, Time, and Humidity

FIGURE 4.6b. Percent Change in Friability Index for Various Combinations of Temperature, Oxygen Content, and Relative Humidity

FIGURE 4.7. Friability Index Variations Versus Temperature

some unconfined cores is shown in Figure 4.8. The main observations concerning the friability index are:

- Temperature, time, and humidity are again the dominant independent variables.
- Oxygen content also has a moderate effect although no explanation is offered for this effect.
- Pressure, carbon dioxide content, and stirring frequency are apparently insignificant.
- All combinations of independent variables tested resulted in an increase in friability.
- The disaggregation might be due to dissolution of the interstitial cements (quartz and carbonate) and associated loosening of the individual grains.
- The disaggregation might account for the observed increases in permeabilities.
- The lack of confining stress and the high liquid-to-solid volume ratio in the autoclave undoubtedly contributes to the disaggregation.
- The multiphase fluid flow facility should permit a more realistic simulation of anticipated CAES field conditions.
- Disaggregation, if it should occur in the field, might be beneficial to a CAES reservoir; however, the potential for consolidation, subsidence, and particle plugging must be considered.

4.5 SUMMARY

The objective of this experimental task is to investigate how anticipated CAES operating conditions might perturb the mineralogical and physical characteristics of porous media reservoir rocks. The first phase of the program involved reacting Galesville sandstone cores in an autoclave facility supporting one of three environments: 1) totally dry (air), 2) partially saturated (air and water vapor), and 3) totally liquid saturated.

(50°C, 336 hours, Liquid)

(300°C, 1488 hours, Liquid)

(300°C, 336 hours, Vapor)

FIGURE 4.8. Increasing Friability of Galesville Samples Reacted in a High Humidity Environment at Elevated Temperature

The dry air tests and partially saturated tests are designed to simulate CAES field conditions. The liquid-saturated tests provide a vehicle for real-time monitoring of groundwater chemical changes that may be attributable to solution, hydrolytic, and redox reactions. Similar reactions may take place in the partially saturated tests but are difficult to monitor during the experiment. The liquid tests may also simulate isolated, low-permeability regions within the reservoir.

The physical properties of primary interest include porosity, gas permeability, liquid permeability, and "friability". Significant changes in Galesville sandstone properties were observed for certain combinations of temperature, humidity, and experiment run time. The main observations and conclusions are as follows:

- The Galesville sandstone (Media natural gas storage field in Illinois) appears to be a reasonable CAES candidate rock. It is a clean quartzose sandstone which supports a gas permeability ranging from 100 to 1500 md.
- The observed increases in porosity, permeability, and friability are correlated with increased temperature, increased humidity, and increased testing time. The Galesville sandstone is apparently insensitive to the fluid pressure, the presence of oxygen or carbon dioxide, and the autoclave type or stirring frequency.
- The changes are apparently not a result of mechanical degradation such as microcracking or differential thermal expansion and contraction. This conclusion is based on the fact that negligible property changes were observed for a dry air environment regardless of the parameter settings. The one exception was an unconfined dry core thermally cycled several times from 200 to 300°C. In this case, the air and liquid water permeabilities were not significantly altered, but the friability index increased by a factor of two.
- As would be expected for a clean quartz sandstone, the observed changes in physical properties are not due to hydrolytic or redox reactions.

- The property changes are apparently due to dissolution of the quartz cement that bonds the individual grains. Although somewhat puzzling, dissolution appears to be significant even in an air and water vapor environment. It is speculated that the vapor is condensing on the core and/or on the top of the vessel. Preliminary experiments designed to investigate the water vapor condensation problem are currently in progress.
- Silica solubility in deionized water is temperature dependent and increases from 14 mg/l at 50°C to 800 mg/l at 300°C. Calcium carbonate has a retrograde solubility and therefore decreases with temperature.
- The sandstone exhibits good stability at all temperatures between 50 and 300°C if tested with dry air. However, if the rock is exposed to vapor and/or liquid water at temperatures above 150°C, significant physical changes are observed.
- One caprock type for the Media natural gas storage field in Illinois is the Eau Claire, which is predominantly shale and siltstone. Samples of this rock showed reasonable chemical and physical stability when heated to 300°C in an air and/or water vapor environment.
- These observations should not be extrapolated to actual CAES field conditions until data can be generated with the multiphase fluid flow facility.

4.5 REFERENCES

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5.0 PRELIMINARY DESIGN AND STABILITY CRITERIA FOR CAES HARD ROCK CAVERNS

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The objectives of this study have been to compile rock properties data from the literature, to formulate a preliminary set of design and stability criteria for underground CAES hard rock caverns, and to identify areas of necessary research. The rock properties compilation has concentrated on assembling and evaluating those physical, chemical, petrophysical, thermal, and mechanical characteristics and properties of igneous, metamorphic, and sedimentary rock types for which the CAES concept is applicable. This survey has indicated that the data base for hydrological and thermomechanical properties is generally inadequate for jointed rock under conditions of elevated temperature and increased moisture presence. In general, the formulation of preliminary design and stability criteria for CAES caverns has been based on information available for large underground caverns utilized for mining purposes.

5.1 INTRODUCTION

In the compressed air energy storage (CAES) concept, air is compressed during off-peak demand periods, stored in underground caverns, and withdrawn and utilized with surface turbine systems to generate electrical power during peak demand periods. This cavern storage concept is generally categorized as:

- 1) Compensated: constant air pressure with varying volume (wet system with hydraulic compensation) or
- 2) Uncompensated: constant air volume with varying pressure (dry system)

In the uncompensated system, a cycle involves pressurization/depressurization of the cavern and an associated temperature fluctuation due to the compression/expansion of the air. In the compensated system, a cycle involves a temperature fluctuation due to compression of the air

during injection and inflow of water at "ambient" temperature during withdrawal of the air. In these situations, the rock surfaces will be subjected to daily contact with hot/cool air (uncompensated) or hot air/cool water (compensated). Because excavation costs for a suitable uncompensated-system cavern are considerably greater than for a compensated-system cavern, the compensated system will receive most attention here. Under this range of conditions, the selection of the rock mass, and the quantification of its material properties and geotechnical characteristics, are important factors in designing the caverns to minimize the risk of either structural or air/water leakage instabilities.

The overall objective of this study is to formulate preliminary criteria for the design and stability of CAES and UPHS (Underground Pumped Hydro Storage) caverns in hard rock. In order to accomplish this task, a complementary goal included the compilation and evaluation of material and structural characteristics and properties of rock types for which the CAES and UPHS concepts are applicable, over the range of anticipated operational conditions. Finally, it was necessary to identify areas of analytical, laboratory, and field-scale research that are necessary for establishing a consistent and applicable set of stability and design criteria. The modes of cavern instability and the design considerations and criteria are of primary concern. Therefore, this discussion will deal almost exclusively with these topics.

5.2 FUNDAMENTAL CONCEPT OF STABILITY/INSTABILITY

For the purpose of the current study, stability is defined as the intrinsic capability of a body to maintain its original constitutional integrity when the body is disturbed from a condition of static equilibrium. The original constitutional integrity of a rock mass is characterized by its macroscopic and microscopic structure. When the rock mass is subjected to a system of applied forces, or other disturbances, the body must undergo a transition from an initial state to a subsequent state of static

equilibrium. If the constitutional structure of the rock mass is not compromised by a loss of integrity during this transition, or during a reversal to the original state of equilibrium upon removal of the forces or other disturbances, stability is maintained. In other words, the structure is capable of accommodating the disturbance through deformations which disappear upon cessation of the disturbances. If, however, loss of integrity does occur, as for example may be evidenced by micro or macro fracturing, the rock mass has experienced instability in the sense of some permanent deformation. Thus, we may define instability in a rock mass as a permanent perturbation of its original constitutional, or structural integrity when the rock mass is disturbed from some initial state of static equilibrium.

The definition of instability for a rock mass, as established above, is quite general and must be further characterized from the viewpoint of application and generic rock type. For example, it is important to realize that instability does not always give rise to detrimental effects. As a case in point, strain hardening increases the yield strength of a solid substance through a process of permanent straining. Transient creep deformation may give rise to a similar situation. Furthermore, strain hardening and localized collapse of pore structure in a rock mass tends to reduce its ability to transmit fluids. This instability feature is beneficial to the containment of fluids under pressure, such as in the case of CAES, but detrimental to the withdrawal or injection of fluids, as in the case of a petroleum reservoir. The instability of a pillar between adjacent caverns in a rock mass may result in some loss in load-bearing capacity of the pillar. However, the remaining capacity under a condition of static equilibrium may be quite adequate for the intended useful lifetimes of the caverns. Certain rock types, such as those of the sedimentary class, tend to experience considerable ductility and strain hardening when subjected to elevated temperature and/or confinement stress. Igneous and metamorphic rocks tend to exhibit relatively higher intrinsic "strengths", but less ductility and strain hardening than sedimentary rocks under similar loading conditions.

For the purpose of establishing preliminary design and stability criteria for CAES caverns, we shall categorize instability from the viewpoints of:

- 1) Global Rock Instability: identified by massive roof falls, wall slabbing, and floor heave, leading to a loss of structural integrity of a cavern and/or its entrance.
- 2) Local Rock Instability: identified by localized spalling and degradation of the rock along the cavern periphery, leading to detrimental effects in the operational use of the compressed air.
- 3) Global Air Leakage Instability: identified by unacceptable air leakage from a cavern during compressed air injection and storage.

In practice, we may define the time periods of instability concern for a system of CAES caverns as: 1) excavation, 2) operation, and 3) decommissioning. The notion of global rock instability applies to the excavation and decommissioning periods, while all three instability concerns apply to the operational period.

5.3 SYNOPSIS OF DESIGN AND STABILITY FACTORS

The design and assessment of stability of a CAES cavern should involve consideration of the following factors:

- 1) Geotechnical Characteristics of the Rock Mass
 - macro and microstructural characteristics, such as rock structure in the classical sense, joint orientation, spacing, and aperture, bedding plane attitude and spacing, folds, faults, and other discontinuities
 - mineralogical composition, including petrofabric characteristics, of each geological component
 - groundwater characteristics, including gradient, degree of saturation, and water chemistry

- hydrological properties, including porosity and permeability
 - geothermal gradient
 - in situ stress state, including magnitudes and orientation of stress components
 - density and weathering characteristics of each geological component
- 2) Thermal/Mechanical Behavioral Characteristics of Each Geologic Component of the Rock Mass
- thermal properties, including thermal conductivity, thermal diffusivity, and specific heat as functions of temperature level and degree of water saturation
 - elastic properties, including Young's modulus of elasticity and Poisson's ratio as functions of temperature and stress level and degree of water saturation for both intact and non-intact rock
 - pre- and post-failure strength and inelastic deformation properties as functions of temperature, confinement stress, and degree of water saturation for both intact and non-intact rock, for conditions of both quasi-static and cyclic loading in compression and tension (or extension)
 - creep rupture characteristics (generally applicable only after cessation of cavern operation)
 - thermal spalling characteristics of intact rock as a function of temperature, stress state, and degree of water saturation
- 3) Cavern Geometry and Construction Characteristics
- shape of the cross-section of each cavern (or crosscut tunnel), including height, width, curvature, and cavern length
 - pillar width (or cavern spacing) and spacing between ends of caverns and crosscut tunnels
 - shape and dimensions of entry-entry intersections
 - orientation of the longitudinal axis of the caverns and crosscut tunnels with respect to the macro- and microstructural characteristics of the rock mass

- excavation method and sequence of each cavern, tunnel, intersection and cavern system as a whole
- 4) Operational Characteristics of Cavern System
- type of CAES system, i.e. either compensated or uncompensated
 - air temperature and pressure cycle characteristics.

Because of the usual scatter in geotechnical and thermomechanical data derived from field and laboratory tests and measurement, statistical treatment of the various data sets will likely be necessary.

The following procedures can be utilized to stabilize a cavern structure in rock, assuming that a prior identification of potential instabilities is possible:

- rock bolting (with wire mesh if necessary) or shotcrete
- cavern shakedown.

Apart from cavern shakedown, detailed descriptions of these preventive measures may be found in the literature.

Additionally, the following measures can be taken to "stabilize" a cavern with respect to air leakage:

- water curtain
- grouting.

5.4 STABILITY CRITERIA

5.4.1 Excavation Phase

An evaluation of the stability of a cavern during the excavation phase should define:

- the global rock stability of the cavern structure during and after excavation
- the states of stress and fluid pressure and the regions of failure in the rock mass around the cavern after excavation is completed.

At a minimum, the criterion for rock stability should be based upon:

- the elastic state of stress in the rock mass as a consequence of creating an opening with free surfaces in an initially stressed medium
- a criterion of rock failure, such as the Mohr-Coulomb condition, for evaluating the potential for instability in the sense of an "index of potential failure" (as described in Section 2.2.3 of Reference 1).

The potential for rock failure, or instability, can be assessed either on a local or global basis (involving an integrated average of the spatially distributed indices of potential failure). An evaluation of this quantitative information involves some subjective judgment as regards the potential severity of a region or regions of an instability, and the need for artificial support measures.

The above approach is satisfactory in the event that the rock mass remains predominately elastic after excavation of the cavern, or if any potential for rock failure can be removed by the use of artificial support measures. However, if the potential for rock failure, or instability, is indicated in spite of the application of artificial support measures, then the effect of stress relief through fracturing or loss of joint cohesion must be evaluated. In this case, the criterion for stability must be based upon an "elastic-plastic" stress analysis with use of a generalized flow law (e.g., the Mohr-Coulomb yield condition). Once again, subjective judgment is required in evaluating the computational results as regards the potential severity of regions of intact rock or non-intact rock failure.

In summary, let us define the following range of criteria for global rock stability of a cavern after excavation is completed:

- 1) The state of stress in the rock mass is totally elastic:
This is an extremely severe criterion and does not allow for any regions of incipient fracture, or instability, whatsoever.

- 2) The integrated average of the spatially distributed indices of potential failure over a large volume of rock around the cavern is greater than one: This criterion does permit the existence of localized regions of potential instability, which probably can be corrected by artificial support measures. The level of confidence in the global structural integrity of the cavern can be enhanced by requiring the integrated average to be substantially greater than one, say two, three, or four.
- 3) The regions of rock failure, as indicated by elastic-plastic analysis, are either sufficiently localized or contained such that the potential for massive roof falls or pillar rib slabbing is not indicated: From a practical viewpoint, this criterion may be the most realistic and acceptable, particularly if some measure of artificial support is provided. Furthermore, because of the allowance for stress relief, this criterion may be more conservative than the preceeding one.

It should be noted that the results of calculations in support of the second and third criteria should indicate regions of the rock mass which would require grouting to minimize air leakage. This conclusion is based on the premise that regions of indicated rock failure will exhibit a greater permeability than regions that remain elastic.

The state of stress in the rock mass around a cavern after excavation forms the reference state of stress for analysis of the operational phase. Furthermore, the inflow of water into the cavern and the corresponding region of "drawdown" during construction are a function of this reference state of stress (as well as many other parameters) by virtue of the dependence of hydraulic conductivity on stress state. Analysis of the drawdown region during excavation is required prior to stability evaluations for the operational phase because these results form in essence the initial conditions.

From the viewpoint of criteria for storage cavern alignment with respect to structural discontinuities and in situ stress state, we may propose that the longitudinal axis be oriented:

- along the line that intersects the maximum intersection angle between the two dominating sets of structural discontinuities (joints, bedding planes, foliation partings), but not parallel to the direction of the third or fourth minor set
- at an angle of at least 25° from steeply dipping structural discontinuities that exhibit smooth surfaces or are filled with clay
- at an angle of 15 to 30° to the direction of the maximum in situ stress in the horizontal plane (or parallel if required by other conditions arising from the orientation of the structural discontinuities)
- at a maximum angle, and at least 35° , to the strike of dipping foliation or bedding planes when the direction of the maximum horizontal in situ stress parallels the strike.

These criteria are based on precedent experience as summarized by Selmer-Olsen and Broch⁽²⁾ (1977), and their substance and range of application should be evaluated for CAES cavern design and stability.

5.4.2 Operation Phase

5.4.2.1 Consequences of Instability

During the operational phase of a CAES cavern, concern must be given to the potential for global rock instability, local rock instability, and global air leakage instability. Conceptually, each of these instabilities could occur independently; however, it is more likely that any two, and possibly all three, would occur in a coupled fashion. For example, extensive local rock instability, in the form of progressive thermal spalling, could set the stage for incipient global rock instability in terms of an increased potential for fatigue failure as evidenced by

massive roof falls or rib slabbing. A global weakening of the cavern structure could give rise to increases in rock mass permeability and in the effective cavern surface area and thereby enhance the air leakage.

The two most important consequences of instability during CAES operation appear to be:

- an unacceptable loss in air volume (compensated system) or air pressure (uncompensated system) from the cavern system
- an unacceptable loss in effective cavern volume due to blockage by massive roof falls and rib slabbing in entry-entry intersections, in the air-entry or water-entry crosscut tunnels, or at the cavern entrances.

Both of the consequences are the result of rock instability, either massive global rock failure or progressive local rock failure. From this frame of reference, we shall consider now the stability and design criteria for the operational phase of a compensated CAES cavern system.

The global air leakage stability criterion for compensated cavern systems may be simply stated as:

- the recoverable air volume over a prescribed time period of the operational cycle shall not be less than a specified percentage of the total available volume.

We note that this criterion also encompasses the situation in which cavern volume is effectively lost by blockage of tunnels, entry-entry intersections, and cavern entrances due to rock instability. The specified percentage of recoverable air is clearly an economic consideration from the viewpoint of the requirements of the power generation equipment on the surface.

Specification of global and local rock stability criteria is difficult due to the unprecedented nature of the physical situation. The primary mechanism of global rock instability is fatigue fracture due to cyclic thermally-induced stresses in the rock mass. For the

mechanism, a specified measure of cumulative rock damage appears to be the appropriate criterion. The secondary mechanism would be progressive rock instability due to localized thermal spalling/cracking and weathering. The appropriate criterion appears to be one in which the rate of degradation is the key feature. Thus, let us specify the criteria for rock stability from the viewpoint of the required operational life of the cavern system:

- The cumulative damage of the rock structure due to cyclic thermally-induced stresses shall not exceed a specified percentage of that maximum damage which gives rise to:
 - fatigue fracture at any given time over the life span of the structure
 - air leakage, through enhanced permeability and effective cavern surface area, which violates the global air leakage stability criterion.
- The rate of degradation of the rock along the periphery of the cavern due to thermal spalling shall not exceed that rate which
 - compromises the fatigue life of the global components of the rock surface
 - compromises the global air leakage stability criterion by enhancement of the effective cavern surface area.

Quantitative definition of either of these criteria is dependent upon generic rock type. Experimental data, under appropriate conditions of stress, temperature, and moisture content, are essentially unavailable for even crude estimates of the values of the parameters in the appropriate constitutive laws. We note that the criterion for fatigue failure may be relaxed to conform with the concept of "finite design life".

As an interim measure, however, until experimental data do become available, we may suggest an alternate criterion based on the use of a quasi-static failure condition and magnitude of strain at incipient

volume dilatation of a rock mass. In this approach, which is primarily applicable as a temporary replacement for the assessment of fatigue fracture, we can only deal with maximum stress states as induced by quasi-steady temperature perturbations in the rock mass. The criterion may be stated as:

- The regions of rock failure, as indicated by elastic-plastic analysis with the Mohr-Coulomb failure condition, shall be sufficiently localized or contained such that the global air leakage stability criterion is not violated.
- The volumetric dilatation of the rock mass shall not exceed a specified percentage of the dilation:
 - that the rock will experience at fracture under quasi-static conditions of confinement stress and temperature
 - that will give rise to permeability perturbations and effective surface area increases which will compromise the global air leakage stability criterion.

Since these alternate criteria are only valid for a single temperature cycle, the specification of allowable dilatation and fracture strength must be extremely conservative in order to compensate for cumulative damage. In fact, it may be necessary to specify the allowable dilation for a single cycle on the basis of the number of cycles over the life of the facility in relation to the total dilation that the rock will experience prior to the initiation of fracture.

As an alternative to the current unavailability of thermal spalling data, it would appear plausible to consider a criterion based on thermally induced surface stresses and a failure condition for the fracture of rock in extension, or in compression as the case may be. This approach would perhaps allow an evaluation of the potential for spalling during a temperature cycle, as well as an estimate of the spall thickness. Once again we are dealing with stress states that are induced by quasi-steady thermal perturbations, and any single-cycle instability must

be assessed in the context of the total anticipated cycles over the intended life of the facility.

Finally, we may state one criterion of rock stability that is based solely on a few results from laboratory tests:

- Regions of the rock mass on the cavern periphery which experience alternating compression-tension cycling should be eliminated, if at all possible, by appropriate design of the cavern shape, or by substantial reinforcement with rock bolts and wire mesh.

This criterion is based on the experimental work of Haimson⁽³⁾ (1974), which indicated that the fatigue strength of rock under cyclic compression-tension loading is significantly less than the fatigue strength under purely cyclic tension.

In the event that analysis indicates violation of any of the criteria, one may resort to the use of such measures as rock bolting, shotcreting, grouting, or water curtains. The ramifications of these techniques, which are intended to reduce or minimize potential for instability, must be considered within the context of the overall program of stability analysis for a generic rock type and conceptual cavern system.

5.4.3 Decommissioning Phase

At the termination of the intended design life of a CAES cavern system, consideration must be given to the decommissioning of the underground facility. If the decision is made to abandon the facility, then an analysis of its long-term stability should be undertaken. In the event that the structure suffers global rock instability on a massive scale through the mechanism of creep rupture, subsidence of the ground surface may occur and eventually terminate with the appearance of a "sinkhole". From the viewpoint of establishing a suitable criterion, we may suggest the following on a preliminary basis:

- the subsidence of the ground surface over an abandoned CAES cavern system shall not compromise

- the topographical integrity of the ground surface so as to substantially exceed the limits of conventional erosional processes, or tectonically produced features, that are representative of the region
- the integrity of the subsurface rock structure so as to permanently alter the groundwater flow pattern in a detrimental fashion.

5.5 CONCLUSIONS

The concept and three modes of instability were identified and briefly discussed: global rock instability, local rock instability and global air leakage instability. A synopsis of design and stability factors was presented including (1) geotechnical characteristics of the rock mass, (2) thermal/mechanical behavioral characteristics of each geologic component of the rock mass, (3) cavern geometry and construction characteristics, and (4) operational characteristics of the cavern system. Stability criteria were advanced for the excavation phase, operational phase, and decommissioning phase of a hard rock CAES cavern.

5.6 REFERENCES

1. P.F. Gnirk, CAES and UPHS in Hard Rock Caverns: III. Preliminary Stability and Design Criteria for Compressed Air Energy Storage Caverns, Topical Report RSI-0079. Submitted to Pacific Northwest Laboratory, Richland, WA, by Re/Spec Inc., February 1979.
2. R. Selmer-Olsen and E. Broch, "General Design Procedure for Underground Openings in Norway", Rockstore 77, Vol 2, p. 219-226, 1977.
3. B.C. Haimson, "Mechanical Behavior of Rock Under Cyclic Loading", Proceedings Third Congress International Society Rock Mech., Denver, CO, Vol. 2, Part A, p. 373-378, 1974.

6.0 NUMERICAL MODELING TO PREDICT BEHAVIOR OF UNDERGROUND HARD ROCK CAVERNS USED FOR COMPRESSED AIR ENERGY STORAGE

A.F. Fossum - Re/Spec, Inc.

This discussion presents the concepts and techniques which have been developed for calculating various failure probabilities of underground compressed air energy storage (CAES) caverns. The emphasis in this development is on the excavation and construction phase. Generally speaking, the CAES concept involves compressing air during off-peak electrical demand periods, storing it in mined storage caverns, and withdrawing and expanding it through turbine systems to generate power during peak demand periods. The cavern storage concept is generally categorized as either compensated (constant pressure with varying volume--wet system with hydraulic compensation) or uncompensated (varying pressure with constant volume--dry system). The work presented in this report is part of an effort underway at Re/Spec Inc. to formulate a consistent and definitive set of rock and air-leakage stability criteria for use in the design of CAES caverns in hard rock. The design process necessarily involves the use of numerical modeling procedures, in conjunction with the geotechnical and thermomechanical properties of the rock mass and the stability criteria, for assessments of cavern stability during excavation, operation and decommissioning. Prior to this study, the physical, chemical, petrophysical, thermal, and mechanical properties of rock types and geological formations for which the CAES concept is applicable were compiled and evaluated.

The numerical procedures are integral parts of an overall CAES simulation model, which models;

- 1) the material characterization of the rock, including the structural discontinuities, within both the elastic and inelastic ranges of behavior
- 2) the geometric construction sequence of the CAES caverns

- 3) the cyclic variation of load parameters within the cavern and the associated rock response
- 4) the motions of air and water within the rock mass.

Figure 6.1 illustrates the conceptual numerical simulation model, which encompasses the required modeling needs. The critical points in the simulation model are labeled numerically from 1 to 4 and indicate the points where the calculated results are compared with performance or stability criteria. The methodology used to develop the means for establishing the performance or stability criteria is dependent on 1) the physical characteristics of the rock mass, cavern, and operational system, 2) the types of instability envisioned, and 3) the cavern failure criteria selected. These topics are briefly addressed in the following paragraphs. A more detailed presentation of a methodology based on probabilistic analysis is provided in Reference 1.

6.1 ROCK AND CAVERN UNCERTAINTIES

Underground design problems involve a complicated process because of the many uncertainties that are unavoidably present. These uncertainties may be categorized broadly into two groups.

1) Statistical Uncertainty: This type of uncertainty may be shown by experiment to be physically random, some examples of which include physical, chemical, thermal, and mechanical properties of rock. These random variables are usually presented in terms of sample means and variances and histograms.

2) Nonstatistical Uncertainty: This type of uncertainty is sometimes referred to as "professional" uncertainty and is manifest by the simplifying assumptions which must be made when knowledge is lacking regarding design factors that would ordinarily be statistical. Some examples are the uncertainties caused by testing procedures. That is, rock properties measured in the laboratory such as cohesion, angle of internal friction, or modulus may be different than the corresponding in-situ properties. Inaccuracies of laboratory measurements could be

FIGURE 6.1. Conceptual Numerical Simulation Model for Evaluation of the CAES Concept in a Generic Rock Type

due to size effect, stress release during sampling, disturbance from sample preparation, handling and storing, initial in-situ stresses, and instrumentation procedures. Other types of nonstatistical uncertainties include model uncertainties such as the assumption of plain strain conditions and the assumption of various boundary conditions for a finite-element mesh.

In addition, uncertainty may exist in the definition of various loads on the system. The design loads may include the possibility of overloading such as occurs when extremely hot air is accidentally injected into a CAES cavern. The strength of some materials, such as jointed rock, may not be known because of insufficient or nonexistent test data. Also, there may not be general agreement with regard to what constitutes failure in the material or what failure theory is most adequate.

The above discussion simply serves to point out that many assumptions are required in a typical design procedure. Conventional rock mechanics design practice relies to a large extent on a factor of safety analysis. The desirability of probabilistic design theory is that it provides a mechanism for introducing into the design algorithm the variability associated with each assumption or design factor.

In summary, a probabilistic design approach has been adopted for the following reasons:

- 1) Most of the design factors involved with a CAES system, such as loads and strength properties, possess significant statistical variability. In a probabilistic design approach, statistical data are incorporated explicitly into the design algorithms.
- 2) It is more meaningful to be able to state that a system has a 10^{-4} probability of failing after some length of time than to say that the factor of safety is 2.5 for example. The basic design criterion in probabilistic design is the minimum allowable reliability.

- 3) Since the probability of failure, P_f , is a meaningful description of structural performance, a rational comparison can be made between two or more competing designs.

6.2 MODES OF CAVERN INSTABILITY

Before estimates of failure probability can be made, failure modes must be defined. There is general agreement with regard to the types of instabilities that are possible in CAES cavern geometries, including:

- 1) Local Rock Instability: identified by localized thermomechanical spalling and thermomechanical disintegration of rock over the cavern periphery, leading to detrimental effects in the operational use of the compressed air.
- 2) Global Rock Instability: identified by massive roof falls, wall slabbing, and floor heave, leading to the loss of structural integrity of the cavern and/or its entrance.
- 3) Global Air Leakage Instability: identified by unacceptable air leakage from the cavern during compressed air injection and storage (due to greatly enhanced hydraulic conductivity as a result of induced fracturing or joint dilation).

During the excavation-construction phase, item 2 and possibly item 1 are of concern.

6.3 CAVERN FAILURE DEFINITION

Two fundamental methods are available for the calculation of probabilities of failure, depending on the notion of what constitutes failure. In the first approach, the term failure refers to the failure of any material point according to a failure criterion such as the Mohr-Coulomb criterion. Designing against this type of failure will ensure both local and global rock stability. Thus, the use of the term failure in this sense is an extremely conservative one since it is unlikely that a single-point load-strength combination would be defined as critical for the failure of the entire underground structure. This model, which

will be referred to subsequently as a Material Failure Probability Model, is based on an elastic analysis. In the second approach it is assumed that some material failure is acceptable. Probability of failure in this case refers to the failure of a region of material which cannot be supported by artificial means such as rock bolting. Failure modes in this method are identified as massive roof falls, wall slabbing, and floor heave. Thus, this method, referred to as a Modal Failure Probability Model, is concerned with item 2 above. This model requires the use of a nonlinear analysis.

6.4 SUMMARY

A brief discussion of the elements influencing analysis of CAES cavern stability in hard rock is provided. Major elements include 1) rock and cavern uncertainties, 2) definition of modes of instability and 3) identification of failure criteria. A conceptual model for evaluation of CAES acceptability is also outlined. Details of the proposed methodology are available in Reference 1.

6.5 REFERENCES

1. A.F. Fossum, On The Analysis Procedures for Formulation of Stability and Design Criteria for CAES in Hard Rock Caverns, I. Excavation Phase. Topical Report RSI-0077, Submitted to Pacific Northwest Laboratory, Richland, WA, by Re/Spec, Inc. February 1979.

A bibliography of reference material is provided in Reference 1.

7.0 LABORATORY TESTING OF HARD ROCK SPECIMENS SUBJECTED
TO LOADING AND ENVIRONMENTAL CONDITIONS
APPROPRIATE TO CAES

A.F. Fossum - Re/Spec, Inc.

7.1 INTRODUCTION

Compressed air energy storage (CAES) requires large underground reservoirs to store air in sufficient quantities to meet peak power demands of a utility. The specification of CAES caverns in hard rock immediately categorizes the situation to one involving igneous (granitic), possibly metamorphic, and certain sedimentary (limestones, marbles, dolomites) rocks. The categorization "hard rock" is an implication of relatively great strength and resistance to large ductile and creep deformation. Thus, we may eliminate from consideration such rock types as salt, shale, and the like. Conversely, however, this categorization must necessarily include the influence of joints (or planes of weakness), permeability (and groundwater presence), and elastic/brittle mechanical behavior (or fracture initiation) on cavern stability. The cyclic temperature and pressure fluctuations in the CAES concept also introduce the possibility of elastic/ductile/brittle rock behavior with "fatigue" and possibly transient "creep rupture" contributions.

7.2 OBJECTIVE

The purpose of this study is to investigate the properties of hard rock specimens, from formations suitable for CAES, that are subjected to the cyclic conditions imposed by a CAES installation, by means of laboratory-scale testing. This program, together with previous PNL-sponsored programs, is designed to formulate preliminary design and stability criteria for CAES caverns to assure their long lifetime suitability and to encourage early commercialization of the CAES concept. The primary objectives of this program effort are to:

- 1) establish and quantify the major physical, chemical, thermal, mechanical, and petrofabric characteristics of hard-rock formations identified as candidate hosts for CAES caverns
- 2) select and procure field specimens of specific rock types designated by PNL
- 3) select specific procedures for rock characterization "before" and "after" testing
- 4) conduct laboratory scale testing of rock specimens by subjecting them to pressure, temperature and humidity fluctuations and chemical environmental conditions projected for a CAES hard-rock cavern; and design and evaluate and/or perform heat transfer experiments to establish cyclic temperature variations with the cavern wall
- 5) formulate stability and design criteria for CAES hard-rock caverns based upon:
 - a) the results of this testing program
 - b) the state-of-the-art survey
 - c) the numerical modeling study.

7.3 PROGRAM TASKS

7.3.1 Determination of Significant Rock Properties

The goal of this task is to establish those significant physical, chemical, petrophysical, thermal, and mechanical properties of rock types and geological formations for which the CAES concept, both compensated and uncompensated, is applicable. This involves establishing these properties over the range of conditions of temperature, pressure, and moisture that exist in CAES systems. Economics of cavern construction makes compensated caverns more attractive; therefore, greater emphasis is placed on that system.

This task is complementary to similar tasks in the state-of-the-art and numerical modeling studies. The intent is not to repeat the elements of the above-mentioned studies, but rather to update the material properties matrix as more data became available.

7.3.2 Procurement of Specimens

The objective of this task is to procure and prepare generic rock samples representative of candidate formations for CAES demonstration. In this regard, Acres American has indicated a willingness to supply Re/Spec with Sykesville rock core which is a foliated metamorphic rock (gneiss). In addition, it is felt that rock cores of at least one igneous intrusive and one sedimentary chemical rock type should be obtained; a granite and a limestone, respectively. Additional rock types will be considered after the program commences.

7.3.3 Selection of Specific Procedures for Rock Characterization Before And After Testing

The objective of this task is to provide the means for which the rocks being tested could be categorized and/or identified by their physical characteristics such as grain size, porosity, permeability, etc. and to identify or investigate accelerated weathering effects of periodic pressure, temperature, and moisture variations. The investigation will begin with 1) an examination of untested and tested samples with the scanning electron microscope (SEM) to try to determine minute chemical changes in the sample, which may indicate leaching of compounds, and 2) observation of microscopic texture and fabric changes. If indications of leaching are present, other tests including spectrochemical analysis, x-ray diffraction, optical petrography, and wet chemical analysis will be performed on an as-needed basis.

Initially, one micrograph will be performed before testing and one after testing until it is clear that one or the other is not necessary. If negligible differences are observed between the two micrographs, then only one will be taken per sample. However, the conditions of the core may warrant more micrographs per sample, and in this event, more micrographs will be performed. The magnifications which will be used could range from 100 to 20,000.

It is estimated that up to 400 characterization tests will be required throughout the duration of the project. This number is quite arbitrary and will depend on how many generic rock types are tested. It is also estimated that at least 20 permeability and porosity tests at operational temperatures and pressures will be required. With the emphasis on compensated systems, this aspect of the testing is very important. The nature of the tests used to evaluate permeability under compensated cavern conditions involves different sample sizes and test conditions than those amenable to analysis of an uncompensated cavern.

7.3.4 Laboratory-Scale Testing of Rock Specimens

The purpose of this task is to obtain and to investigate the properties of hard rock specimens subjected to conditions simulating or approximating the operating conditions of a compensated CAES system. Included in this task is the conventional and nonconventional testing of various generic intact and non-intact rock types. The conventional testing includes unconfined compression, indirect tension, and triaxial compression tests for the purpose of obtaining reference values of elastic and strength properties for each of the generic rock types. The total number of conventional tests will depend ultimately on how many generic rock types will be considered.

Since there will be cyclical thermal stresses induced in the rock because of the difference in temperature between the water and air entering the cavern, nonconventional tests at elevated temperatures will be conducted for the various rock types as well as tests with cyclical thermal stresses. Other nonambient tests will include triaxial tests in which the confining fluid, which will be H_2O , is allowed to make contact with the specimen. The purpose of the nonambient tests is to assess the influence of the nonambient conditions on the rock properties and to evaluate any accelerated weathering which might occur. Both intact and jointed specimens will be used.

In general, the range of temperatures for the nonambient tests will be from 4°C to 35°C for water temperatures and 50°C to 150°C for

air temperatures. Confining pressures will range from 3.45 MPa (500 psi) to 20.7 Mpa (3000 psi).

7.4 FORMULATION OF STABILITY AND DESIGN CRITERIA

The formulation of stability and design criteria will be made on the basis of results of this project, the state-of-the-art surveys, and the numerical modeling studies all being conducted by Re/Spec. From these results and case history studies involving compensated caverns, definitions will be made of what constitutes acceptable cavern rock instability and air leakage instability. The criteria will address the conditions under which problems can be expected, actions required to prevent those problems, and consequences of failures which might occur.

7.5 SUMMARY

A program for the laboratory investigation of hard rock under CAES loadings and conditions is being implemented. This program will utilize the results of previous and ongoing CAES hard rock studies to develop criteria for the development and operation of CAES in compensated caverns. Laboratory studies will focus on property variations resulting from nonambient CAES loadings. Intact and non-intact rock will be studied.

8.0 STATE-OF-THE-ART SURVEY AND PRELIMINARY DESIGN AND STABILITY CRITERIA FOR SALT CAVITIES

R.L. Thoms and J.D. Martinez - Louisiana State University

This study reviewed the existing literature and consulted knowledgeable workers in the storage industry, and then reported state-of-the-art findings relative to long-term stability of compressed air energy storage caverns in salt domes. Further preliminary cavern stability criteria were presented in a form consistent with the amount of information available on cavern performance in salt domes. This study also outlined a methodology for determining the long-term stability of site-specific CAES cavern systems in salt domes.

The study was limited to stability considerations for CAES caverns in salt domes and salt anticlines. Thus, the effects of surface facilities associated with CAES caverns were considered as they relate to cavern stability. Details of surface facility machinery and systems, e.g., types of compressors or turbines, were beyond the scope of this study.

8.1 SUMMARY OF RESULTS

A report on a state-of-the-art survey of CAES salt cavern stability was completed in August 1978.⁽¹⁾ That report provided a review of the state-of-the-art and offered some preliminary stability criteria for CAES in salt caverns. The kernel of that report is presented here for completeness. The reader is encouraged to read the complete report for supporting information.

The fundamental conclusions of the state-of-the-art survey are as follows:

- Field data associated with storage of natural gas in salt dome caverns currently are most directly applicable to long-term stability studies of CAES caverns.

- CAES storage raises more concerns with stability problems than liquid hydrocarbon storage, solution mining, or natural gas storage currently operational in salt dome caverns.
- A number of workers with field experience in the domal storage and mining industry are dubious about the significance of conventional rock mechanics laboratory testing programs relative to predictions of salt dome cavern behavior.
- Test caverns have been employed in West Germany to obtain field data for performance of natural gas storage caverns.
- Laboratory testing programs for determining rock salt behavior have been conducted mainly with compression triaxial or uniaxial tests. However, more infrequently used triaxial extension tests were found to be of primary value.
- Crystal sizes (around 0.25 in. [0.64 cm] "diameter") in polycrystalline rock salt are relatively large, thus scale effects are probable in laboratory tests with relatively small specimens.
- Numerical modeling of rock salt behavior with the finite-element method has been in use for some time.
- Empirical methods combined with field experience have been used successfully in cavern stability studies.
- Stability criteria ultimately must be verified by field data from pilot and/or operational prototype CAES caverns. Relatively sophisticated monitoring equipment now exists for such purposes.
- The study of fundamental rock salt mechanics for all kinds of storage in domes is still in a relatively early stage.
- Concerns with compensated (constant pressure), as contrasted to uncompensated (constant volume), CAES caverns would include possible 1) erosion due to liquid flow, and 2) abrupt loss of cavern pressure.

- Long-term stability criteria for CAES caverns should be concerned with effecting acceptable limits on time dependent creep closure, creep rupture (spalling or slabbing), and superimposed deleterious cyclic loading effect.
- Specific long-term stability criteria for CAES caverns should be developed in a closely coordinated and balanced program utilizing complementary: 1) laboratory- and/or bench-scale testing of site-specific salt, 2) numerical modeling, and 3) field testing.
- Correlation studies should be performed on results from laboratory and/or bench-scale tests, borehole and/or model cavern tests, and prototype cavern tests.
- As part of the study, a list of topics which should be studied to obtain additional information relative to long-term stability of CAES caverns in salt domes was established. The list includes the following items:
 - long-term creep, with creep rupture, of rock salt
 - effects of pressure and temperature loading rates
 - low-frequency fatigue, with coupled cyclic pressure, temperature and wetting conditions
 - progressive air penetration of salt fabric
 - cavern monitoring methods
 - correlation of laboratory, analytical, and field results

Preliminary stability criteria were formulated for CAES in salt dome formations. These criteria are presented below:

- The site-specific utilization history of potential air storage salt structures should be researched to insure man-made effects will not threaten the integrity of the containing salt.
- The geology of potential air-reservoir salt domes, including the cap rock and neighboring formations, should be studied and reported in the early stages of planning for CAES facilities.

- The material properties of the salt and adjoining geologic units, e.g., cap rock, should be established so that stability analyses will have a basis for precluding cavern failure under environments associated with cyclic CAES operations.
- The configuration of a potential CAES dome must be capable of accommodating a system of caverns suitable for a compressed air reservoir.
- The loading cycles for CAES operations must range within bounds obtained from an engineering analysis and a verified data base.

8.2 CONCLUSIONS

Caverns in salt domes offer perhaps the most attractive type of geostorage for compressed air energy. Storage of hydrocarbons in salt dome caverns has been practiced in the U.S. Gulf Coast region for approximately twenty-seven years; however this kind of storage has involved mainly liquids and relatively slowly varying pressure loadings. Compressed air energy storage (CAES) in salt caverns will involve continuous daily cycling of pressure, temperature, and humidity. Possible deleterious effects due to cyclic loadings must be controlled such that the CAES caverns remain stable and functional over time periods of approximately thirty-five years. Long-term stability criteria are discussed relative to CAES caverns in salt domes. The criteria are based on a review of the technical literature and interviews with persons knowledgeable about storage in salt domes. The methodology for development and implementation of quantitative criteria specific to any particular potential CAES dome also was presented.

8.3 REFERENCES

1. R.L. Thoms and J.D. Martinez, Preliminary Long-Term Stability Criteria for Compressed Air Energy Storage Caverns in Salt Domes. PNL-2871. Report to Pacific Northwest Laboratory by Louisiana State University, August 1978.

9.0 NUMERICAL MODELING OF BEHAVIOR OF CAVERNS IN SALT FOR COMPRESSED AIR ENERGY STORAGE

S. Serata and T.E. Cundey - Serata Geomechanics Inc.

The objective of this study was to examine the behavior of salt cavities when subjected to conditions simulating CAES operation. The efforts addressed in 1978 were 1) determination of ranges of important variables, and 2) development of computer simulation techniques. The most important variables involved were identified as: 1) cavern geometry (length, diameter), 2) cavern spacing (in multiple cavern arrangements), 3) cavern air pressure and temperature cycle, 4) in-situ stresses, 5) material properties of salt, and 6) permeability of salt. A literature review on cyclic loading and thermal effects on rock salt was performed. Limited laboratory testing on salt strength and creep properties when subjected to cyclic loads was initiated as was preliminary numerical modeling.

9.1 SALT PROPERTY DATA - LITERATURE REVIEW

The literature review examined available data on the effects of cyclic loading and high temperatures on rock salt mechanical properties. Permeability of rock salt was also addressed.

9.2 CYCLIC LOADING

There is a large amount of geotechnical literature on the response of sands and clays to cyclic loading. Most of this literature is fairly recent and has resulted from research in designing earthquake-resistant structures and offshore platforms, in which cyclic loading conditions are prevalent. There is a much smaller but still significant volume of cyclic loading research that has been published using rock rather than soil materials. This literature was searched, but no information pertaining to rock salt was found. Some of the significant findings of other investigators using other rock types are summarized below. Although the mechanical differences between rock salt and the harder

rock types used in these studies are recognized, it is nevertheless useful to review the methods and results of the work done to date.

The most comprehensive investigation was conducted at the University of Wisconsin under the direction of B. C. Haimson⁽¹⁾ in work sponsored by the U.S. Advanced Research Projects Agency. Five hard rock types (Tennessee marble, Georgia marble, Indiana limestone, Berea sandstone, and Westerly granite) were tested cyclically under unconfined compression and unconfined tension. Westerly granite was also tested cyclically under triaxial compression and unconfined tension-compression.

The results of Haimson's study were evaluated in regard to conditions of CAES application in salt. The evaluation indicates that rock salt would suffer much less damage than the other rocks when subjected to cyclic loading. The basis of this projected interpretation of Haimson's work is summarized as follows:

- 1) Plastic Nature of Salt

The rock media increase their resistance to cyclic loading damage nearly logarithmically with decrease of their brittleness. Rock salt is far less brittle and more plastic than any of the rocks tested. Judging from the trend of the plastic effect, no appreciable damage to a specimen of rock salt is expected with a similar testing condition in the laboratory, as estimated in Figure 9.1.

- 2) Three-Dimensional Confinement

The three-dimensional confined condition prevailing in the salt media surrounding the CAES cavern will greatly reduce any potential damage directly from the cyclic loading.

- 3) Residual Strength

All rocks, including granite, are capable of maintaining a substantial portion of the original strength even after a failure has occurred. After the initial damage to the rocks, they can withstand a large number of cyclic loadings.

FIGURE 9.1. Estimated Effect on Rock Salt of the Compressive Cyclic Loading Used by Haimson Based on the Yielding Nature of Rock Salt(2)

4) Nature of Cyclic Loading

The rock salt media around the CAES cavern will be subjected to the stress state comparable to compression loading only. There is no possibility of the salt being subjected to the more vulnerable tension or tension-compression loading states.

5) Peak Stress of Salt

The peak stress expected in the salt is limited to a fraction of the overburden pressure. This intrinsic limitation of the peak stress as well as maximum range of the cyclic loading is expected to eliminate any large unexpected damage to the salt.

Haimson's work also indicates some areas of CAES concern. These areas include:

- 1) The volume increase that occurs during extensive stress cycling means that the intergranular space is continuously increasing, making the rock media more porous and permeable to air.

- 2) The increase of permeability reduces the strength of the rock media or salt at the cavern boundary by reducing the effective stress.
- 3) The cylindrical geometry of the CAES cavern may cause a sharp concentration of closure strain at the cavern boundary. This is due to the combined effect of plastic deformation, volume expansion, air penetration, and strength decrease in the large salt medium surrounding the cavern.

9.3 PERMEABILITY

Although the published literature on permeability of soils and some rock types is relatively abundant, few data specifically related to rock salt are available. The most useful data were found in the research work on rock salt conducted by Chia-Shing Lai⁽³⁾ and Shosei Serata⁽⁴⁾ at Michigan State University (MSU) from 1961 to 1971. The result of the permeability aspect of this work was presented in the Ph.D. dissertation of Chia-Shing Lai (1971). Results of this study showed that the behavior of rock salt consists of two separable tensor relations of the octahedral shearing stress-strain and mean stress-strain. This finding led to the hypothesis that permeability of rock salt should be a function of the two independent variables of the octahedral shearing stress and mean stress. Lai conducted the laboratory testing, establishing the permeability of rock salt as a quantitative function of the two variables. The permeability of rock salt decreases with increasing mean stress (σ_m) and increases with increasing octahedral shear stress (τ_{oct}). The following empirical relationship was developed from the laboratory data:

$$\log K = 0.62 - 0.00067\sigma_m + 0.00139\tau_{oct}$$

where:

- K = permeability (millidarcies),
- σ_m = mean stress (psi), and
- τ_{oct} = octahedral shear stress (psi).

The combined effect of τ_{oct} and σ_m is presented in the three-dimensional diagram of Figure 9.2.

Although Lai's work appears to be the best available research related to fluid flow through rock salt, certain cautions should be exercised in applying his results to CAES caverns. Lai's work employed kerosene as a permeant, rather than air, and maintained a differential pressure of only 125 psi across the specimen. Further, the testing did not include elevated temperatures. Higher temperatures might be expected to retard the penetration of air into the salt because of the thermal expansion of the salt grains as well as the plastic fusion of the halite crystals.

FIGURE 9.2. Three-Dimensional Plot of Mean Stress, Octahedral Shearing Stress, and Permeability(4)

9.4 TEMPERATURE

Serata⁽⁴⁾ (1959) demonstrated in his Ph.D. dissertation at the University of Texas that the elevated temperature reduces the viscoplasticity of the material greatly but affects the elasticity very little in both uniaxial and triaxial loading conditions, as shown in Figure 9.3. These conventional testing results were not found useful for quantitatively analyzing the effect of the elevated temperature on the material property coefficients.

Later study on the temperature effect conducted at the Serata Geomechanics Inc. (SGI) laboratory in Berkeley, California, was found to be most useful for the objective of the CAES work. The extent and intensity of the study are judged adequate for the preliminary computer simulation analysis of the CAES cavern sensitivity to various elevated

FIGURE 9.3. Effect of Elevated Temperature on Stress-Strain Relation of Cubic Specimen, Uniaxially Loaded Without End Friction Reducer, Demonstrating Reduction of Viscosity with Temperature Increase⁽⁶⁾

temperatures up to 300°F. The most significant aspect of the study is Serata's approach of establishing the rheological constitutive equations as a function of temperature, which was accomplished by experimentally determining a specific temperature function for the individual values of the property coefficients. Among the ten basic coefficients, the two viscoplastic coefficients are found to be most sensitive so that their effects probably overshadow those of the others.

Other than Serata's work, no systematic work on the temperature effect useful for the CAES work was found. Although Serata's work is logical and comprehensive, further refinement is needed for higher accuracy. Refinement work on the viscoelasticity and viscoplasticity for temperatures over 300°F is particularly needed.

9.5 NUMERICAL STUDIES

Plane strain analyses of a horizontal section of a single vertical cavern have been completed. The five parameters investigated were section depth (H), cavern air pressure (P_i), excess in-situ lateral stress (ΔP_L), octahedral shear strength of salt (K_o), and salt material properties (K_i). Four sets of base conditions have been studied, as shown in Table 9.1. From each set of base conditions the principal parameters were varied one at a time to study the individual effect of each.

TABLE 9.1. Numerical Studies Base Conditions

<u>Base Set</u>	<u>H (feet)</u>	<u>P_i (atm)</u>	<u>ΔP_L (%ΔP_{Lmax})</u>	<u>K_o (psi)</u>	<u>K_i</u>
1	2000	50	50	600	WEAK
2	2000	50	0	600	WEAK
3	1000	50	50	600	WEAK
4	3000	50	50	600	WEAK

Figure 9.4 shows the results of varying the depth (H) of the section from 500 to 5000 feet. The boundary strain begins to increase sharply once the depth exceeds about 3500 feet. The yielded region expands with increasing depth, extending to about 8 cavern radii from the boundary when the depth is 5000 feet. Strain results show significant boundary strains at depths of 3500 feet or more, with a maximum boundary strain of about 13 percent at the depth of 5000 feet.

Figure 9.5 shows the effect of varying cavern air pressure, which in these analyses was assumed constant rather than cyclic. The boundary strains are very small (less than 2 percent) even in the case of complete depressurization of the cavern. The yielded region radius attains a maximum of about 3 cavern radii when cavern pressure is 0.

The effect of the excess lateral stress ΔP_L , which is the amount by which the in-situ horizontal stress exceeds the overburden pressure, P_V , is shown in Figure 9.6. In theory, the lateral stress, P_L , in a salt formation is related to the overburden pressure as follows:

$$P_V - \frac{3}{\sqrt{2}} K_0 \leq P_L \leq P_V + \frac{3}{\sqrt{2}} K_0 \quad (9-1)$$

which leads to

$$-\frac{3}{\sqrt{2}} K_0 \leq \Delta P_L \leq +\frac{3}{\sqrt{2}} K_0 \quad (9-2)$$

where K_0 is the octahedral shear strength of salt. Figure 9.6 indicates that boundary strain increases sharply when the excess lateral stress reaches 90 percent of its theoretical maximum. The boundary strain of about 4.4 percent when the excess lateral stress is maximum is considered safe, however. Very little difference is observed when octahedral shear strength is varied between 550 and 750 psi. This indicates that for this set of base conditions K_0 is relatively unimportant.

FIGURE 9.4. Radial Boundary Strain Versus Depth Base Conditions I

FIGURE 9.5. Radial Boundary Strain Versus Cavity Air Pressure Base Conditions I

FIGURE 9.6. Radial Boundary Strain Versus Excess Lateral Stress Base Conditions I

Figure 9.7 shows the change in boundary strain that occurs when all salt properties are changed from "weak" to "strong". These properties were chosen from our experiences in laboratory testing and field work with salt from many different locations, and represent typical average values ("medium" salt) as well as typical low ("weak" salt) and high ("strong" salt) values for the material property coefficients. Although the boundary strains are noticeably different from the three different material property sets, they are very small even for weak salt. The differences are expected to be more critical at greater depths and for larger pressure differences between the cavern air pressure and the in-situ lateral stress.

FIGURE 9.7. Radial Boundary Strain Versus Salt Properties Base Condition I

9.6 CONCLUSIONS

Laboratory data is not complete concerning the effects of CAES operating conditions. Several items of particular concern include the response of rock salt to cyclic loading (no data available) and the variation of permeability with stress state, temperature, and possibly strain and strain rate. The effect of pore pressure on rock salt behavior is not well understood. Numerical modeling has proceeded to investigate the effects of varying cavern depth, operating pressure, lateral stress, octahedral shear stress, and basic salt strength. Results indicate that cavern depth, air pressure, and lateral stresses are significant factors affecting cavern closure. Octahedral shear stress and basic salt strength are not very significant. All comments pertain to and are limited to the preliminary results available.

9.7 REFERENCES

1. B.C. Haimson, "Aspects of Mechanical Behavior of Rock Under Static and Cyclic Loading." Annual Technical Progress Report, University of Wisconsin, Madison, Wisconsin, 1972.
2. B.C. Haimson, "Aspects of Mechanical Behavior of Rock Under Static and Cyclic Loading." Final Report, University of Wisconsin, Madison, Wisconsin, 1973.
3. Chia-Shing Lai, "Fluid Flow through Rock Salt under Various Stress States." Ph.D. dissertation, Michigan State University, 1971.
4. S. Serata, "Development of Design Principle for Disposal of Reactor Fuel Waste into Underground Salt Cavities." Ph.D. dissertation, University of Texas, Austin, Texas, 1959.

10.0 LABORATORY TESTING OF SALT SPECIMENS

R.L. Thoms - Louisiana State University

10.1 INTRODUCTION

Caverns in salt domes have become increasingly utilized for a variety of storage purposes. Some of the earliest uses of salt dome caverns included storage of liquefied propane gas (LPG) and other hydrocarbon products, e.g., ethane. More recently caverns in salt domes have been utilized for storage of natural gas and crude oil, e.g., the U.S. Strategic Petroleum Reserve plan. Other possible uses include storage of liquefied natural gas (LNG), high-level radioactive wastes, and possibly hydrogen. Caverns in salt domes also appear to be among the most suitable reservoirs for compressed air energy storage (CAES).

The objective of this testing program is to establish a data base for long-term stability criteria appropriate to CAES reservoirs in salt. The data base will be obtained from laboratory testing of rock salt core specimens and also from in-situ testing in a salt mine. This section briefly describes the efforts planned to fulfill the objective described above.

10.2 SCOPE

Rock salt specimens will be tested in the laboratory over a range of loading environments selected to span conditions experienced by salt surrounding CAES reservoirs. The testing will be performed with six testing machines designed specifically for testing relatively large rock salt specimens with diameters of 4 in. (10 cm) and lengths of 8 in. (20 cm) under cyclic thermal and triaxial loading conditions. Rock salt specimens will be obtained and tested from: at least one south Louisiana salt dome (Jefferson Island), Kansas (bedded salt), and, if possible, Huntorf, West Germany.

Boreholes in the south Louisiana salt mine, from which specimens are taken, will be tested to determine effects of cyclic thermal, pressure, and humidity loading conditions. Because the confining pressure around the core holes will not be as high as prototype CAES reservoirs, the mine test results will be used to establish a conservative bound on the disintegration behavior of salt fabric exposed to CAES operating conditions. Data from the in-situ testing program will be correlated by statistical methods to laboratory testing of specimens taken from the same core holes.

Data obtained from the laboratory and mine borehole testing programs will be analyzed and used to formulate long-term stability criteria for CAES reservoirs. Data from these testing programs also will furnish baseline data for workers doing numerical modeling of CAES reservoir behavior.

Results from laboratory testing and the subsequent data analyses and criteria formulation will be presented in the form of a comprehensive report at the end of the study. Attention will be focused primarily on establishing bounds on magnitudes and rates of operating thermal and pressure loadings for CAES reservoirs over a range of realistic depths, e.g., 2000-5000 ft (610-1524 m) in rock salt.

10.3 SIGNIFICANCE

Currently little data exists on cyclic loading effects on rock salt. The described testing program represents the first comprehensive CAES testing program in which thermal and triaxial stress cyclic loading conditions will be applied simultaneously, thus accounting for any possible coupling of these effects. Further, the borehole testing program in the mine will represent the first cyclic testing of in-situ rock salt.

The long-term cyclic test data will furnish a data base for long-term stability criteria for CAES reservoirs in salt. The test results will be available, in report form, for other workers in rock salt

mechanics working on CAES stability studies. Thus any worker can use the data base in deriving material parameters to fit his particular material models used, for example, in numerical analyses. Some workers also may use the data to compare with results based on more empirical analyses, e.g., physical models or experience-based "rules of thumb".

11.0 GAS FLOW CYCLIC VENTILATION OF POROUS MEDIA AT ELEVATED TEMPERATURE AND PRESSURE

H.J. Pincus - University of Wisconsin

11.1 INTRODUCTION

Studies of property changes of porous media subjected to cyclic ventilation with hot dry air are being carried out at the University of Wisconsin-Milwaukee. The goal of these studies is the determination of effects of CAES operation on host porous media.

Fabric studies during 1978 were effectively summarized in Reference 1. Studies have continued to address several tasks including: 1) compressed-air pressure-temperature cycling, 2) property testing, and 3) optional experiments.

Progress with respect to each of these tasks is described as follows.

11.2 COMPRESSED AIR TEMPERATURE-PRESSURE CYCLING

The multi-mode cycling system has been modified to provide more efficient, reliable heating of air. With this change, air has, for example, be heated at 400 psi to 350°F in the heat chamber.

The specimen chamber of the multi-mode system can be replaced with two triaxial cells (U.S. Bureau of Mines type) which can accommodate longer specimens (up to 6 inches long) and which provide a more reliable seal for confining pressure than does the present system. These cells plus a third modified cell can also be used in triaxial tests with or without simultaneous ventilation, and possibly also in studies of the effects of cyclic displacement of the air-water interface. What is needed now to use these in the multi-mode system is an auxiliary air chamber to provide the required storage capacity on the "far" sides of the specimens; this is currently being constructed.

The heating subsystem of the multi-mode cycling system (high-pressure, high-temperature system) has been modified by:

- replacing the single heating element in the heat chamber with two heavy-duty heaters and installing a dual temperature control system; one heater provides a base level of heat while the other heater provides make-up heat to compensate primarily for cycling losses.
- installing external heating tapes on the heat chamber, the piping to the manifold, the manifold, and the specimen chamber. A three-circuit control system (230 V, three-phase input; three 110-V single-phase outputs) has been constructed by the electronics shop to provide variable power for the heating tapes.

The relief valve on the back-pressure chamber of the multi-mode system, which controls the minimum pressure in the pressure cycle, has failed on several occasions. In one case, the sudden loss of flow-through pressure on the specimen resulted in damage to the specimens and their membranes because the difference between the flow-through pressure and the confining pressure suddenly rose to the value of the confining pressure. The situation is being dealt with by:

- operating at lower pressures (under 500 psi) until a relief valve with a much higher pressure rating (1500 psi) has been installed
- constructing an aperture in the line leading to the relief valve to check sudden surges of air
- designing a system that will drop the confining pressure when the flow-through pressure drops below a predetermined value. The main problem here is to shut off the air from the tank providing make-up air to the confining pressure system when the confining pressure is dropped.

A flow-meter for the multi-mode system has been designed and is being constructed. Installation is planned for a cycle-counter on the multi-mode system.

In the multi-mode system, it was found that the specimen membranes expand sufficiently above 300°F (tests have been conducted up to 475°F) to require allowance for expansion in seating all of the fittings. Without such allowance, the membranes buckle sufficiently to permit leakage from the confining air to the flow-through air. Procedures have been developed that deal quite successfully with this situation.

Requirements for modifications and repair of the multi-mode system and the training of personnel in its use have occupied much of the time devoted to this part of the work. Consequently, few specimens have been cycled in this system; however, the point has been reached at which it appears quite feasible to ventilate specimens on a production basis. Tests are being conducted initially at lower-pressure (less than 500 psi), lower temperature (less than 350°F) levels, although the equipment has been proved out at high pressures and temperatures.

11.3 PROPERTY DETERMINATION AND ANALYSIS

Pairs of ventilated and unventilated specimens have been processed through regular test procedures (mechanical, thermal, fabric analysis, etc.). Fabric studies are being applied to matched faces of ventilated and unventilated specimens. Some specimen pairs have been examined with the scanning electron microscope over a range of magnifications.

An error analysis of the optical correlation technique has been completed. This has consisted of measuring changes in correlation outputs from systematic errors of translation, rotation, and scale in the location of the input transformers.

Thin sections of potential reservoir rocks have been successfully impregnated with a dye-bearing cement. The spatial information in these sections can now be processed in the same way as the spatial information in photographs of paint-impregnated rock surfaces in reflected light.

The system for measuring pulse velocities of specimens under triaxial loads has been tuned and is ready for testing.

Repairs have been completed on an analog unit used to provide continuous square root and integrated outputs of optical transform profiles.

The thermal conductivity equipment is now fully on line and generating good results, thanks to a two-day visit of the manufacturer's laboratory manager. A dilatometer for pressure measurement of thermal expansion is on order. The drop-calorimeter is fully operational. With these three instruments, high-quality measurement of thermal properties of rocks will be available. One graduate student will use these properties in his thesis work.

A chamber for independent measurement of permeability of NX size specimens is being constructed. This will be used with a standard water permeameter, already on hand.

11.4 OPTIONAL EXPERIMENTS

Efforts have begun to investigate 1) the effects of cyclic movement of the air-water interface in cylindrical (NX) rock specimens, 2) mechanical property testing of specimens at the temperature at which they have been ventilated, or cycled, and 3) the ventilation specimens with moist air.

11.5 SUMMARY

Significant modifications have enhanced the capabilities and reliability of the multi-mode cyclic ventilation system. Additional property data have been gathered and analyzed. The results of these tests are consistent with those reported earlier.⁽¹⁾ Experimental programs investigating air-water interface movement (and its effects on porous media characteristics) and ventilation with moist air are currently under consideration.

11.6 REFERENCES

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PART II - ADVANCED CONCEPTS

PART II - ADVANCED CONCEPTS

W.V. Loscutoff - PNL

1.0 INTRODUCTION

1.1 OBJECTIVE

The objective of these studies is to evaluate new CAES concepts and promote technological development of advanced concepts that could reduce or even eliminate the dependence of the CAES system on petroleum fuels.

1.2 BACKGROUND

In contrast to energy storage concepts that would replace gas turbines as a utility peaking system (e.g., storage batteries, flywheels and pumped hydro), a conventional CAES system would only improve the effectiveness of a gas turbine in using fuel and reduce the consumption of premium fuels by about 60 percent. Current CAES plant designs require, at best, 4400 BTU of fuel per kilowatt-hour of electricity produced. The Huntorf CAES plant requires 5500 BTU/kilowatt-hour. These figures compare favorably with the nearly 14,000 BTU/kilowatt-hour required by gas turbines and could provide an annual saving in excess of 100,000,000 barrels of oil per year if current gas turbines were replaced by CAES plants. However, the conventional CAES concept is based on the use of petroleum fuels, and this dependence could become a major barrier to general implementation of the CAES concept by the utilities. Recognizing this barrier, a number of studies have been initiated by DOE and EPRI. These studies include evaluation of a wide scope of ideas, ranging from replacing petroleum fuels with coal to integrating CAES with solar collectors. Initial screening of the various ideas has reduced the number of promising concepts to three. These are a CAES system with a coal-fired fluidized-bed combustion process, a CAES system with a coal-fired low-BTU gasifier, and a CAES system with various amounts of thermal energy storage. The limiting case of the last concept is an adiabatic CAES system that would have sufficient thermal storage capacity so that it would not require any fuel for the turbines.

1.3 SCOPE

The program plan covers a range of activities in the investigation of advanced CAES systems:

- 1) equipment evaluation and development for advanced CAES systems
- 2) system feasibility studies of alternative fuels and technologies such as; adiabatic systems (requiring no supplementary fuel), hybrid systems that would utilize both thermal energy storage and fuel, coal-fired fluidized-bed combustion processes integrated with CAES, and coal-fired low-BTU gasifiers integrated with CAES
- 3) evaluation of development of other advanced CAES concepts that require little or no premium fuel for operation
- 4) a joint venture with a utility, Tennessee Valley Authority (TVA), starting with feasibility studies and progressing into demonstration of an advanced concept if the studies are positive.

The project structure for Advanced Concepts Studies is shown in Figure 1.1. Only the major tasks are shown in the figure; however, subtasks that fall within the major tasks are also reported. This section reports on the progress achieved in these tasks during 1978.

FIGURE 1.1. CAES Advanced Concepts Studies

2.0 ALTERNATIVE FUELS AND TECHNOLOGIES

J.W. Shupe, D.K. Kreid and G.L. DeHaan - PNL

During 1978, two alternatives were being studied; utilization of nuclear waste decay heat and utilization of coal-fired technologies. In addition, a cursory examination of the benefits of integrating CAES with magnetohydrodynamics was made. The nuclear waste heat and magnetohydrodynamics studies were completed this past year. The coal-fired technology studies are continuing, and a report of the preliminary findings will be contained in a topical report to be prepared during FY-1979.

2.1 UTILIZATION OF NUCLEAR WASTE DECAY HEAT

A preliminary assessment has been made of the utilization of decay heat from canisters of solidified waste fission products for augmenting a compressed air energy storage (CAES) system. Although there are many considerations involving the economic, social, political and environmental impacts of nuclear waste decay heat utilization in conjunction with a CAES system, the primary focus of this study was an assessment of the technical feasibility of the concept. The results of the study did not support follow-on studies to address the other considerations.

The approach was to design a CAES system that would provide optimum utilization of the nuclear waste heat. The system cycle is based on a high-pressure CAES system having two stages of expansion and exhaust heat recuperation. Waste heat recovery is accomplished with a heat exchanger between two expansion turbines. As in a conventional CAES cycle, the primary source of heat is fuel consumed in a combustor at the inlet to the low-pressure turbine. This heat is supplemented by the nuclear decay heat. A schematic of the system is shown in Figure 2.1.

For this analysis, a 100-MW plant was selected with a 10-hour duty cycle and a 14-hour reservoir charging period. Table 2.1 lists the parameters used in the calculations. Current nuclear waste canister technology suggests that the waste would be in stainless steel cylinders

LPC - Low Pressure Compressor
HPC - High Pressure Compressor
HPT - High Pressure Turbine
LPT - Low Pressure Turbine

FIGURE 2.1. CAES System Utilizing Nuclear Waste Decay Heat and Turbine Exhaust Recuperation

of 12 to 24 inches (0.3 to 0.6 m) in diameter and 10 to 15 feet (3 to 4.6 m) in length, with maximum skin temperatures between 500 and 800°F (260 and 427°C), heat loadings of 3.5 kW/cylinder and 13 kW/cylinder, and maximum allowable cyclic temperature fluctuations of 200°F.⁽¹⁾ The canisters used in this study were assumed to be 16 inches (40.6 cm) in diameter and 10 feet (3.04 m) long with a power output of 3.26 kW.

The evaluation of the energy input of the waste heat was made by comparing the system of Figure 2.1 to a similar system that by-passed the heat exchanger utilized in connection with the waste storage cells. Calculations showed that the percentage of the total heating requirement that could be contributed by the nuclear waste was slightly greater than 18% (depending on the assumed expansion ratios and temperatures).

TABLE 2.2. Canister Design for Nuclear Waste Storage/CAES

Waste Density	200 $\frac{\text{lb}}{\text{ft}^3}$	(3203 $\frac{\text{kg}}{\text{m}^3}$)
Waste Specific Heat	0.3 $\frac{\text{Btu}}{\text{lbm}^\circ\text{R}}$	(1.26 $\frac{\text{W}\cdot\text{s}}{\text{g}\cdot^\circ\text{C}}$)
Waste Volume per Canister	13 ft^3	(0.368 m^3)
Average Power Density per Canister	3.26 kW	
Total Waste Volume	30,200 ft^3	(855 m^3)
Canister Diameter	16 in.	(0.4 m)
Canister Length	10 ft.	(3.04 m)
Fin Height	2 7/8 in.	(7.30 cm)
Fin Thickness	3/16 in.	(4.73 mm)
Fin Pitch	1 3/16 in.	(3.02 cm)
Canister Area to Volume Ratio	19.66 per ft	(64.5 per m)

The overall conclusion reached by the authors of this study is that nuclear waste decay heat utilization in conjunction with a CAES system is probably feasible from a technical viewpoint, but that the potential for saving turbine fuel is not sufficient to warrant further analysis. The thermal advantage that could be gained appears to be too small to justify the additional complexity and expense that is likely to be associated with such an arrangement. Also, problems with licensing, environmental concerns, and siting are expected to be severe. As a consequence, no further consideration of this concept is currently planned.

2.2 GASIFICATION

A preliminary study was made to assess the possibilities of augmenting CAES with coal gasification.

Gasification is the process of converting solid coal to a clean gaseous fuel. Most processes use air and oxygen with steam to react with the coal. The product fuel gas may have a heating value range of

TABLE 2.1. Assumed Values for Optimized System

Air storage pressure	50 atm	(5000 kPa)
Air storage temperature	150°F	(66°C)
HPT inlet temperature	1000°F	(538°C)
LPT inlet temperature	2000°F	(1093°C)
Recuperator effectiveness	80%	
HPT efficiency	80%	
LPT efficiency	85%	
Waste heat-heat exchanger effectiveness	80%	
Ideal gas Polytropic coefficient	1.4	
Specific Heat	$0.245 \frac{\text{Btu}}{\text{lbm}^\circ\text{R}}$	$(1.03 \frac{\text{W}\cdot\text{s}}{\text{g}\cdot^\circ\text{C}})$
Nuclear waste density	200 lb/ft ³	(3203 kg/m ³)
Nuclear waste specific heat	$0.3 \frac{\text{Btu}}{\text{lbm}^\circ\text{R}}$	$(1.26 \frac{\text{W}\cdot\text{s}}{\text{g}\cdot^\circ\text{C}})$
Nuclear waste heat canister wall	800°F	(427°C)

Additional analysis was done to determine the air velocity required across unfinned waste canisters in order to obtain heat transfer coefficients sufficient to utilize the available thermal energy effectively. Calculations were made for reasonable localized temperature differences (canister wall temperature minus air temperature). In even the most optimistic case (greatest ΔT), the required air velocity for unfinned canisters was close to 200 feet per second (61 m/s).

This result led to the conclusion that the heat transfer area would have to be increased. A "reasonable" value for the air velocity across the canisters was chosen; a heat transfer coefficient was computed, based on the assumed velocity; and a surface area-to-volume ratio was calculated to give the required heat transfer. The resulting canister design is given in Table 2.2. Canisters with external fins were then designed which would provide the necessary area-to-volume ratio. The resulting design was evaluated regarding various practical aspects of its ultimate implementation.

100 to 1000 Btu/scf* (12.1 to 121 kWh/sm³*) depending on the process. The heating value of the product gas has been divided into three major categories. They are: low-Btu gas (LBG) with heating values from 75 to 175 Btu/scf (9.08 to 21.2 kWh/sm³), Intermediate-Btu gas (IBG) covers the 250 to 400 Btu/scf (30 to 48 kWh/sm³) range, and high-Btu or pipeline-quality gas (HBG) with a 925 to 1000 Btu/scf (112 to 121 kWh/sm³) range. Air-blown reactors produce LBG whereas oxygen-blown reactors produce MBG. HBG requires expensive shift reaction and methanation processing of MBG. In general, the thermal efficiencies of the conversion process decrease with increasing heating values while the ease of storing and transporting the gas increases.

Gasifier development has produced a multitude of different processes. Gasifiers are generally classified according to their coal flow relative to the gas flow. Under this system, three types can be identified: fixed-bed, fluidized-bed, and entrained-flow gasifiers. Other classification systems are also used, such as pressure level, source of oxygen (air- or oxygen-blown), number of stages, or ash removal method.

Power generation systems that use coal as their primary fuel are high in capital cost with respect to oil and natural gas systems. Coal gas-fired systems would be even higher in capital cost. High capital costs and the inability for daily turning off of gasifiers dictates that the gasifier facility be operated continuously and preferably at full capacity. The continuous operation would also help to defray their high capital cost.

The application of coal-derived fuel gas to CAES has now been narrowed to three general alternatives. They are:

- The gaseous fuel produced during compression periods would be sold and distributed to industrial users that are located nearby.
- Excess fuel produced during compression periods would be stored to be used during generation periods.

*Standard conditions (standard temperature & pressure)

- The turbines of the CAES would operate continuously, using all the fuel gas as it was produced.

The first alternative has control difficulties and is limited to sites near large industrial users. If the users are willing to use off-peak power, then they could load level directly without the expense of a coal gasification/CAES plant.

The second alternative requires storage of gaseous fuel. The technical problems associated with isolating gas and air storage could make site selection very difficult. Current gasifiers are operated below 200 psi (1379 kPa) which would require large storage volumes for the gas or a means of compressing the gas into smaller volumes. The additional gas storage cost added to the already high cost of the gasifier makes the option less attractive than the alternatives.

The last alternative allows continuous operation of the gasifier without the need to sell or store the product gas. The main operational characteristic is continuous combustion of the product gas as it is being produced. The acronym CGC/CAES (Continuous Gasification and Consumption CAES) will be used to denote this alternative. This option is conceptually different in that the plant's output would change by switching compressor trains on or off. The compressors would be on during storage and off during operation. The turbines would be operated continuously. Conventional CAES alternates running the compressor and turbine trains.

The CGC/CAES by-passes the major disadvantages of other gasification options, namely, storing or selling fuel gas. It is this advantage along with the ability to accommodate a coal gasifier that operates continuously and at near full capacity that makes CGC/CAES the most attractive of the coal gasification/CAES system. The CGC/CAES concept will be studied in greater detail next year. The extent of the study will depend on the results and direction of the coal gasification/CAES work being done by EPRI.

2.3 MAGNETOHYDRODYNAMICS

Magnetohydrodynamics (MHD) systems were found to be prime candidates for CAES applications since approximately twenty percent of the output is used to compress air. Our studies indicate that optimum use of MHD and CAES requires that they be located at the same facility. This would also allow the heat of compression of the CAES system to be used to heat feedwater for the MHD bottoming cycle.

Incorporation of CAES with MHD would allow a facility to have base- and intermediate-load capability. The facility may be able to supply peak loads also. The system would derive all of the air storage compression power internally and would not have to rely on power from the utility grid during off-peak periods. The ultimate goal of the continuously operated CAES/MHD plant might be to supply the entire spectrum of the demand curve and to do so at efficiencies close to that of base-load power generation.

Presently the MDH system with best compatibility with CAES is an open-cycle MHD with a steam bottoming plant as shown schematically in Figure 2.3. To combine the system of Figure 2.3 with CAES, the compressor must be replaced by a CAES plant which includes an expander turbine whose outlet pressure is ten atmospheres. During retrieval of air from storage, the ten-atmosphere (1000-kPa) expander turbine exhaust will become the air supply to the combustion chamber of the MHD system. Such a CAES/MHD combination would allow an MHD plant with a base output of 970 MW to become a plant that can deliver a range of power from 628 MW to 1346 MW. Preliminary calculations indicate the combined CAES/MHD plant can supply mid-range power at efficiencies close to base-load efficiencies.

Before MHD/CAES can be demonstrated, MHD will have to be successfully demonstrated on a commercial scale. Many MHD problems remain to be solved before that time. The most obvious and hardest MHD problems are associated with high-temperature materials for electrodes. There are several other problems which are currently preventing MHD from being a

FIGURE 2.3. Open-Cycle MHD With a Steam Bottoming Plant

near-term option for power generation; end current losses, electrode arcing, large-scale dc-ac power conversion, avoidance of shocks, and seed separation.

Our preliminary evaluation indicates that MHD would be a good companion for CAES, and that cost evaluations of MHD include the combination. However, we recommend that additional development of MHD/CAES systems be delayed until most of the MHD problems are well on the way to solution.

2.4 REFERENCES

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3.0 COAL-FIRED FLUIDIZED BED COMBUSTION

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3.1 INTRODUCTION

A potential long-term weakness of the conventional CAES concept is its reliance on clean petroleum fuels during power generation. It seems appropriate, therefore, to investigate advanced CAES concepts designed to substitute coal for petroleum fuels.

Application of coal-fired fluidized-bed combustion (FBC) to the CAES concept creates the potential for a large number of possible FBC/CAES power plant system configurations incorporating atmospheric fluid-bed combustion (AFBC) or pressurized fluid-bed combustion (PFBC). In principle, all of these configurations would use a coal-fired FBC to replace the petroleum-fired burner of the conventional CAES arrangement (Figure 3.1).

A feasibility study of FBC integrated with CAES was initiated during 1978. The purpose of this study is to conduct a technical and economic assessment of the feasibility of coal-fired FBC-augmented CAES system concepts. This study will include a technology assessment of fluid bed combustion, a systems integration and preliminary screening analysis, a preconceptual plant design and a preliminary market analysis. The program is managed by the United Technologies Research Center (UTRC). Besides its program management role, UTRC is playing a key role in the technical assessment of the coal-fired FBC/CAES concept including the integration and screening analysis, in the market analysis, and in the turbomachinery portion of the preconceptual design. Specialized subcontract assistance for the FBC technology assessment and the FBC portion of the preconceptual design is being provided by Coal Processing Consultants (CPC) of the United Kingdom. In addition, specialized subcontract assistance on conceptual plant design is being provided by Acres American, Inc. (AAI).

FIGURE 3.1. Fluidized Bed Combustion Concept. Simplified Coal-Fired FBC/CAES Configuration

The subjects addressed in this overview are fluidized bed combustion technology and turbomachinery technology. The FBC technology coverage includes a technology review and assessment, a parametric characterization, a discussion of component availability, and R&D cost assessment. The turbomachinery technology coverage is generally parallel in nature in that it includes a technology review and assessment relative to FBC/CAES power plant systems, a discussion of component availability and an R&D cost assessment.

3.2 FLUIDIZED BED COMBUSTION TECHNOLOGY

A fluid bed is produced by turbulent flotation of crushed, inert material in a rising air stream. The principle of bed fluidization is quite simple. When a static bed of relatively dense particles is subjected to an upward, low-velocity flow of gas, the gas passes through the bed without disturbing the particles. If the velocity of the gas is continually increased, however, a point will eventually be reached at which the individual particles will be forced upwards by the aerodynamic drag force, and incipient fluidization will begin. If the velocity is further increased, expansion of the bed occurs, permitting an increase in the gas flow rate. The bed becomes highly turbulent and rapid mixing of the particles occurs. The surface is no longer well defined but appears diffuse and bubbles of "gas" similar to those formed in a boiling liquid rise through the bed. A bed in this state is said to be fluidized. Still further increases in gas velocity cause progressively larger particles to become entrained in and carried off (elutriated) by the gas stream. Consequently, for a particular bed with a given particle size range, there will be an upper and lower limit of velocity (fluidizing velocity) between which satisfactory fluidization is considered to have been established.

In fluid bed combustion, the particles forming the bed are composed of suitable inert mineral matter. For coal burning, these would probably be the residual ash from previously burned coal and graded limestone or dolomite to absorb sulfur dioxide during combustion. The fluidizing gas is the combustion air. Coal is fed continuously into the bed in the quantity required to maintain the desired bed temperature.

The design of a coal-fired fluid bed combustor is significantly influenced by the operating conditions. The most important of these are bed temperature, fluidizing velocity, operating pressure, and particle size. The bed temperature of the fluid bed combustor must be controlled within fairly narrow limits, i.e., 1425 to 1650°F (775 to 900°C). This control is necessary to achieve high combustion

efficiency, obtain high heat transfer rates to in-bed tubes, maximize sulfur retention, avoid ash sintering, limit the metal temperature of heat transfer surfaces in the bed, and reduce emissions of nitrogen oxides and alkali metal salts. The fluidizing velocity must also be controlled within fairly narrow limits, i.e., 2.5 to 4.5 ft/sec (0.75 to 1.4 m/s) for a PFBC and 2.5 to 8 ft/sec (0.75 to 2.5 m/s) for an AFBC. Operation within this range will establish bed fluidization, provide oxygen for combustion, and limit elutriation of bed particles. The selection of operating pressure will influence combustion efficiency, sulfur retention, nitrogen oxides emission levels, and capital costs. Operation at elevated pressure (PFBC) will produce beneficial results for all of these parameters as opposed to operation at atmospheric pressure (AFBC). The choice of particle size is related to the choice of fluidizing velocity. The lower limit of particle size is determined by the requirement to avoid excessive carry-over of combustible material, unreacted sorbent, and bed material. The upper limit is determined by the desire to achieve high heat transfer rates to in-bed tubes and effective solids mixing without localized segregation. The design of FBC for FBC/CAES applications is also influenced by factors unique to the application. These include load following, hot gas particulate cleanup, and alkali emission reduction.

3.3 TURBOMACHINERY TECHNOLOGY

The design of turbomachinery is also significantly influenced by the operating conditions. The operating conditions for the turbomachinery in a FBC/CAES power plant system will depend on whether an AFBC or a PFBC is used. In either case, however, the operating temperature will be characteristic of conditions which were attainable twenty years ago.

The application of an AFBC would require relatively minor modification of clean fuel-fired turbomachinery designs. The AFBC would be used as an air heater, and this heated air would be expanded in the turbine. Although the turbine would be relatively simple to design, an AFBC/CAES

system would still be faced with a materials problem. The extensive heat transfer surfaces immersed in the bed and in the hot convective zone following the bed must contain the high-pressure compressed air while being subjected to high temperature.

The use of a PFBC would present more of a design challenge to ensure high reliability and low maintenance for the turbine. The size and amount of particles entering the turbine would have to be controlled within narrow limits by effective hot gas cleanup to minimize turbine erosion and particle deposition. A limited amount of particles between 2 and 10 microns could be tolerated; however, particles greater than 10 microns would have to be removed from the PFBC effluent gas stream before the turbine. Small particles (1 micron and less in size) have an affinity to adhere on impact; therefore, concentrations sufficient to cause fouling of the airfoils must be avoided. The level of volatilized alkali metal salts in the PFBC effluent gas must be kept to a minimum and corrosion-resistant materials or coatings must be used to reduce the potential for excessive corrosion.

3.4 AVAILABILITY AND R&D REQUIREMENTS

Off-the-shelf FBC and turbomachinery equipment does not presently exist for FBC/CAES applications.

3.4.1 Fluid Bed Combustors

Small scale, commercial fluid bed boiler systems can be engineered now. However, the larger, high-temperature FBC equipment associated with CAES systems requires continued development.

The major areas in which R&D on fluid bed combustors is required include feeders for the coal and sorbent, devices for ensuring efficient lateral distribution of fuel in the bed, containment for the combustor, distributors for the fluidizing and combustion air, heat transfer surfaces for both in-bed and above-bed tubes, depressurization systems for spent sorbent and fuel ash, tube bundles for minimizing bed depth, and control systems for load following.

3.4.2 Turbomachinery

If an AFBC were used in a CAES power plant system application, the modification of existing petroleum-fired turbomachinery should not produce any significant problems. However, the turbines for expansion of gases from a PFBC represent a major design uncertainty at this time.

The major areas of turbomachinery R&D would be directed toward compatibility between a PFBC and the turbine. The effect of erosion on gas turbines must be better documented and effective hot gas cleanup systems must be developed to control particulates. Methods must be developed which will limit deposition. The corrosion mechanism must be better understood and materials must be developed that will not only withstand corrosion but the combined effects of corrosion and erosion.

3.4.3 FBC/CAES Commercialization

Successful completion of the development activities mentioned above could lead to commercialization of an AFBC/CAES system with air heater tubes in the fluid bed limited to 1200°F (650°C) by 1985. This could be followed in 1990 by a PFBC/CAES system with the same tube metal temperature limitation. It is envisioned that the air heater tubes in the bed could operate up to the bed temperatures for both the AFBC/CAES and PFBC/CAES system by 1995.

4.0 ECONOMIC ANALYSIS

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C. Knutsen - Knutsen Research Consultants

A major factor in assessing the feasibility of any engineering alternative is the cost. For Compressed Air Energy Storage this can be done through a determination of the incremental cost of electricity that results from using the CAES system in question. The value of the analysis is dependent on economic factors (such as year of pricing, interest, escalation, etc.) as well as the engineering factors.

4.1 CAPITAL EQUIPMENT COMPARISON

Cost estimates for the reference CAES system are for a system with mined hard rock air storage caverns. These estimates were obtained from a recent study conducted by Acres American, Inc..⁽¹⁾ The scenario used in that study, and adopted here, calls for the construction of a 750-MW CAES system over a 6.5-year period with the start-up of the first 250-MW unit in July, 1984.⁽²⁾ The second and third 250-MW units are brought on line by January, 1985. All costs are price level adjusted to that date so that the bottom line in Table 4.1 represents the total installed cost for each system in January, 1985 dollars/kW.

The reference CAES cost estimates are used as a basis for the equipment costs in the Thermal Energy Storage (TES) system. The differences are the result of differences in operation and performance or in system configuration.

After all the costs are accumulated, the reference CAES system has an installed cost of \$384/kW (See Table 4.1). The two TES systems are higher than this. The resulting incremental capital costs are \$63/kW for the hybrid system and \$119/kW for the double-stage/adiabatic system.

TABLE 4.1. Capital Cost Comparison (\$1000)

	<u>Reference CAES System</u>	<u>Hybrid System</u>	<u>Double-Stage Adiabatic System</u>
Land, Structures, and Plant Equipment	\$ 5,538	\$ 5,538	\$ 5,228
Turbo Machinery			
Intercoolers	1,664	1,241	449
Aftercoolers	780	-	-
Compressor Recuperator	-	22,000	-
Compressors	24,972	24,972	37,458
Compressor Motors	17,304	19,207	31,946
Turbines	18,354	18,354	27,531
Turbine Exhaust Recuperator	8,501	8,501	-
Other Turbo Machinery	27,735	27,735	26,199
Storage Facilities			
Air Storage & Associated Costs	34,509	34,509	51,764
Thermal Storage	-	2,030	6,090
Fuel Storage	428	428	-
Electrical and Miscellaneous	<u>10,625</u>	<u>10,625</u>	<u>10,625</u>
	\$150,410	\$175,140	\$197,290
Engineering and Construction Management	<u>22,562</u>	<u>26,271</u>	<u>29,594</u>
	\$172,972	\$201,411	\$226,884
Contingency	25,946	30,212	34,033
Escalation	50,387	58,672	66,092
Interest During Construction	<u>31,436</u>	<u>36,604</u>	<u>41,234</u>
July 1984 \$	\$280,741	\$326,899	\$368,243
January 1985 \$	287,759	335,071	377,449
Plant Capacity	750 MW	750 MW	750 MW
Cost/kW 1985 \$	\$384/kW	\$447/kW	\$503/kW

4.2 ENERGY USE COMPARISON

4.2.1 Turbine Fuel

Based on the difference in turbine heat rates⁽³⁾, the hybrid system uses about 13% less turbine fuel than the reference CAES system. The double-stage/adiabatic system uses no turbine fuel.

4.2.2 Compression Energy

About 11% more compression energy is required in the hybrid system because of its lower specific-mass-flow in the compressor.⁽³⁾ The double-stage/adiabatic system will require about 85% more compression energy because it has both a smaller compressor specific-mass-flow and a larger turbine specific-mass-flow.

4.3 LEVELIZED COST OF ELECTRICITY

The cost of electricity for the reference CAES system given in 1985 price levels is 112.5 mil/kWh (Table 4.2). This was calculated using the assumptions in Table 4.3. The values for the parameters shown were taken directly from the Acres American study.⁽⁴⁾ The exact values were used to provide consistency with that study and, based on other studies, these base case values can be viewed as representative.⁽⁵⁾

TABLE 4.2. The Reference CAES System Levelized Cost of Electricity

<u>Component</u>	<u>Cost (mil/kWh)</u>
Capital	27.2
O & M	
Fixed	3.9
Variable	.6
Turbine Fuel	31.5
Compression Energy	<u>49.3</u>
Total	112.5

TABLE 4.3. Base Case Assumptions^(a)

Plant Storage Capacity	20 hours
Plant Capacity	750 MW
Operation and Maintenance Costs	
Fixed	\$4.85/kW
Variable	0.32 mil/kWh
Operation and Maintenance Escalation Rate	5.5%/yr
Fuel Cost	\$4.00/10 ⁶ Btu
Fuel Cost Escalation Rate	7.0%/yr
Compression Energy Cost	30 mil/kWh
Compression Energy Cost Escalation Rate	7.0%/yr
Cost of Money	12%
Fixed Charge Rate	15.5%
Life of Plant	35 yr
Capital Cost Escalation Rate	5.0%/yr
Capacity Factor	25.0%

^(a) All costs are in terms of 1985 price levels

The incremental costs of electricity for the hybrid and double-stage/adiabatic systems are made up of the same components as the reference CAES system cost of electricity (Table 4.4). The incremental costs, however, represent only the changes in the cost that are a result of the differences among the three systems.

TABLE 4.4. Incremental Costs of Electricity

Incremental Cost Component	Hybrid System (mil/kWh)	Double-Stage/ Adiabatic System (mil/kWh)
Capital	+ 4.5	+ 8.4
O & M	0	0
Energy Consumption		
Turbine Fuel	- 4.1	-31.5
Compression Energy	+ 5.4	+41.9
Total Incremental Cost	5.8	18.8

4.4 SENSITIVITY ANALYSIS

The incremental costs of electricity for the TES systems are most sensitive to changes in the values of capacity factor, turbine fuel cost and compression energy cost (See Table 4.5). The results when capacity factor and turbine fuel are varied are shown for two compression energy costs, 20 mil/kWh and 30 mil/kWh, respectively.

TABLE 4.5. Levelized Incremental Cost of Electricity
(mil/kWh)

	<u>Hybrid System</u>		<u>Double-Stage Adiabatic System</u>	
	<u>Case A</u>	<u>Case B</u>	<u>Case A</u>	<u>Case B</u>
Reference Conditions		5.8		18.8
Capacity Factor ^(a)				
10%	10.8	12.6	17.4	31.4
15%	7.0	8.8	10.4	24.4
20%	5.1	6.9	6.9	20.9
25%	4.0	5.8	4.8	18.8
30%	3.3	5.1	3.4	17.4
35%	2.7	4.5	2.4	16.4
Turbine Fuel Cost ^(a)				
\$3.00/10 ⁶ Btu	5.0	6.8	12.7	26.7
\$3.50/10 ⁶ Btu	4.5	6.3	8.7	22.7
\$4.00/10 ⁶ Btu	4.0	5.8	4.8	18.8
\$4.50/10 ⁶ Btu	3.5	5.3	.9	14.9
\$5.00/10 ⁶ Btu	3.0	4.8	- 3.0	11.0
Compression Energy Cost ^(a)				
10 mil/kWh		2.2		- 9.1
20 mil/kWh		4.0		4.8
30 mil/kWh		5.8		18.8
40 mil/kWh		7.6		32.8
50 mil/kWh		9.4		46.7

Case A uses a compression energy cost of 20 mil/kWh
Case B uses a compression energy cost of 30 mil/kWh

(a) Holding other reference conditions constant

Figure 4.1 provides a graphic representation of the sensitivity of the double-stage/adiabatic system cost to changes in turbine fuel cost. A pair of curves is shown for both the 20 mil/kWh and 30 mil/kWh compression energy costs. The dashed line in each pair demonstrates the

FIGURE 4.1. Double-Stage/Adiabatic System Fuel Cost Sensitivity

low sensitivity to the uncertainties in capital costs. When the curves go below the zero line (when the incremental cost is negative) the double-stage/adiabatic system costs less to operate than the reference CAES system.

4.5 REFERENCES

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4. M.J. Hobson, et al., Feasibility of Compressed Air Energy Storage As a Peak Shaving Technique in California. Acres American, Inc. for the California Energy Commission, Table 8-3, p. 8-29, May 1978.
5. California Electricity Generation Methods Assessment Project. TRW Energy Systems Management Division, 1459.77.009 EJ, Figure 1-4, p. 1-7, January 1977.

5.0 A THERMODYNAMIC CYCLE ANALYSIS CODE

L.L. Eyler and G.L. DeHaan - PNL

CYCLOPS-MOD1 is a FORTRAN code written for an IBM 7094 computer⁽¹⁾. It was written to perform design point thermodynamic cycle calculations of systems comprising pumps, turbines, compressors, heat exchangers, phase separators, and flow mixing, splitting, and throttling devices. It was capable of handling water/steam, air, nitrogen, and parahydrogen working fluids. The modular form of the code allowed any combination of components to be treated, and logic was incorporated to allow parameterization of cycle configurations.

A copy of the original code, CYCLOPS-1^(a), was obtained from Argonne Code Center for use in analyzing advanced CAES concepts at PNL. However, numerous modifications have since been made to the code that simplify its usage as well as greatly expand its capabilities. Improvements incorporated for the user include a shorter, more concise input, more simplified parameterization capabilities, and various output options which allow more flexibility in interpreting results. Expanded code capabilities include the addition of treating fluidized-bed combustors, ideal and fueled combustors, and a simplified gasifier. A fluid property combustion products which result from the fueled combustors or gasifier.

5.1 CODE DESCRIPTION

The original FORTRAN version of CYCLOPS-1 was written for an IBM 7094 computer⁽¹⁾. A copy was obtained from the Argonne Code Center and converted to the UNIVAC system for use at PNL. At an early stage of the conversion process, it was learned that the version obtained from ACC did not contain the water properties subroutines. A separate library of routines for ASME water/steam properties have since been added.

Also at an early stage in the conversion process, it was recognized that the code did not have the capabilities of treating combustors,

^(a) CYCLE OPTimization System

fluidized beds, or gasifiers. Since these components were integral to CAES advanced concepts being studied, subroutines were added to model these components. A description of these subroutines are presented subsequently along with the description of the other components CYCLOPS treats.

During the conversion process, numerous other modifications were made to the original version. Some modifications were made for user convenience while some were made to enhance overall capabilities as well as improved input/output. The modified version is hereafter referred to as CYCLOPS-MOD1. The general code description and capabilities of the modified version are presented in more detail below.

5.1.1 General Structure

The general structure of the code consists of three sections. These are:

- 1) a control section
- 2) a components library
- 3) a properties library.

The first section of the code is the control section. It reads input data which determines the cycle to be calculated. The input data is interpreted and appropriate component, specialty, and property subroutines are called at the correct time. The called subroutine then calculates exit conditions for the components which are then used as inlet conditions for the next component. At the completion of cycle calculations, the main program calls subroutines to write out thermodynamic conditions along with mass flows at the entrance and exit of each component. A subroutine is also called which writes out a summary of heat flows and power results for the cycle. For multi-stage turbines, pumps, and compressors, additional information for each stage is also written.

The second section is the components library. Each subroutine in this library simulates the characteristics of that component. Each of these subroutines was written in a general form so that any fluid properties in the properties library may be used. The turbine, pump,

and compressor routines can be used as design programs or as simple single-stage components. As design programs, they utilize the similarity parameter concept of Balje^(2,1) and size effect corrections from Marks^(3,1). The heat exchanger in the current version is not a design program.

The third section is the properties library. It contains properties for water/steam, air, nitrogen, and parahydrogen. In addition, combustion products can be treated in an approximate form. These properties are available to the other sections of the code at all times, thereby enabling a user to analyze cycles with more than one working fluid.

The code is modular and is capable of handling any thermodynamic cycle composed of the following components:

- 1) axial flow turbines (up to 24 stages with bypass flow)
- 2) pumps (up to 24 stages)
- 3) compressors (up to 20 stages)
- 4) phase separators
- 5) heat exchangers
- 6) flow mixing devices
- 7) flow splitting devices
- 8) flow throttling devices
- 9) combustors
- 10) fluidized bed combustor heat exchangers
- 11) a simple gasifier.

In addition, there are six specialty routines designed for further generality. These are:

- 1) an input routine to enter input conditions at any point in the system
- 2) a transfer routine used to transfer all the thermodynamic conditions from one point to another point
- 3) an iteration routine used to obtain a desired parameter at some point in the system calculation
- 4) an accumulator routine to sum or move one parameter from one point to another

- 5) a subroutine which marries the various fluid properties in the properties library to the rest of the code
- 6) an output routine to write out state point results and summarize net heat flow and power results.

At the end of a cycle calculation, several options are available. The program can be stopped, a parameterization may be done, or a new cycle may be input and calculated.

If the parameterization option is used, one or more of the conditions specified on the original input cards may be changed and the reference cycle rerun. This option is quite useful if, for example, one were interested in determining the net electrical power produced as a function of turbine inlet temperature. The parameterization card would then specify a new turbine inlet temperature, and the whole cycle would be rerun. Since this option is available again at the end of this first variation, any number of temperatures may be specified on subsequent parameterization cards, and a series of results from the parameterized cycles is obtained.

If the option is chosen to use a new cycle, the code transfers control all the way back to the original input position. At this point completely new cycle calculations could be commenced. Parameterization of this new cycle may also be done if desired.

Now that some familiarity has been gained in the organization of the code, more detailed descriptions of the individual component subroutines and the auxiliary specialty routines are presented.

5.2 COMPONENTS DESCRIPTION

The modular form of the code allows components to be connected in any cycle configuration. In addition, auxiliary subroutines are available for iteration of a specified parameter to a desired value at a specified state point, accumulation of a specified parameter at a specified state point, and transfer of all thermodynamic conditions from one state point to another. These routines are described below.

5.2.1 Turbines

Axial-flow, adiabatic turbines are modeled in the subroutine TURB. Up to 24 stages with moisture control and by-pass flow can be treated for wet and superheated steam. The subroutine may be used in either a design mode or as a simple single-stage adiabatic expander. The latter mode is a convenient way of modeling a gas turbine, such as is used in a CAES application, without requiring a significant amount of detailed information about a specific turbine design.

In the single-stage adiabatic expansion mode, outlet conditions are determined from known inlet conditions using thermodynamic relations described in any standard thermodynamics textbook. An option is available to specify either the outlet pressure or an expansion ratio.

An iterative process is used to determine the turbine efficiency and turbine reheat factor. To start, both are assumed. A new efficiency is calculated at each iteration using a 1% convergence criterion. Once convergence on efficiency is reached, reheat factor is calculated, and the whole process is repeated until the reheat factor also converges.

Stage loading can be specified as equal for each stage, unequal according to an input table, or resulting from input specification of stage pressure ratios. Moisture control effectiveness parameters are applied at each stage according to the specific speed of a stage. By-pass can also be applied at each stage. By-pass flow may be specified as a weighted factor or percent of flow and may be reinjected at any state point in the cycle.

5.2.2 Pumps

The subroutine PUMP is a design mode model using the method of Balje^(2,1). The subroutine calculates pump performance for up to 24 stages using specific speed and specific diameter as similarity parameters in a manner not unlike that done for a turbine. Specific details may be found in the user's manual⁽¹⁾ and are not further discussed here. A simplified one-stage compression is available if design calculations are not desired.

5.2.3 Heat Exchangers

The heat exchanger subroutine, HEX, is not a design mode model and hence does not compute physical geometries. The type of heat exchanger is not required knowledge and as such has no effect on the manner in which the subroutine solves for the specific properties. The code computes overall heat balance from enthalpy and mass conservation. Pressure drop options allow the user to either specify a ΔP , specify ΔP as a fraction of inlet pressure, or specify ΔP as a fractional quantity related to a reference mass flow, $\Delta P/W_{Ref}^2$.

Four paths through the subroutine exist. A specified heat rate, Q , may be given, in which case outlet properties are determined after the enthalpy change is calculated. The outlet temperature or enthalpy may be specified in which case the heat rate is determined from the enthalpy change and mass flow. The temperature or enthalpy change across the heat exchanger may be specified. Neither of these three options require knowledge of the opposite side of the exchanger. The fourth option is used when calculating the opposite side. Enthalpies previously determined for the first side are used to perform an overall balance from which outlet conditions on the second side are determined.

The fourth option also incorporates an input ΔT approach check. If the ΔT approach is not satisfied, the code will automatically iterate any necessary portion of the cycle until the ΔT approach is satisfied. When no solution is found, an error message is printed to warn the user of the condition. An effectiveness calculation is also included if a correct heat balance is obtained.

5.2.4 Separators

The subroutine SEP is capable of separating a fluid into a vapor stream and a liquid stream when inlet quality is specified. It also includes the option of determining the required inlet flow for a given inlet quality and a given vapor flow rate.

5.2.5 Compressors

The design mode of the subroutine COMP models gaseous compression in a manner similar to that previously discussed for a pump. As a single-stage adiabatic compressor, the subroutine models gaseous compression according to common thermodynamic relations. The user has the option of either specifying an outlet pressure or a compression ratio.

5.2.6 Flow Mixing, Splitting, and Throttling

The subroutine DUCT is capable of modeling flow mixing, flow splitting, and flow throttling. Flow mixing of two, three, or four streams into one stream can be handled. The outlet pressure is assumed to be equal to the minimum of the inlet pressures. Outlet enthalpy is determined for the outlet stream as a summation of the inlet enthalpy flows divided by the sum of the inlet mass flow. Subsequently, outlet properties are then determined with a call to the properties library.

Flow splitting of a single stream into two, three, or four streams can be handled. Depending upon the number of outflows, the user has the option of specifying actual mass flows or fractions of the inflow for each outlet stream. Outlet properties for each of the streams are then determined.

Flow throttling is modeled as an isenthalpic process. The user has the option of specifying a ΔP , specifying a $\Delta P/W_{Ref}^2$, a ΔP as a fraction of inlet P or outlet P . Outlet properties are then determined from the outlet enthalpy and pressure.

5.2.7 Combustor

The subroutine CBUST has been added to the original code with three options available to the user. These include treating the combustor as an ideal heat source, treating it as an ideal combustor using specified input fuel properties, or treating it as a real combustor using specifications concerning the fuel's constituents. For each of the modes, the user may specify an outlet pressure, specify a pressure drop, or specify a pressure drop as of fraction of inlet pressure.

As an ideal heat source, a desired combustor outlet temperature must initially be specified. CBUST then determines what heat rate must be provided to attain the specified outlet temperature independent of any knowledge of the fuel. In this case, the combustor's outlet mass flow is the same as its inlet and no account is made for property variations that might be caused by combustion products.

As an ideal combustor, physical properties of the fuel, such as its high heating value (HHV), must be input along with the fuel's inlet temperature and desired combustor outlet temperature. A mass and energy balance then determines what flow rate of the fuel must be supplied. Outlet mass flow is thus increased but no variations in combustion properties are considered.

5.2.8 Fluidized-Bed Combustor Heat Exchanger

A fluidized-bed combustion air heater model has been incorporated as FBCOMB. The model describes an idealized tube/bed air flow, constant combustion temperature heat source. Combustion kinetics, effect of combustion products on fluid properties, and effect of combustion products on bed side mass flow are neglected for simplicity. A pseudo-design mode is optionally available to the user in which tube size and number, bed and tube side heat transfer coefficients, and tube length may be optionally used in various combinations in order for overall sizing characteristics to be determined. Tube side outlet pressure may be specified, determined by specifying a pressure drop, or specifying a drop as a fraction of inlet pressure. Bed side pressure drop is currently defaulted to a fraction of bed side inlet pressure. Improvements to the model may readily be incorporated should the need for more details be required.

5.2.9 Gasifier

The routine GASSER was written to specifically model a Foster-Wheeler gasifier and simulates the performance data predicted by Bissett⁽⁴⁾. The model is a moderate-pressure, two-stage, air-blown,

entrained-flow gasifier in which the fuel gas composition and HHV remain the same throughout a range of inlet pressures. The gasifier maintains an 80% cold gas conversion efficiency. Effects of throughput on efficiency are neglected. An air preheater maintains the required inlet temperature, and pressure drop across the unit is specified as input.

5.2.10 Iteration Routine

The specialty subroutine ITER provides the capability of changing a variable in one part of the system until a specified parameter in another part of the system reaches a desired value. A desired value may be specified for any of the thermodynamic properties as well as efficiency, power, flow rate, etc. Any of these parameters may then be varied at any station in the cycle until the desired value is attained to within a specified percentage. A regula falsi method is used and if no solution is reached after 10 iterations, an error message is printed, all answers at that point are printed, and calculations through any remaining portions of the cycle are continued. Provisions are made for any number of nested iteration loops. When used in conjunction with the ACCUM subroutine, this procedure is a very powerful and flexible iteration capability.

5.2.11 Accumulation

The specialty subroutine ACCUM provides the capability to select at a specified station any of the thermodynamic variables or component parameters, multiply it by a constant, and either place it or add it to any of the variables at any other station. This routine is designed to work properly even within an iteration loop by subtracting out previously added amounts before adding a current value.

5.2.12 Transfer

The specialty subroutine TRANS provides the capability of transferring all of the properties on any station to any other station. This routine is useful in closed-cycle calculations and in conjunction with the iteration routine.

5.2.13 Properties Library

The properties of the original code, CYCLOPS-1, contained water/steam properties and real gas properties of air, nitrogen, and parahydrogen. The ASME water/steam properties are self-contained in a separate library of routines and the real gas properties are internally incorporated in a routine called PAN. These routines are continually available to the code and are married through the routine called PROP.

In addition to the original version's properties, an approximate method for treating combustion products has been incorporated. The approximation has been shown to work very well for combustion of the fuel produced by the above-described gasifier. However, further improvements could still be made.

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6.0 THERMAL ENERGY STORAGE

G.T. Flynn and J.L. Nash-Webber - M.I.T.

6.1 STUDIES OF COMPRESSED AIR ENERGY STORAGE FOR SOLAR APPLICATIONS

A subcontract was solicited to make a study of the economic aspects and feasibility of the joint application of solar thermal energy and compressed air energy storage. This work was done by Lincoln Laboratory, at Massachusetts Institute of Technology and excerpts from a draft report⁽¹⁾ are presented here.

The report describes a storage system that combines an adiabatic compressed air storage plant with a solar thermal central receiver. Two design variants of a CAES system augmented by solar thermal energy were considered. A packed pebble bed is used to store the heat of compression generated during the charging of the compressed air reservoir. This heat is then returned to the air on discharge of the reservoir. This stored thermal energy minimizes the solar thermal energy required to raise the air temperature to turbine inlet temperature. The system described is based on a central receiver design proposed by Boeing. The turbomachinery is within the state-of-the-art, but would be built specifically for this application. The second variant uses a fueled backup for the (smaller) thermal storage capacity. This hybrid system is marginally competitive with conventional CAES on the basis of levelized fuel costs of \$3.55/10⁶ Btu and nuclear off-peak pumping costs of 7.0 mil/kWh.

The solar energy raises the turbine inlet temperature from the adiabatic 800°F to 1500°F (427 to 815°C). This has the effect of increasing the energy return ratio from 0.75 to 1.2, thus decreasing charging costs. It also decreases turbine mass flow rate, hence cavern volume and Thermal Energy Storage (TES) costs. For the variant using sensible-heat storage as a backup system, the costs were not competitive with gas-turbine peaking. At a low assumed busbar charging cost of 10 mil/kWh, the estimated delivered electricity cost was 67 mil/kWh. The projected 1980 delivered electricity cost from a gas turbine peaking plant is 65 mil/kWh.

The economic unattractiveness of solar thermal heating of the air after CAES storage is due principally to the high cost of the solar plant components. Performance and cost models developed in the study were used to evaluate a number of potentially useful pure energy storage and solar-coupled CAES system configurations. Use of adiabatic CAES as a storage mode to better match the output of a solar thermal electric power-generating plant to a load demand also does not show any advantage over less complex sensible-heat storage systems. The authors⁽¹⁾ recommended no further work on solar/CAES coupled systems for the present.

6.2 LIMESTONE MINE STORAGE AND HARD ROCK CAVERN STORAGE

In the same study⁽¹⁾, two viable, economically attractive adiabatic pure (without solar) CAES system variants are identified. These can be built today using essentially available technology, even though the available hardware is not optimum for the application. The two variants: a high-pressure (~ 80 -atm) two-stage system using excavated, deep, hard-rock storage caverns; and a low-pressure (~ 20 -atm) single-stage system using moderate-depth abandoned limestone mines. The choice between these variants is dependent on the off-peak electricity costs and the siting resources available to a utility.

Eight two-stage design options were considered. These studies show that acceptable near-term adiabatic systems can be designed with currently available turbomachinery. Furthermore, even when using mined storage caverns in each case, the cost of such a system is competitive with fuel-fired CAES and with Underground Pumped Hydro-Storage (UPHS). Delivered electricity costs are competitive with all other peaking options for busbar charging costs of 10 kWh. Even with a doubled charging cost of 20 mil/kWh, all system designs considered are still competitive with fuel-fired CAES and UPHS, and the best design options remain marginally competitive with gas turbine peaking in the near term.

⁽¹⁾
The study indicates that using currently available turbomachinery technology, a single-stage system is cost-justified by the availability

of low-cost, large, moderate-pressure, storage volumes, (e.g., an abandoned mine). Limestone mines are strong candidates for consideration.

Eight designs (single-stage) for two specific mine sites, were considered. These proved to be the lowest-cost energy-storage options of the study. Delivered electricity cost was estimated as 66 mil/kWh even with a high assumed busbar charging cost of 25 mil/kWh. This compares favorably with a projected 1980 cost of 65 mil/kWh from a peaking gas turbine. The single-stage adiabatic CAES is the "lowest technology" (simplest) no-fuel storage/peaking option now available.

The authors⁽¹⁾ point out that the two adiabatic CAES variants are:

- economically superior
- competitive with gas turbine peaking at expected fuel costs
- strategically superior by fuel saving
- less complex than most (except for surface-hydro storage) competing technologies.

They recommend that these variants be improved by a program of study, building, and testing.

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7.0 TURBOMACHINERY FOR COMPRESSED AIR ENERGY STORAGE PLANTS

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A compressed air energy storage (CAES) power plant can be divided into four subsystems: a turbine system, compressor system, motor/generator, and an underground air storage reservoir. The turbine system consists of a low-pressure gas turbine (LGT) and combustor (C_2), a high-pressure gas turbine (HGT) and combustor (C_1), and a recuperator as shown in Figure 7.1. The LGT is a turbine modified from a conventional gas-turbine peaker unit. For proposed CAES plants, the HGT is a modified steam turbine operating at gas temperatures of about 1000°F. Optimized designs for compressed-air turbines that operate at high temperatures have been investigated.⁽¹⁾ The combustors can use designs modified from conventional gas-turbine peaker units. Preliminary studies indicate that recuperators can be designed that are economically feasible for CAES application. The recuperators differ from those for conventional gas-turbine peaker units because of the high-pressure air from the reservoir.

The compressor system contains a low-pressure compressor (LC), high-pressure compressor (HC), booster compressor (BC), intercoolers, and an aftercooler (see Figure 7.1). Intercooling is required to operate the compressors within limits tolerable for standard materials. An aftercooler is used to cool the air to avoid possible thermal-stress damage to the storage reservoir.

The performance of a CAES plant can be characterized in terms of four specific parameters and an overall plant efficiency. The four parameters are the specific air flow (mass flow rate of air supplied to the turbine system per kilowatt power generated), the specific heat rate (which is directly proportional to fuel consumption and is equal to the product of specific fuel consumption and the lower heating value of fuel), the specific storage volume (volume of reservoir required per kilowatt of power generated), and the specific compression rate (the energy equivalent of the power supplied to the compressors per kilowatt

FIGURE 7.1. Schematic Diagram of CAES Plant

of power generated). The overall plant efficiency is equal to the total energy output from the turbines divided by the sum of the energy input from the fuel and off-peak energy to the compressor system.

This section presents a study of possible turbomachinery options for CAES plants with particular emphasis on the turbine system. The performance and cost of the complete plant resulting from different turbomachinery options are presented. The turbine system design parameters considered are the reservoir storage pressure and the inlet gas temperatures to the LGT and HGT. The LGT was selected on a nominal pressure ratio of 16:1 because previous studies^(2,3) have indicated that this pressure ratio has a minor effect on performance. Water-compensated mined caverns, constant-volume salt caverns, and aquifer reservoirs were considered as possible air storage reservoirs.

7.1 PERFORMANCE EVALUATION

7.1.1 Thermodynamic Analysis

A thermodynamic analysis was carried out on each subsystem of a CAES plant, and the results were combined to evaluate overall plant performance. Design parameters considered in the analysis include air storage pressure and inlet gas temperatures to the high-pressure gas turbine and low-pressure gas turbine. The details of the analysis are presented in Reference 4.

7.1.2 Performance Results

The results of a parametric study are presented in Reference 5. In this reference, performance is presented in terms of the four specific performance parameters and overall plant efficiency as a function of air storage pressure (p_0) and inlet gas temperatures to the HGT and LGT.

From the performance analysis, the following trends were observed:

- 1) Specific air flow rate and storage volume decrease as p_0 , T_3 , or T_5 increases.
- 2) Specific heat rate decreases as p_0 increases and increases as T_5 increases but is relatively insensitive to T_3 .
- 3) Specific compression rate, in general, slightly increases as p_0 increases; it decreases with increasing T_3 or T_5 .
- 4) In general, overall plant efficiency increases as T_3 increases but is only weakly affected by p_0 or T_5 .

From the above, it can be concluded that optimum performance results from the use of a high storage pressure and high inlet gas temperature to both turbines.

7.2 ECONOMIC ANALYSIS

7.2.1 Capital Costs

Direct capital cost of the CAES plant was divided into the cost of

underground air storage cavern, the cost of turbomachinery equipment, and the balance of the plant.

The cost of the storage reservoir was based on a nominal storage capacity of 20 h/wk and operation time of 2190 h/yr. The major emphasis of the study was placed on the use of water-compensated mined caverns using the storage related costs presented in Reference 6. The effect of using aquifer reservoirs or constant-volume salt caverns on capital cost was also investigated. From Reference 7, the cost of aquifer reservoirs and salt caverns are about 75% and 50%, respectively, of that of mined caverns. In the analysis, these percentages were considered constant at any storage pressure.

Estimation of the turbomachinery costs was based on Reference 1. In this reference, selling prices are estimated for 10, 20, and 50 units. Based on an evaluation of regional markets and development potential for CAES conducted by Harza Engineering Company,⁽⁸⁾ a 50-unit selling price was used in this study. The cost of the LGT with a cycle pressure ratio of 16:1 was determined by the inlet gas temperature and the cost of the HGT was determined by both the inlet gas temperature and air storage pressure. Costs of the LC and HC with the overall compression ratio of 1:16 were estimated from the air flow rate, and the cost of BC was determined by the air flow rate and storage pressure. An additional cost of 25% was added for the ducting and installation of the turbomachinery equipment.

The remainder of the plant equipment, which includes the clutches, motor/generator, recuperator, combustors, fuel storage, coolers, electrical power system, land, and plant structure was denoted as the balance of plant. This item is relatively insensitive to CAES design parameters and a fixed cost of \$80/kW was used for the balance of plant for all cases of this study.

Total capital cost of the plant was estimated from the direct capital cost considering the following allowances: 15% of direct costs

for contingency, 10% of direct costs for engineering and administration, and 30% of direct costs, contingency, engineering, and administration for escalation and interest during the construction period.

7.2.2 Operating Costs

Operating costs of the CAES plant consist mainly of capital charge, cost of fuel to the combustors, off-peak electricity to the compressors, and operation and maintenance. Annual capital charge was estimated from the total capital cost based on the fixed capital charge rate of 18% per year. Estimation of the cost of premium fuel was made by multiplying the specific heat rate by the cost of No. 6 oil. Cost of off-peak electricity to the compressors was estimated from the specific compression rate and the electricity cost from the base plant. A value of 2 mil/kWh was used as the cost of operation and maintenance for all cases.

7.2.3 Economic Results

7.2.3.1 Capital Costs

Capital cost of a CAES plant using a water-compensated mined cavern varied from \$285/kW to \$406/kW for the range of design parameters specified in the study. The cost of the underground storage cavern was found to be the highest component cost for most cases, varying from 26-46% of the total capital cost, and the cost of the turbomachinery equipment varied from 16-31% of the total direct capital cost. In general, it was found that higher turbine inlet temperatures result in higher turbomachinery costs.

Total capital cost is presented in Figure 7.2 as a function of storage pressure for four different combinations of inlet gas temperatures to the HGT and LGT. Capital cost sharply decreases with increasing storage pressure for all the cases up to 7 MPa (70 atm) and either slowly decreases or increases thereafter. Higher turbine inlet temperatures result in lower capital cost at low storage pressures, for example, at 3 MPa (30 atm). However, at storage pressures greater than 7 MPa

FIGURE 7.2. Effect of Turbine Options on Capital Cost

(70 atm), higher turbine inlet temperatures result in higher capital costs. Among the cases considered in the study, the design parameters that result in the lowest capital cost are $T_3 = T_5 = 114 \text{ K}$ (1600°F) and $p_o = 10 \text{ Pa}$ (100 atm).

7.2.3.2 Operating Costs

The operating cost of the CAES plant is presented in Figure 7.3 as a function of the design parameters. The cost of premium fuel was selected as $\$8.52/10^3 \text{ kWh}$ ($\$2.50/10^6 \text{ Btu}$) and the electricity cost was 15 mil/kWh. In this figure the operating cost varies from 44.8-55.5 mil/kWh.

FIGURE 7.3. Effect of Turbine Options on Operating Cost

The capital charge was found to be much higher than the cost of fuel or electricity amounting to 52-60% of total operating cost. Consequently, the operating costs in Figure 7.3 show a similar trend to that of the capital costs. The figure illustrates that the operating costs decrease with increasing air storage pressure for all cases except for the case of $T_3 = T_5 = 1589 \text{ K}$ (2400°F), which has a minimum at about 7 MPa (70 atm). It also shows that, among the cases studied, the lowest operating cost results when $T_3 = T_5 = 1144 \text{ K}$ (1600°F) for $p_0 > 5.8 \text{ MPa}$ (58 atm) and $T_3 = T_5 = 1580 \text{ K}$ (2400°F) for $p_0 > 5.8 \text{ MPa}$ (58 atm). However, in the pressure range of 5-9 MPa (50-90 atm), which is the most likely range for CAES with a water-compensated reservoir, the difference in operating costs between turbine systems is less than about 3 mil/kWh.

The data in Figure 7.3 also illustrates that for $T_3 = 811 \text{ K}$ (1000°F) and $T_5 = 1144 \text{ K}$ (1600°F), the difference in operating costs between a modified steam turbine for the HGT and a new, high-efficiency design is negligible (i.e., less than 1 mil/kWh). Thus, the use of a modified steam turbine would be favored because of its proven reliability and availability.

The dotted curve in Figure 7.3 represents the cost of a plant using a modified steam turbine ($\eta_{\text{HGT}} = 78\%$) for the HGT, which operates at an inlet gas temperature of 811 K (1000°F). The solid curve for $T_3 = 811 \text{ K}$ (1000°F) and $T_5 = 1144 \text{ K}$ (1600°F) is based on the assumption that the cost of this new high-efficiency HGT ($\eta_{\text{HGT}} = 90\%$) would be the same as that of the modified steam turbine. The actual cost of this new turbine would depend upon the development cost and the number of units sold. Thus, the actual high-efficiency cost curve will probably lie somewhere between the solid and dotted curves. The net result is that the cost differences would be negligible, and thus, would also favor the use of the modified steam turbine.

7.2.3.3 Effect of Electricity and Fuel Costs on Operating Costs

Data that illustrate the effect of electricity and premium fuel costs on the overall operating costs of a CAES plant are presented in Reference 5. Two plant designs were compared -- Plant A for which $T_3 = 811 \text{ K}$ (1000°F) ($\eta_{\text{HGT}} = 78\%$) and $T_5 = 1144 \text{ K}$ (1600°F) and Plant B for which $T_3 = T_5 = 1144 \text{ K}$ (1600°F). These two plants bracket the highest and lowest estimated operating costs.

The data illustrate that for fixed electricity cost, the percentage difference in operating costs for the two plant designs decreases as the fuel cost increases. The result means that if fuel costs increase faster than electricity costs, the type of plant design (i.e., the selection of turbine system) becomes less significant. This scenario would favor using Plant A because of the proven reliability and availability of the equipment.

For fixed fuel costs, the percentage difference between the operating costs of the two designs increases as the electricity cost increases. This result means that if the cost of base-plant electricity increases at a faster rate than fuel costs, Plant B would be favored. In this case, the use of a new, high-efficiency HGT would probably be justified.

7.2.3.4 Effect of Reservoir Type on Capital and Operating Costs

The effect of reservoir type on costs is illustrated in Figures 7.4 and 7.5. Both the capital and operating costs are significantly reduced using an aquifer reservoir or constant-volume salt cavern in place of a water-compensated mined cavern. For example, at storage pressure of 7 MPa (70 atm), capital costs are reduced by about \$28/kW and \$51/kW for an aquifer reservoir and salt cavern, respectively. The reduction in operating costs is about 2 mil/kWh for an aquifer and 4 mil/kWh for a salt cavern.

FIGURE 7.4. Effect of Reservoir Type on Capital Cost

FIGURE 7.5. Effect of Reservoir Type on Operating Cost

The effect of reservoir type on the spread of operating costs for different turbine system designs was investigated considering Plants A and B (as defined in the previous subsection). The percentage difference in operating costs between plants decreases slightly using either an aquifer reservoir or salt cavern. For example, at a storage pressure of 7 MPa (70 atm), the percentage difference is about 4.4% using a water-compensated mined cavern, 4.3% using an aquifer reservoir and about 4.1% for a salt cavern.

7.3 CONCLUSIONS

The performance and cost of possible turbomachinery options for CAES power plants have been investigated in this section. Particular emphasis was directed toward the turbine system of the plant. The main design variables were the reservoir storage pressure and the turbine

inlet gas temperatures. Water-compensated mined caverns, aquifer reservoirs, and constant-volume salt caverns were considered as air storage reservoirs.

From the performance analysis, it is concluded that optimum performance results from the use of high storage pressures and high inlet gas temperatures to both turbines. The economic analysis, however, illustrates that minimum costs (capital and operating) do not necessarily correspond to optimum plant performance. Considering the specific operating costs (i.e., mil/kWh), which can be considered the true indicator of plant costs, at storage pressures below 6 MPa (60 atm), the highest temperature turbine system considered in this study (i.e., $T_3 = T_5 = 1589 \text{ K}$ (2400°F)) results in the lowest costs for storage pressures less than 6 MPa (60 atm). However, for pressures above 6 MPa (60 atm), the turbine system with $T_3 = T_5 = 1144 \text{ K}$ (1600°F) results in the lowest cost.

A significant result is that for the pressure range of 5-9 MPa (50-90 atm), which is the present range of interest for water-compensated caverns, the operating costs for all of the turbine systems considered in this study are within about 3 mil/kWh of each other with an average value of about 47 mil/kWh. Furthermore, it was demonstrated that if the cost of premium fuel increases at a faster rate than the cost of base power electricity, which seems to be a logical scenario for the future, the cost difference between turbine systems decreases.

The use of an aquifer reservoir or constant-volume salt cavern instead of a water-compensated mined cavern significantly reduces capital and operating costs and slightly reduces the difference in operating costs between CAES plants using different turbine systems.

The economic study indicated that for a turbine system with $T_3 = 811 \text{ K}$ (1000°F) and $T_5 = 1144 \text{ K}$ (1600°F), the use of a new, high-efficiency, high-pressure turbine could not be justified and a modified steam turbine could be used with little cost penalty.

Based on the above factors, the overall conclusion of this study is that the turbine system can be constructed using available turbines with proven reliability without significantly sacrificing cost. The HGT can be a modified steam turbine and the LGT can be obtained from a peaker unit which operates at an inlet gas temperature of about 1144 K (1600°F) or lower, and which requires little, if any, cooling air. Interestingly, this is the approach being used at the Huntorf Plant,⁽⁹⁾ which is the world's first CAES plant.

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8.0 THE COMPOUND-ENGINE CONCEPT FOR COMPRESSED AIR ENERGY STORAGE PLANTS

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The use of reciprocating engines in compressed air energy storage (CAES) plants can result in increased plant performance and reduced plant capital and operating costs. A compound-engine concept which uses reciprocating engines for high-pressure expansion and gas turbines for low-pressure expansion results in the optimum combination to provide these benefits. The expected advantages compared to plants using conventional turbomachinery are reduced reservoir size and cost, reduced compression energy requirements, and increased overall plant efficiency. The performance of possible engine and plant configurations is evaluated and presented.

The performance and cost of a CAES plant using the compound-engine concept was compared to plants using both near-term and advanced turbine systems. The compound engine requires 39% less air flow than the near-term turbine system. When the compound engine is combined with standard turbocompressors for the compression part of the CAES cycle, savings of 11.8% in capital costs and 11.2% in operating costs result as compared to the near-term turbine system. If the high-pressure reciprocating engine is designed for reversible operation, acting as both an expander and compressor, savings of 17.4% in capital costs and 14.1% in operating costs as compared to the near-term turbine system can be realized.

The world's first CAES plant, the Huntorf Plant,⁽¹⁾ and proposed plant designs for the ongoing DOE/EPRI Demonstration Program use turbines for power expansion and turbocompressors for compression. Substitution of reciprocating engines, such as modified diesel engines, for some or all of this turbomachinery has been investigated.^(2,3) The expected advantages compared to plants using turbines and turbocompressors are reduced reservoir size and cost, reduced compression energy requirements, and increased overall plant efficiency.

The results of studies of two different plant configurations are presented in References 2 and 3. In the first one, reversible reciprocating engines are used for expansion and compression. Power generation results from operation of the engines as internal-combustion expanders, and compression is accomplished using the same engines as reciprocating compressors. In the second configuration, internal combustion engines are used only as high-pressure (HP) expanders. A gas turbine is used as the low-pressure (LP) expander for this case. Compression is then accomplished either by using separate turbocompressors (i.e., axial and centrifugal booster compressors) or by operating the HP expanders as reversible reciprocating compressors. This second configuration is referred to as a compound engine.

It was shown in Reference 3 that the use of reversible, expander/compressor reciprocating engines significantly improves CAES plant performance, but results in increased equipment costs due to the high cost of using reciprocating engines for LP expansion. However, the evaluation indicated that both increased plant performance and reductions in plant capital and operating costs result from the use of compound engines in CAES plants.

A detailed evaluation of the performance and cost of the compound-engine concept as applied to CAES plants is presented in this section. The most recently available cost and performance data have been used in the analysis. The economic evaluation represents the best assessment of the concept without the involvement of an engine manufacturer. An engine manufacturer could supply the necessary cost and performance information to precisely evaluate this apparently attractive concept.

8.1 PLANT DESIGN

A schematic diagram of a conventional CAES plant is presented in Figure 1. A diagram of a plant using the compound-engine concept is presented in Figure 8.2. In the configuration using the compound-engine concept, the reciprocating engine is a reversible, high-pressure expander/compressor engine (HP E/C) connected through a shaft to a motor/generator (M/G).

On a separate shaft, an LP turbine and axial compressor are connected to an M/G through couplings. In this practice, the HP engine and LP turbine may each consist of several separate units that are manifolded together.

Comparing Figures 8.1 and 8.2, the HP turbine and combustor, and booster compressors of a conventional CAES plant are replaced with a reversible HP expander/compressor engine. The LP turbine and axial compressor are used for low-pressure duty. Since the exhaust from the HP engine will be sufficiently high (e.g., 1360 K), a LP combustor is unnecessary. However, the HP engine requires a radiator (e.g., cooling tower) to dissipate the heat absorbed in the water jacket.

During the compression mode of operation, valves C, D, and G are closed; both M/G units operate as motors, receiving off-peak power from a base-load power plant; coupling B is disconnected; and the HP engine operates as a compressor. Ambient air is compressed in the axial compressor, intercooled; further compressed in the HP reciprocating compressor, cooled

FIGURE 8.1. Conventional CAES Plant

FIGURE 8.2. CAES Plant Using Compound Engines

in the aftercooler, and delivered to the storage reservoir. During compression, cooling water circulates through the HP engine.

In the expansion mode, valves B, F, and E are closed, both M/G units operate as generators, coupling A is disconnected, and the HP engine operates as an expander. Air from the reservoir is preheated in the recuperator using exhaust gas from the LP turbine. Preheated air and injected fuel are burned and expanded in the HP expander. The products of combustion are further expanded in the LP turbine and then flow through the recuperator. In order to reduce engine metal temperatures, the cooling water removes part of the heat of combustion.

8.2 PERFORMANCE EVALUATION

A thermodynamic analysis was conducted of the plant schematically illustrated in Figure 8.2.⁽³⁾ The analysis considered a constant-pressure combustion engine (as defined in Reference 3) for high-pressure duty and a modified gas turbine for low-pressure operation. Overall CAES plant performance was evaluated in terms of four parameters: specific air flow rate (the amount of reservoir air required per unit of generated power), specific heat rate (the product of specific fuel consumption and the lower heating values of the fuel), the ratio of expansion power to compression power, and overall plant efficiency (plant output per total energy input).

The performance of a CAES plant using the compound-engine concept is compared to three turbine-based CAES plant systems in Table 8.1; some performance characteristics of the expansion equipment are presented in Table 8.2. The Huntorf plant is included because it is the world's only operational CAES plant. The principal reason that the performance of the Huntorf plant is lower than the two other turbine-based plants is that presently it does not include a recuperator. Addition of a recuperator would bring all system performance parameters closer to those of the near-term turbine system.

The near-term turbine system can be implemented using conventional turbomachinery. For this system, a modified system turbine with an inlet gas temperature of 811 K (1000°F) can be used as the HP turbine. The LP turbine, which has an inlet gas temperature of 1144 K (1600°F), can be a modified gas turbine from a peaker unit. This turbine will not require vane or blade cooling but will require some auxiliary cooling.

The advanced turbine system selected for this study consists of an advanced HP turbine and a modified, high-temperature, gas turbine from a peaker unit. The HP turbine, operating at 1366 K (2000°F) inlet gas temperature, will require significant amounts of cooling air. This turbine does not exist at the present time but represents an attainable

TABLE 8.1. Comparison of Performance Parameters for Compressed Air Energy Storage Plants Using Various Types of Expansion/Compression Equipment

	Huntorf Plant(1)	Plant Using Near-Term Turbine System	Plant Using Advanced Turbine System	Plant Using Compound- Engine System
Reservoir Pressure, MPa	6.89	7.09	7.09	7.09
(atm)	(68)	(70)	(70)	(70)
(psia)	(1000)	(1029)	(1029)	(1029)
Specific Air Flow Rate, kg/MJ	1.46	1.41	1.20	0.86
(lb _m /kWh)	(11.59)	(11.18)	(9.55)	(6.80)
Specific Heat Rate, J/J	1.61	1.11	1.17	1.38
(Btu/kWh)	(5500)	(3793)	(4000)	(4726)
Expansion Power/Compression Power	1.24	1.27	1.68	2.36
Overall Efficiency, %	41.5	54.4	56.7	55.4

TABLE 8.2 Performance and Cost of Expansion Equipment

	Inlet Pressure		Inlet or Maximum Temperature		Total Mass Flow ^(c)		Net Power Output	Cost ^{(d),(e)}
	MPa	psia	K	°F	kg/s	lbm/s	MW	\$/kW
Near-Term Turbine System								
High-Pressure Turbine ^(a)	5.85	(848)	811	(1000)	371	(817)	92.0	21.9
Low-Pressure Turbine	1.15	(167)	1144	(1600)	371	(917)	200.0	11.5
Advanced Turbine System								
High-Pressure Turbine	5.96	(865)	1366	(2000)	296	(653)	111.7	38.0
Low-Pressure Turbine	1.15	(167)	1366	(2000)	376	(829)	200.0	17.2
Compound-Engine System								
High-Pressure Reciprocating Engine ^(b)	5.96	(865)	2102	(3324)	296	(653)	238.0	51.3
Low-Pressure Turbine	1.15	(167)	1366	(2000)	376	(829)	200.0	17.2

^aModified steam turbine

^bEight modified diesel engines

^cIncludes coolant flow

^dIncludes ducting, mountings, and installation

^eExpressed in 1976 dollars

extension to the state-of-the-art of gas-turbine technology. The LP turbine, which operates with an inlet gas temperature of 1366 K (2000°F), will also require a considerable amount of cooling air.

The data presented in Table 8.1 illustrate that a CAES plant using the compound-engine concept requires a significantly lower specific air flow rate than the turbine-based designs. For example, the compound-engine system requires about 39% less air than the near-term turbine system. This situation is reflected in the favorable values shown for the ratio of expansion power to compression power and overall plant efficiency. Several factors enter into the low specific air flow value for the compound engine, of which the most important is the required air/fuel ratio. Actual air/fuel ratios will be dictated by engine operation -- that is, by the need to limit emissions or to operate at lower temperatures.

The plant heat rate is lower for the compound-engine system than the unrecuperated Huntorf design, but higher than the other two turbine-based designs. This result is partially caused by the higher operating temperatures of the HP engines. The advanced turbine system has a higher heat rate than the near-term turbine system for the same reason (i.e., additional fuel is required to raise combustion temperatures). The incentive for using this turbine design is to improve other performance parameters.

8.3 ECONOMIC ANALYSIS

In order to assess the economic feasibility of the compound-engine concept, the capital and operating costs of CAES plants using this system were estimated. In addition, costs for plants using turbine-based systems were also estimated for comparative purposes. The analysis was carried out using the performance information presented in the previous subsection. The costs are based on a plant having a 20-h nominal storage capacity which could yield a generation time of 2190

h/year. The storage cavern was assumed to be a water-compensated, mined cavern with a storage pressure of 7.09 MPa (70 atm) and storage temperature of 322 K (120°F).

Capital costs were divided into direct and indirect categories. The direct capital costs consist of those for the expansion and compression equipment, the storage cavern, the surface reservoir, and the balance of plant. The storage cavern cost included the costs of the cavity, the air and water shafts, development and mobilization, and completion. The costs of the air and water shafts were based on cavern depth which was determined from the selected air storage pressure. The size of the cavity was estimated from the specific air flow and nominal storage capacity required and with a 10% capacity margin added. The surface reservoir was considered in the analysis because a water-compensated (constant-pressure) system was chosen. The balance of the plant includes items such as clutches, motor/generators, a recuperator, combustors for turbine-based systems, fuel storage, intercoolers, an aftercooler, electrical power systems, land, and the plant structure. Indirect costs include allowances for contingency (15% of direct costs), engineering and administration (10% of direct costs), and escalation (30% of direct costs, contingency, and engineering and administration).⁽⁴⁾

The operating costs of a CAES plant include the capital charge, fuel costs for the engine and/or combustors, the off-peak charge for the electricity required to run the compressors, and the charges for operation and maintenance. The annual capital charge was estimated from the total capital cost and was based on a fixed capital charge rate of 18% per year, assuming a yearly generation time of 2190 hours. The fuel cost was estimated using a cost rate of \$8.53/10³ kWh (\$2.50/10⁶ Btu). Electricity costs were figured using a charge rate of 15 mil/kWh.

8.3.1 Results of Economic Analysis

Performance and capital cost data for the expansion equipment of the various power generation systems considered are presented in

Table 8.2. For the turbine-based system, an LP turbine that would generate 200 MW was first selected. The HP turbine was then selected to match the flow requirements of the LP turbine. Following the selection of the expansion equipment, the size of the storage reservoir to provide the required air flow was estimated. Information on performance and costs of turbines was obtained from Reference 5. For the modified steam-turbine used as the HP expander for the near-term turbine system, the output and cost had to be obtained using an interpolation scheme since flow rates presented could not be matched directly to the flow requirements of the LP turbine. The turbine costs are based on assumed economies of scale resulting from a total market potential of 50 identical units.⁽⁶⁾ The cost of HP reciprocating engines was obtained from Reference 7. This reference provides capital cost information on large oil-fired diesel engines. The largest engines available were chosen and the performance evaluation indicated that eight of the engines would be required. The cost is a conservative estimate since some of the auxiliaries will not be required for the present application. The costs for both the turbines and reciprocating engines include allowances for ducting, mountings, and installation.

A comparison of cost estimates (1976 dollar values) for CAES plants using the various types of expansion/compression equipment is presented in Table 8.3. The total capital costs of the near-term and advanced turbine systems are nearly identical. The operating cost for the advanced turbine system was slightly less (3.4%) than for the near-term turbine system -- the main difference was due to lower electricity costs for compressor operation resulting from the smaller storage capacity required. The balance of plant capital cost was found to be relatively insensitive to CAES design parameters for turbine-based systems and, based on cost data presented in Reference 4, was estimated to be \$80/kW.

Two separate cost scenarios were considered for the compound-engine system. In the first one, the flow from the HP reciprocating

TABLE 8.3. Comparison of Cost Estimates for Compressed Air Energy Storage Plants
Using Various Types of Expansion and Compression Equipment(a,b)

	Turbine Systems		Compound-Engine Systems	
	Near-Term	Advanced	Using Conventional Turbocompressors	Using Reversible High-Pressure Expanders/Compressors
Capital Cost, \$/kW				
Expansion/Compression Equipment ^(c)	35.5	43.4	49.0	38.6
Storage Cavern	65.8	58.4	41.6	41.6
Surface Reservoir	5.5	4.7	3.4	3.4
Balance of Plant	80.0	80.0	70.8	76.8
Indirect Costs ^(d)	116.8	116.5	103.0	96.5
Total	303.6	303.0	267.8	250.9
Difference ^(h)		- 0.2%	-11.8%	-17.4%
Operating Cost, mil/kWh				
Capital Charge ^(e)	25.0	24.9	22.0	20.6
Fuel ^(f)	9.5	10.0	11.8	11.8
Electricity ^(g)	10.9	8.9	6.3	6.3
Operating and Maintenance	2.0	2.0	2.0	2.0
Total	47.4	45.8	42.1	40.7
Difference ^(h)		- 3.4%	-11.2%	-14.1%

(a) Costs are expressed in 1976 dollar values.

(b) The storage cavern was assumed to be a water-compensated mined type with storage pressure - 7.09 MPa (70 atm) and storage temperature = 322 K (120°F). Nominal storage capacity was assumed to be 20 h yielding a generation time of 2190 h/yr.

(c) Turbines, reciprocating engines, and/or compressors (including ducting, mountings, and installation).

(d) Indirect costs consist of engineering and administration (10% of direct costs), contingency (15% of direct costs), and escalation and interest during construction (30% of direct costs plus engineering, administration, and contingency).

(e) The capital charge was 18% per year for a generation time of 2190 h/year.

(f) The fuel cost used was \$8.53/10³ kWh (\$2.50/10⁶ Btu).

(g) The electricity cost used was 15 mil/kWh.

(h) As compared to the near-term turbine system.

engines was matched to that required by the 200-MW LP turbine. The resulting system required eight modified diesel engines which produced a power output of 238 MW. For the compression portion of the CAES cycle, conventional turbocompressors were used. In the second scenario, the reciprocating engines could function not only as HP expanders, but also as booster compressors. The cost of this reversible engine was assumed to be about 20% more than an advanced HP turbine (on a specific cost basis). However, in Reference 2, it is indicated that only four of the eight engines would have to be reversible in order to provide the required compressed air. All other direct plant costs for this second scenario were assumed to be the same as for the first scenario.

For both cases, the balance of plant costs was lower than for the turbine-based systems. This result occurs because of the elimination of the combustors and reduction in size of the recuperator for the compound-engine system. It was assumed that the cooling system costs of the reciprocating engine would be balanced by savings resulting from the elimination of some of the auxiliaries included in the diesel-engine costs and the reduction in size of the intercoolers and aftercooler. Total operating costs were figured in a manner similar to that used for the turbine systems. The operating and maintenance costs for the diesel engines were estimated from data presented in Reference 7. These costs were found to be of a magnitude similar to those of turbine-based systems.

As can be seen from Table 8.3, significant savings in both capital and operating costs result from the use of compound-engine systems in CAES plants rather than conventional turbine systems. By using a compound-engine system with conventional turbocompressors, capital costs are reduced by 11.8% as compared to the near-term turbine system and 11.6% as compared to the advanced turbine system. Although the storage cavern size was the same for both the plant using an advanced turbine system and that using a compound-engine system, the use of the compound engine increases power output from about 312 to 438 MW, thus

resulting in a lower specific cost for the storage cavern and surface reservoir. Operating costs are reduced by 11.2% when this compound-engine system is used. Again, the higher output of the plant results in lower specific operating costs. By designing the reciprocating engine for reversible operation and applying the cost scenario described for this system, capital costs could be reduced by as much as 17.4%, and operating costs could be reduced by 14.1% as compared to the near-term turbine system. In reality, the actual reduction in costs probably lies somewhere between the costs for the two compound-engine scenarios.

8.4 CONCLUSIONS

Most designs for CAES plants only consider the use of conventional turbomachinery for power expansion and compression. The possibility of replacing some or all of these turbines and turbocompressors with reciprocating engines was investigated in this section. The evaluation considered using one or more modified diesel engines manifolded together to feed a conventional gas turbine from a peaker unit for power expansion and conventional turbocompressors for compression. In addition, the feasibility of using a reversible reciprocating engine as both a high-pressure expander and booster compressor along with a low-pressure turbine and turbocompressor was also investigated.

Based on the most recently available cost data for turbines and diesel engines, it appears that the use of compound engines in CAES plants could result in significant savings in both capital and operating costs. Capital cost savings could range from 11.8-17.4%. Operating cost savings could be in the range of 11.2-14.1%. The cost and performance information for the turbine-based system equipment was based on studies aimed at application to CAES plants. Unfortunately, similar data were not available for reciprocating engines, and hence, cost and performance had to be estimated from data for conventional diesel-engine applications.

Other reciprocating engine concepts could also be applied to CAES plants. For example, each individual reciprocating engine could have

its own turbine for low-pressure power expansion. This concept is presently being developed by diesel-engine manufacturers in the form of the turbocompound engine. This engine uses an exhaust-gas-driven turbocharger and a power turbine geared to the crankshaft. In a CAES application, the turbocharger turbine and the power turbine would both be geared to the engine crankshaft.

In conclusion, the assessment of the compound-engine concept and other concepts using reciprocating engines is incomplete without a detailed evaluation by diesel-engine manufacturers. The economic attractiveness of these concepts with respect to CAES plants indicates that further study is merited.

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