FY-1977 Progress Report

Stability and Design Criteria Studies for Compressed Air Energy Storage Reservoirs

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March 1978

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Richland, Washington 99352
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FY-1977 PROGRESS REPORT

STABILITY AND DESIGN CRITERIA STUDIES FOR
COMPRESSED AIR ENERGY STORAGE RESERVOIRS

by
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March 1978

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Overall project management was provided by W. V. Loscutoff of PNL.

SUMMARY

This report summarizes the progress made during FY-1977 in establishing design criteria to ensure the successful operation and long-term stability of Compressed Air Energy Storage (CAES) reservoirs in underground porous media, such as aquifers. The formulation of pertinent criteria is important since the long-term stability of air storage reservoirs is probably the item of greatest risk to the successful demonstration and commercialization of the CAES concept.

This study has been divided into four phases: 1) state-of-the-art survey, 2) analytical modeling studies, 3) laboratory studies, and 4) field testing. The first of these phases, the state-of-the-art survey for air storage in porous reservoirs, has been completed on schedule and is reported in Section 2 of this report. Sections 3 and 4 are progress reports on Phases 2 and 3. No work has been done on Phase 4. It is planned that the field testing phase of this study will be carried out in conjunction with the Department of Energy/Electric Power Research Institute (DOE/EPRI) CAES Demonstration Program. This phase is not scheduled to begin until FY-1979.

STATE-OF-THE-ART SURVEY

Preliminary stability and design criteria for storage of compressed air in porous media have been determined on the basis of a survey of open literature and the experience of experts in industry and universities. These criteria specify, within the limits of available information, a number of reservoir design and operating guidelines that will minimize the potential for unacceptable degradation of the reservoir. The objective was a 30-year operating life for a reservoir used for cycling compressed air.

The results were separated into two categories; criteria for low temperature (less than 200°F/93°C) air injection and criteria for high temperature (200°F/93°C to 650°F/343°C) air injection. One of the primary conclusions reached from the evaluation of the criteria of low temperature injection is that technology currently exists to handle the potential engineering and operational problems. Therefore, a demonstration CAES plant could be built

now. Results given are maximum and/or minimum bounds for a number of parameters such as porosity, permeability, closure, storage pressure, caprock thickness, delta pressure and caprock slope.

The criteria for high temperature injection were based on a potential maximum air temperature of 650°F. Most of the criteria established for low temperature injection were applicable. A number of areas of uncertainty were identified as a result of the high temperature effects. These include:

- presence of liquid phase water,
- potential for adverse chemical reactions,
- generation and transport of particulate matter,
- integrity of caprock at elevated temperatures, and
- thermal/mechanical response of the well casing and cementation materials.

The results of this phase of the study were used to recommend the analytical, laboratory, and field studies necessary to establish the final design and stability criteria for CAES.

NUMERICAL MODELING

Preliminary numerical investigations of flow and thermal effects on the operation of a dry, one-dimensional (radial) aquifer reservoir were performed. Several reservoir parameters were examined to determine their influence on reservoir operation. Injection of hot air was shown to reduce well deliverability as the reservoir is heated. The influence of well bottom diameter was shown to become important only for high flow rates. The need for moderately high (500 md) reservoir permeability was demonstrated, but a diminishing importance of very high permeability was also observed. It was shown that for a fixed number of wells and given permeability, the deliverability of a reservoir is about the same whether the total storage volume is spread out over a large area or concentrated within a smaller, more porous region. The potential for error in assuming Darcy flow throughout a reservoir was also demonstrated. This was shown to be small at the lower flow rates.

Thermal development of a CAES porous rock reservoir subjected to cyclic hot air injection was examined and shown to occur very slowly. After one

year of cycling no temperature change was observed beyond about 100 ft from the wells, with high temperatures remaining fairly localized around wells. Temperature cycling is fairly pronounced near the wells but becomes negligible as close as 10 ft from the well bore. Changes in reservoir properties such as permeability have little effect on thermal development with the minor exception of the thermal conductivity of the reservoir rock. This phase of the overall CAES study is progressing according to schedule. The development of more sophisticated models is planned to predict the flow dynamics and the thermal and mechanical response of multi-dimensional, water-bearing porous reservoirs.

LABORATORY STUDIES

The laboratory work done on this project in FY-1977 is the first step toward determining the effects of cyclic ventilation with heated, compressed air on rocks. The rocks of chief interest are porous sandstones and their associated caprocks. Some of the latter may also be suitable hosts for cavern storage. Several sandstones were cycled in temperature and pressure. Property tests showed that cycling did induce changes in Young's modulus and compressive strength. However, the changes were both positive and negative. This is apparently due to the content of the sandstones.

Fabric analyses were also performed on the test specimens. The results showed that, for some sandstones, the fine particles may have been dislodged from large pores and moved to small pores by the cycling. Other sandstones showed just the opposite effect.

The laboratory effort will continue in FY-1978. The main objective of the FY-1978 work will be to determine the effects of compressed air cycling under confined compression designed to simulate in-situ conditions.

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NOMENCLATURE

C_p = constant pressure specific heat of fluid

C_s = specific heat of solid

$\bar{F}$ = shear and drag force vector

$\bar{g}$ = gravity vector

h = enthalpy of fluid

H_v = volumetric heat transfer coefficient

K = fluid thermal conductivity

K_s = solid thermal conductivity

K_e = equivalent thermal conductivity

m = mass flow rate

$M_{\max}$ = maximum mass in reservoir during week

P = pressure

$P_{\max}$ = maximum weekly reservoir pressure

P_o = initial aquifer pressure

r = radial distance from well center

R = gas constant

s = reservoir thickness

t = time

T = fluid temperature

T_s = solid temperature

v = radial superficial flow velocity

$\bar{v}$ = superficial flow velocity vector

$\underline{v}_a$ = velocity absolute value component tensor

$\bar{v}_o$ = open flow velocity vector

Z = gas compressibility factor
 β = turbulence factor
 κ = permeability
 λ = fraction of total air mass cycled
 μ = viscosity
 ϕ = porosity
 ρ = density of fluid
 ρ_s = density of solid
 $\underline{\tau}$ = fluid stress tensor
 Φ = energy dissipation function for open flow
 Φ_p = energy dissipation function for flow through porous media
 ψ = fraction of energy stored over weekend

 C = flow conductance
 F = weighted volumetric flux
 H = weighted heat flux
 K = thermal conductance
 j = spatial index
 n = temporal index

1.0 INTRODUCTION

Among the unknowns affecting the technical and economic feasibility of Compressed Air Energy Storage (CAES) 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 stresses generated by the pressure and temperature fluctuations and by elevated storage temperatures could conceivably cause chemical and mechanical changes to porous aquifer structures and cavern walls. Certain conditions might lead to material deterioration which could contribute to permeability reductions or particle carryover to the turbines. In mined caverns, spalling of the walls could lead to the generation of particulate matter and even cavity closure. The possibility of these and other potential problems is often alluded to in the literature; however, very little data are available to predict the conditions for which problems might be expected, actions required to prevent their occurrence, or the consequences associated with their occurrence. Presently, there are no criteria that may be used to describe stability of air storage reservoirs subjected to daily temperature, pressure, and humidity fluctuations over a period of 30 years, or about 7,500 cycles.

The objective of this project is to develop design and stability criteria for underground reservoirs used in CAES plants. The purpose is to assure the utilities of long-term stability of these reservoirs in order to promote early commercialization of the concept. The CAES Reservoir Stability Program is divided into three subprograms according to the type of reservoir (porous media, hard rock, salt), and each subprogram is subdivided into four phases. These phases are:

- Phase 1 - State-of-the-art survey
- Phase 2 - Analytical modeling studies
- Phase 3 - Laboratory studies
- Phase 4 - Field testing and/or demonstration.

An outline of the program is given in Figure 1-1.

FIGURE 1-1. Outline of the Reservoir Stability Criteria Program

This report reviews the activity on the program during FY-1977. The bulk of the effort was concentrated on establishing stability and design criteria for reservoirs in porous media. The first phase of this effort is to establish preliminary stability and design criteria for porous media reservoirs based on a detailed survey of open literature and the experience of experts in industry and universities. This information is expected to establish the state of the art of porous media air storage and to provide direction for analytical and experimental studies.

The analytical studies phase will seek to supplement the preliminary design and stability criteria established on the basis of the state-of-the-art survey with results from numerical studies of the behavior of storage reservoirs subjected to temperature and pressure fluctuations.

To verify the theoretical investigation and provide additional input towards development of final stability and design criteria, a laboratory scale testing program is also being conducted and a full scale field test is planned.

The results of the state-of-the-art survey are reported in Section 2 of this report. Sections 3 and 4 report the progress made during FY-1977 in the analytical and laboratory testing phases, respectively.

2.0 STATE-OF-THE-ART SURVEY

Compressed Air Energy Storage (CAES) appears to be an economically and technically viable method for energy storage. The surface facilities are conventional in nature and the natural gas storage industry supports over 50 years of subsurface storage experience. However, it was deemed necessary to explore how a reservoir might respond over a 20- to 40-year time frame to the somewhat unique temperature, pressure, and humidity characteristics associated with CAES.

Candidate reservoirs for the storage of compressed air include: 1) porous media such as sandstone aquifers or carbonate reefs, 2) solutioned salt cavities, and 3) hard rock caverns. Due to the relative number of interesting phenomena and the abundance of natural gas storage literature, the porous media alternative was initially addressed. An anticlinal (domed) sandstone aquifer system overlain by a shale caprock is presented as the base system for discussion purposes. Subsequent reports on the hard rock and salt alternatives will be available in FY-1978.

Any conclusions or recommendations contained in this phase of the report are based solely on the experience and judgement of the research team and on the available literature. It is envisioned that results from planned numerical, laboratory, and field investigations will significantly augment the information contained in this report.

The specific objectives of this initial phase of the study are:

- to specify, whenever possible, reservoir design and operating guidelines that will minimize the potential for unacceptable degradation of the wells, storage matrix, and containment strata, and
- to delineate areas of uncertainty and recommend appropriate analytical studies, laboratory experiments, and field investigations.

It is of primary interest to delineate any constraints on the design and operation of a CAES facility that might be imposed by the reservoir. In other words, it is important to specify maximum and/or minimum bounds for parameters such as injection temperatures, pore pressure fluctuations,

or interstitial water contents. The remainder of this phase of the report is divided into the following areas:

- conclusions and recommendations
- background on the CAES concept
- reservoir development and operation, and
- major potential problem areas in aquifer storage.

2.1 CONCLUSIONS AND RECOMMENDATIONS

This section is organized into two subsections: 1) conclusions and recommendations associated with low temperature air injection ($<200^{\circ}\text{F}/93^{\circ}\text{C}$), and 2) conclusions and recommendations associated with high temperature injection ($>200^{\circ}\text{F}/93^{\circ}\text{C}$). It is anticipated that the first CAES demonstration facility will operate in the low temperature regime with the heat of compression being removed from the air prior to injection into the storage reservoir.

The reasons for exploring the elevated temperature concept include: 1) a potential governmental ban on the use of premium fuels for the generation of electricity, 2) a potential escalation in premium fuel prices, 3) a potential minimum injection air temperature to expedite the dewatering of the critical (near-wellbore) zone, 4) a potential requirement to store air at elevated temperatures in coupled energy concepts such as solar - CAES, and 5) an increased cycle efficiency if inter and aftercoolers can be eliminated.

The distinction between the low and high temperature storage concepts should be kept in mind. Due to the added complexity associated with elevated temperatures, the majority of the discussion in this report is biased towards the advanced concept. The technical viability of this adiabatic cycle remains to be demonstrated via numerical, experimental, and field investigations. The low temperature storage concept, on the other hand, appears to be relatively straightforward. The possible exception is the necessity for near-wellbore dehydration and the potential for not being able to accomplish this with undersaturated low temperature air because of its relatively low vapor carrying capacity. If this problem can be negated, then the consensus of the research team is that the technology now exists to handle the pertinent engineering and/or operational problems, and that a full scale demonstration facility can be designed and constructed.

This conclusions section is designed to present a brief overview of the conclusions and recommendations from this initial study phase and as such is devoid of verbal and illustrative detail.

2.1.1 Low Temperature Air Injection

This section includes the conclusions and recommendations associated with low temperature air injection (<200°F/93°C). Several preliminary design and stability criteria are summarized in Table 2-1.

The category of sandstone and carbonate reef aquifers spans a broad spectrum of possible storage configurations and media properties. The anticlinal sandstone aquifer will be considered the base case for this report. However, there is certainly potential for other structural and stratigraphic traps such as monoclines and terraces, fault bounded inclinal beds, domal structures associated with salt and igneous intrusives, lenses, up-dip wedges, etc. Furthermore, it is necessary to differentiate between sandstone aquifers and carbonate reef structures. The carbonate structures generally owe their porosity and high permeability to secondary solutioning processes and as such their extent is always highly suspect until proven by careful exploration. Vugular permeability tends to be strongly anisotropic and may exhibit preferential characteristics near the top of the structure only. In addition, the chemistry and mechanics associated with the carbonates is radically different to that of sandstones, especially at the higher temperatures and pressures. High permeability carbonate structures (i.e., Indiana limestones, etc.) are certainly viable candidates for a CAES facility and as such must be addressed in detail. However, for the purposes of this report, the reference case will be the anticlinal sandstone aquifer.

The storage matrix must exhibit adequate continuity of permeability to allow for interstitial water displacement. This is a function of the required air mass (plant size), the storage zone porosity, thickness and areal extent, formation anisotropy, and the presence or absence of natural barriers. Growth

TABLE 2-1. Preliminary Design and Stability Criteria
For Low Temperature Injection

Parameter	Maximum	Minimum
Injection Temperature	200°F (93°C)	?
Porosity	N.A. ^(a)	10%
Closure	N.A.	150 ft (46m)
Centerpoint Thickness	N.A.	30 ft (9m)
Permeability	N.A.	300 md
Depth	4000 ft (1220m)	600 ft (183m)
Mean Storage Pressure	120 atm (122 bars) ^(b)	18 atm (19 bars)
Maximum Charging Pressure	218 atm (221 bars) ^(c)	33 atm (33 bars)
Caprock Thickness	N.A.	20 ft (6m)
Caprock Slope	10-15 degree	N.A.
Delta Pressure ^(d)	1/2 threshold	N.A.
Liquid Phase Water Permissible in Critical Zone	0%	N.A.
Liquid Phase Water Per- missible in Remainder of Working Air Zone	Residual	N.A.

(a) N.A. = not applicable

(b) Site specific, based on 0.43-0.52 psi/ft of depth.

(c) Site specific, based on 0.8 psi/ft of depth.

(d) Delta pressure = Maximum Charging Pressure less the discovery hydrostatic pore pressure.

of the air bubble and the associated pressure, temperature, and volume characteristics depend on the ability to compress the sand and water constituents and ultimately displace the interstitial liquids^(a). If the matrix permeability is bounded in some fashion, the water cannot be displaced, and in the absence of costly surface extraction of the liquid, the back pressure at the wellbore will tend to increase. Examples of such natural barriers are: pinchouts, low permeability shale layers, and certain types of faults. It should be emphasized that not all faults are barriers. If the fault offset results in complete sand/shale contact, then a barrier may be created. However, sand/sand contact can be an effective transmitter and shale/shale contact can be an adequate seal.

The porosity of the reservoir must support storage of the air within an acceptable volume. This general rule is dependent on the characteristics of the storage horizon (thickness, dip, etc.), the desired temperature and pressure characteristics of the air, and the monetary value of the associated surface acreage. Although not a fixed value, 10% porosity is recommended as a minimum.

For an anticlinal or domal structure, closure >150 ft (46 m) and center-point thickness >30 ft (9 m) is desirable. Closure is defined as the vertical distance from the top of an anticline to the highest adjoining valley and represents the size of the container closed to normal horizontal movement. The axial thickness generally represents the storage zone thickness. The 30 ft (9 m) will allow for reasonable air bubble thickness and communication with a perforated casing. This criterion is conservative and should not be construed to mean that other potentially less desirable configurations cannot function as CAES reservoirs.

A permeability in excess of 300 millidarcys ($3.0 \times 10^{-13} \text{ m}^2$) is desired for the storage zone. Permeability appears to be one of the most important

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(a) Flushing of the matrix by the air will result in displacement of most of the interstitial water. However, up to 30% of the porosity may remain saturated. Water will reside in hydraulically isolated pockets, dead end pores, and pores that support a capillary retention force in excess of the air displacement pressure. This water will be considered the residual component of the interstitial liquid.

reservoir characteristics in determining the rate of water displacement and air deliverability. Although the lower limit on permeability will be determined by the economics of a given site, recent analytical efforts demonstrate that the work required to displace water or inject and extract air at reasonable rates increases dramatically for permeabilities below 300 millidarcys.

The time integral of the storage pressure curve relative to the initial ambient aquifer discovery pressure must equal zero if a net bubble volume change is not desired. In other words, if the maximum pressure used in the reservoir or the kilogram-days in a week above the original aquifer pressure are not equal to the kilogram-days below, a gradual air bubble volume change will result. This condition cannot be changed suddenly by pressure manipulation because of the large difference in the viscosities of water and air.

Maximum charging pressure should not exceed 0.80 psi/ft of depth (0.18 bars/m). Lithostatic pressure is generally 1.0 psi/ft of depth (0.23 bars/m). If the pore pressure exceeds the lithostatic pressure, the overburden material will experience tensional stress. For most common rocks, tensile strength is much lower than compressive strength. As a result, fractures can develop. The natural gas industry has injected at 0.78 psi/ft of depth (0.18 bars/m) without perceptable problems.

The caprock should have a thickness in excess of 20 ft (6 m). This is to ensure spacial integrity and adequate surface area for cement bonding of the casing within the wellbore.

The caprock slope should be less than 10-15 degrees to minimize the potential for movement on pre-existing glide planes.

The caprock should have a threshold pressure greater than twice the maximum anticipated delta pressure (charging pressure above initial reservoir discovery level). Threshold pressure is essentially that gradient required to initiate water displacement within the caprock. The low permeability of a typical caprock is due to this high capillary retention force associated with

high surface area to volume ratio (small diameter) pores. The pores remain fully saturated with water as long as the local differential air pressure does not exceed this threshold capillary retention level.

The residual water may occupy 10 to 30% of the available porosity. This water should not be ignored in the design and operation of a CAES facility. A porous media aquifer exhibits macroscopic heterogeneity and anisotropy. If air is injected into the matrix at a pressure in excess of the local interstitial fluid pressure (entry pressure), then the majority of the pore liquid will be displaced from the injection region and should no longer be of significant concern. However, in zones that 1) support only a single communications channel (throat) with the rest of the matrix, 2) support capillary retention forces in excess of the imposed air pressure gradient, or 3) are hydraulically isolated, the interstitial liquids will not be displaced by the advancing air front. This volume of groundwater is known as the reservoir residual liquid saturation. The potential consequences associated with the liquid phase, at least near the wells, include: 1) decreased air deliverability, 2) introduction of liquid and vapor phase water to the wells and surface facilities, 3) geochemical reactions, 4) increased apparent thermal diffusivity, and 5) reduction of effective air storage capacity.

Within the zone ideally defined by a radial distance r_{crit} from a given wellbore, a state of total interstitial dehydration must be rapidly attained and continually maintained for the life of the project. The actual extent of this critical (near-wellbore) region has not as yet been quantified. Basically, it refers to the zone around the wellbore where "high velocity" airflow and elevated temperatures ($>212^{\circ}\text{F}$, 100°C) are observed. Preliminary estimates suggest a 15 to 50 ft (5 to 15 m). Reservoir anisotropy, air injection temperatures and flow rates, and relative permeabilities will be important parameters in determining r_{crit} . It is anticipated that two-dimensional, multi-phase, anisothermal fluid flow computer models in conjunction with laboratory and field investigations will be required to adequately define the extent of this critical region and the time factors associated with the

dehydration process. The predominant mechanism for dehydration appears to be the utilization of very dry air as the working fluid. It should be noted that the moisture carrying capacity of air increases dramatically with temperature.

Beyond the critical zone, the residual water content should not significantly affect the operation of the CAES facility. Therefore, interstitial dehydration of the remainder of the working air zone^(a) and the cushion air zone should not be required. At the low airflow velocities expected in the regions away from the wells, the residual water will be essentially immobile in its liquid state. Furthermore, for temperatures of 200°F (93°C) or less, a totally saturated air mass is less than 1% water vapor. Since the flow field is ideally axially symmetric, a permeability reduction in a zone defined by a radial distance in excess of r_{crit} should have negligible impact on air deliverability. In other words, the bottleneck is near the wellbore. Apparently the only adverse impact will be in the reduction of the effective air storage volume which may impact the required number of wells, the spacing, and the necessary surface acreage.

The temperature and degree of undersaturation of the injected air stream must be such that the net transport of water vapor is out of the reservoir. Drying of the injected air may have to be accomplished by cooling and subsequent reheating of the airstream since solid desiccants and refrigeration may be too expensive. Regardless of the method, the air must be sufficiently undersaturated to preclude condensation within the working air zone as a result of the decreasing radial temperature profile. Analytical and experimental studies will help quantify this criterion.

Safeguards are required to preclude accidental injection of humid air.

Subsurface anisotropy and heterogeneity must be ultimately evaluated. This would include analysis of initial wafering and the mechanism of crossflow communication among zones of preferential flow. In addition, the potential

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(a) The working air zone will vary from site to site and is defined by the maximum radial distance that the mass of air cycled over a week will protrude into an ideal storage zone. This distance will possibly be 30 to 90 ft (9 to 27 m).

for channelized air spill, water entrapment, and the existence of barriers to gravity drainage of condensate must also be evaluated.

2.1.2 High Temperature Air Injection

The following conclusions and recommendations are associated with high temperature air injection ($>200^{\circ}\text{F}/93^{\circ}\text{C}$).

Criteria for some parameters are temperature independent. They are: porosity, closure, centerpoint thickness, permeability, depth, mean storage pressure, maximum charging pressure, caprock thickness and slope, and threshold pressure.

The injection air temperature^(a) should be such that:

1. completion cement is maintained at a temperature $\leq 650^{\circ}\text{F}$ (343°C),
2. casing materials are maintained at a temperature $\leq 650^{\circ}\text{F}$ (343°C), and
3. system is not exposed to temperatures that would initiate in-situ vaporization of interstitial liquids (Figure 2-1).

When developing the cushion air bubble, the first several cycles should be accomplished with low injection air temperatures ($150^{\circ}\text{F}/66^{\circ}\text{C}$). This is to ensure that displacement of the liquid phase water, above the residual level, has been accomplished within the working air zone.

Radial heat losses, as the air stream proceeds down the wellbore, must be minimized. This is to ensure that the cylindrical zone of caprock interfacing with the borehole is not exposed to elevated temperatures that may lead to its physical or chemical degradation. In other words, the thermal loading rate must be controlled. Before this criteria can be quantified, the response of saturated shale specimens to elevated temperatures should be evaluated experimentally.

The main areas of uncertainty associated with high temperature injection center around the wellbore and the working air zone and include the following:

- (a) Additional maximum temperature restrictions may result from studies of thermal stresses in the caprock, geochemical reactions and reservoir anisotropy.

FIGURE 2-1. Saturation Pressure Versus Temperature for Water

1. the thermal/mechanical response of wellbore casing and cementation materials,
2. the presence and consequences of liquid phase water and high vapor pressures,
3. the potential for geochemical reactions,
4. the generation and transport of fine particulate matter, and
5. the integrity of the caprock.

These topics are dependent upon the interactions and characteristics of the rock constituents, free oxygen, water, and elevated temperatures.

Temperatures will decrease rapidly with distance from wellbore. Thermal energy associated with the injected air mass will be partitioned into: 1) vertical heat losses (5 to 10%), 2) latent heat of vaporization of liquid phase water, and 3) stored energy within the reservoir constituents. Thermal development of the reservoir will be slow and will depend in part on the amount of residual water present.

The thermal energy lost from the air stream in transit down the borehole is thought to be relatively minor. However, vertical heat losses from the storage zone into the confining strata may be significant. Additional study is required to assess the potential heat transport mechanisms and energy flux associated with this vertical loss.

Additional study is required to determine how deep into the storage zone the well should be completed to prevent coning (water production) and enhanced heat losses.

Drying of the near-wellbore region is critical. The process of dehydration with undersaturated air may dictate a minimum temperature criterion based on the vapor carrying capacity of air as a function of temperature. Analytical and experimental studies will help characterize this process.

The thermal energy will be stored in the solid rock constituents in the vicinity of the borehole. Additional study is required to establish realistic temperature profiles. The total volumetric heat capacity of the rock matrix is much greater than that of the air, and it is expected that the air, water, and rock constituents will attain thermal equilibrium very quickly. This will dictate rapid attenuation of the temperature with radial distance from the borehole. If liquid phase water is present, temperature profiles will tend to flatten somewhat due to liquid and vapor transport of thermal energy and higher thermal conductivity. If solid/solid conduction and gaseous diffusion are the only working mechanisms, the thermal development will be very slow.

Given the uncertainties associated with the temperature, pressure, and humidity characteristics associated with high temperature storage, it is

recommended that pertinent hydrolytic and oxidation/reduction reactions be experimentally investigated with respect to the storage matrix and caprock constituents.

The potential for differential thermal expansion and/or microfracturing of mineral grains and cementation material leading to fine particle production should be investigated in a laboratory experimental program.

The potential for physical and chemical degradation of the cylindrical caprock zone interfacing with the wellbore cannot presently be dismissed. Radial heat losses from the air stream and short range conduction may expose this material to elevated temperatures. Therefore, any experimental program should address the high temperature response of shale and other caprock materials.

At the lateral interface between the storage horizon and the caprock, shale or anhydrite material may experience physical and chemical degradation over a vertical span of one or two meters. Given the high permeability contrast between the storage zone and the caprock zone, the air mass will tend to flow totally within the storage zone. Thus, no advective heat transport mechanism should be active in the caprock. Conduction and gaseous diffusion appear to be the only heat and mass transfer mechanisms associated with an intact caprock. Similarly, any adverse oxidation products generated within this 3- to 5-ft (1- to 2-m) caprock zone must rely on gaseous diffusion in response to a concentration gradient to proceed towards the borehole. Furthermore, these gaseous oxidation products will buffer the overlying material from further oxidation reactions.

Differential thermal expansion between the storage zone and the caprock may result in unacceptable stresses. Numerical modeling efforts will assess this potential problem.

Field testing at elevated temperatures should be conducted in conjunction with the proposed DOE-EPRI demonstration facility designed for low temperature air. Results from a few high temperature wells at the periphery of the cushion air bubble would be more advantageous than a separate small scale test facility since the large cushion air bubble would already be developed. The time scale of the project may be some concern, however.

2.2 BACKGROUND ON CAES TECHNOLOGY AND PRESENT AND FUTURE STUDY AREAS

The objectives of this section are: 1) to familiarize the reader with porous, permeable media as potential air storage reservoirs, 2) to introduce a number of subject areas that were addressed in this study, and 3) to delineate those areas requiring additional study.

Figures 2-2 and 2-3 give a schematic representation of a hypothetical CAES project with aquifer storage. Current designs are based on low temperature

FIGURE 2-2. Flow Diagram for Compressed Air Storage Plant⁽³⁾

FIGURE 2-3. Components of Underground Air Storage Flow System with Nomenclature(3)

(200°F/93°C) air injection. One of the primary conclusions of the workshop conducted as part of this study is that the technology now exists to handle the pertinent engineering and/or operational problems, and a full scale demonstration plant could be designed and constructed in the near future. The only significant question remaining concerns the near-well drying problem. Low temperature air may not have adequate vapor transport capacity to remove the residual water in an expedient manner.

Storage of the thermal energy of compression by injecting the air into the storage horizon at elevated temperatures (200 to 650°F/93 to 343°C) is also being investigated. Some additional uncertainty resides with this high temperature concept. Specifically, this includes: 1) wellbore and reservoir engineering and operation, 2) thermodynamic cycle efficiencies and the usability of low quality energy, 3) surface facilities design and reliability, and 4) overall economics.

This study is restricted to wellbore and reservoir engineering and operational aspects of the overall concept. The list of topics addressed in this study is presented in Table 2-2. Those requiring further study are delineated in Table 2-3. It must be emphasized that most of the topics in Table 2-3 are oriented towards elevated temperature storage since this concept has the most unknowns. No attempt has been made to prioritize the list at this time. Section 2.4, however, will expand on the five areas considered most important.

Section 2.3 is a brief discussion of reservoir development and operation and Section 2.4 is a detailed presentation of the following topics: 1) well casing and completion cement integrity, 2) liquid and vapor phase water, 3) caprock integrity, 4) geochemical reactions, and 5) physical response of the porous rock.

2.3 RESERVOIR DEVELOPMENT AND OPERATION

Some of the required characteristics of an underground storage zone are:

1. a zone of reasonable porosity exceeding 30 ft (9 m) in thickness and having a permeability in excess of 300 millidarcys ($3.0 \times 10^{-13} \text{ m}^2$),
2. a closure in excess of 150 ft (46 m),
3. sufficient areal extent, thickness, and depth to permit the desired air storage volumes and pressures, and
4. a caprock with sufficiently high threshold pressure characteristics and a thickness in excess of 20 ft (6 m).

To develop an air storage bubble within such an aquifer, air is injected at pressures exceeding local hydrostatic pore pressure (0.43 to 0.52 psi/ft). The water and sand matrix is compressed by this advancing air front. The constituent densities increase as a function of the injection temperature and pressure and their respective compressibilities (Figure 2-4). As can be seen from the figure, water has a very low compressibility. However, since the term aquifer implies a reasonable continuity of the water storage zone, the total volume of water compressed even slightly is very large.⁽³⁾

TABLE 2-2. Subjects Addressed During the Study

I. Temperature Effects

- A. Casing and grouting response to elevated and cyclical temperatures and associated gradients
  - 1. thermal expansion and fatigue
  - 2. cement dehydration
- B. Reduced capillary forces in the caprock and subsequent migration of the wetting-nonwetting phase interface
- C. Vaporization of liquid phase water within the near-wellbore zone and subsequent mass and heat transfer mechanisms
- D. The temperature profile within the storage matrix as a function of time
- E. Condensation of injected water vapor
- F. Temperature dependence of geochemical reactions and product transport
  - 1. the space-time association of elevated temperatures and liquid phase water
  - 2. chloride stress corrosion and silica and calcite scaling
  - 3. hydrolytic and redox reactions
- G. The potential for and temperature dependence of inelastic pore and vug deformation
- H. Fracturing and/or buckling of the caprock due to differential thermal expansion
- I. Decreases in air deliverability with elevated temperatures (viscosity effects)
- J. Residual hydrocarbon oxidation at elevated temperatures
- K. Radial and vertical heat losses
- L. Thermal cycling and attenuation with time
- M. Heat storage in the rock constituents (axially symmetric case)
- N. Increase in cushion air volume and/or pressure with elevated temperature
- O. Thermal expansion of grains into pore interstices
- P. Degradation of grains and cementation and associated particulate production

II. Effective Stress Effects

- A. Caprock threshold pressures and the maximum allowable delta pressure (pressure above discovery hydrostatic) during a cycle
- B. Pressure manipulations during and subsequent to cushion bubble growth and the impact of flow resistance
- C. Potential for tensional stresses from high injection pressures
- D. Matrix fatigue from pore pressure cycling
- E. Pore deformation resulting from a rapid reduction in pore pressure
- F. Pressure solutioning
- G. Movement along high angle glide planes in the caprock
- H. Communication among preferential flow zones (wafering and channeling)
- I. Relative permeabilities
- J. Air/water/rock compressibility

III. Liquid and Vapor Phase Water Effects

- A. Impact on air deliverability (permeability decrease, water migration, β factor increase)
- B. Impact on surface facilities
- C. Weakening of rock constituents (hydrolytic weakening)
- D. Geochemical reactions and smectite migration and swelling
- E. Apparent thermal diffusivity characteristics
- F. Vaporization and transport of residual water in the near-well region.

IV. General Effects

- A. Formation anisotropy and heterogeneity
- B. Loss of surface facilities such as dehydration
- C. Air storage and deliverability as a function of permeability, porosity, viscosity, and wellbore size
- D. Types of reservoir and caprock material

TABLE 2-3. Areas Requiring Further Investigation^(a)

I. The Critical (near-well) Zone and the Remainder of the Working Air Zone A. The humidity problem 1. minimum degree of undersaturation and minimum temperature required for the injected air mass 2. size of the critical zone 3. time to dehydrate the critical zone and ability to maintain it free of liquid phase water for the project duration 4. consequences associated with liquid phase water a. air deliverability b. geochemical reactions c. accumulation of water in the well bottom and/or transport to surface facilities d. thermal diffusivities B. Well casing and grouting response to elevated and time varying temperatures 1. stress-strain response of the casing 2. cement failure due to thermal stress, fatigue, or dehydration C. Rock degradation 1. geochemical reactions 2. particulate matter generation and production	D. Heat losses 1. radial losses from descending air stream 2. vertical losses from the storage zone II. Caprock A. Physical and chemical decomposition 1. dehydration and loss of containment capacity 2. geochemical reactions and product migration 3. movement on high angle glide planes 4. differential thermal expansion B. Mass and heat transfer 1. convection/conduction/diffusion (relative magnitudes) 2. vertical heat losses C. Inhomogeneity III. Cushion Bubble Zone A. Temperature, pressure, and saturation profiles 1. time variance 2. impact on potential geochemical reactions and mechanical stability B. Optimal conditions for cushion bubble development C. Formation anisotropy and heterogeneity and the potential for wafering and channel losses

(a) Refer to "Presentation of Specific Topics" for further discussion on what are considered to be the five most important problem areas.

FIGURE 2-4. Compressibility of Pure Water⁽³⁾

The pressure wave associated with air injection moves radially outward. Actual displacement of interstitial water lags this pressure front but eventually liquid phase water above the residual level is expelled by the advancing air mass. In general, the mass of water, not displaced during this development of the cushion air bubble, may occupy up to 30% of the available pore volume. It has a preference for the smaller pores where the surface area to volume ratio is maximized. In other words, this residual liquid phase is contained in pores that support a high capillary retention pressure relative to the air injection pressure. Furthermore, some liquid phase water may be trapped in dead end pores and hydraulically isolated pockets.

As long as the charging air pressure exceeds the ambient aquifer hydrostatic pressure the air bubble will expand and water will continue to be displaced. Conversely, if the injection pressure is decreased to a level below the water drive head, the bubble will ultimately respond with a volume reduction.

Development of this cushion or base air bubble will typically require a period of 2 to 4 years. Further enlargements may be accomplished over the first 10 years of operation. In general, the total quantity of cushion air required to support a 600 MW facility will be on the order of $1.5 \times 10^9 \text{ lb}_m$ ($0.68 \times 10^9 \text{ kg}$). For comparison purposes, Table 2-4 presents approximate project design parameters for four different porous media reservoirs.

The initial several cycles of the cushion air bubble development should be accomplished at temperatures below about 150°F (66°C). A general rule is that liquid phase water above the residual level must be removed from the zone that will ultimately contain the working (weekly cycle) air mass prior to the introduction of high temperature air. Furthermore, the inner critical zone associated with high velocity airflow must be totally dehydrated and perpetually maintained in that state (Figure 2-5). Motivation for this stipulation will be discussed subsequently. The size of the working air zone will depend on the specific project design, however it may have a radial extent of 30 to 90 ft (9 to 27 m) from the borehole. Similarly, the critical zone may be on the order of 15 to 50 ft (5 to 15 m).

After the cushion air bubble is of sufficient size to support weekly plant operation, the working air mass will be injected and withdrawn in the cyclical nature depicted in Figure 2-6. A one-dimensional (gas/solid) computer model was developed to lend perspective to the problem. Simulation of this weekly mass flow cycle and the associated temperature cycling over a period of one year was conducted. The following conditions were used:

- reservoir ambient temperature   100°F (38°C)
- charging temperature   450°F (232°C)
- initial ambient reservoir pressure   735 psi (50 bars)
- charging mass flow rate   427 lbm/hr-ft (634 kg/hr-m)
- storage zone permeability   500 millidarcys ($500 \times 10^{-15} \text{ m}^2$)
- storage zone porosity   20%
- rock and air thermal conductivity   1.0 Btu/hr-ft-°F ($1.56 \times 10^5 \text{ W/m-°C.}$)

TABLE 2-4. Comparison of Preliminary Project Designs or Reservoirs⁽³⁾

Design Parameters	Belle River Mills	Herscher Galesville	Brookville Galesville	Media
Type of Reservoir	reef	aquifer	aquifer	aquifer
Depth, ft	2150	1780	780	2150
Natural Pressure, psi	1132	715	240	840
Surface Acres	1400	2800	3700	5000
% Porosity	10	19	18	17.2
md Permeability	320	400-3000	400-600	488
MW Power	600	600	600	600+
hr/week	50	50	50	50
Airflow, MMcf/hr	100	100	135	100
Turbine Air, psi	588	588	147	730
Reservoir Pressure Range, psi	693-760	651-722	217-263	818-862
Maximum Weekly Air Stored, Bcf	2.15	2.15	2.9	2.15
Base Air Used, Bcf	22.3	20	13.5	34
Number of 1/W Wells	100	253	539	100
Estimated Cost of Storage Project,				
\$M	25	38	40	35
\$/kW	41	63	67	60

FIGURE 2-5. Conceptual Presentation of Various Zones Within a Multiwell Reservoir

It was assumed that the storage zone was totally free of water and that the rock constituents and the air mass attained thermal equilibrium instantaneously.

The most apparent results are: 1) the temperature profile attenuates rapidly with radial distance from the borehole (Figure 2-7), 2) there is very little outward migration of the profile in the first year compared to the first week, and 3) temperature cycling attenuates rapidly with radial distance (Figure 2-8). All of these observations can be explained if the volumetric heat capacities and the active mass and heat transport mechanisms are analyzed.

FIGURE 2-6. Daily Pressure Fluctuations

The ideal storage zone is axially symmetric with respect to the borehole. Therefore, the volume available for the storage of thermal energy increases as a function of the radial distance to the second exponential power. Furthermore, the quantity of heat required to raise the temperature of a unit volume of the rock constituent by 1°F is 45 to 75 times that of an equal volume of air under expected reservoir conditions. Furthermore, the solid constituent occupies 80% of the available volume compared to 20% for the air. Thus, if one assumes that the air/rock contact area is reasonably large and that the solid constituents and the air rapidly attain thermal equilibrium, then the observed attenuation in the temperature profiles becomes very plausible. The conclusion is that the thermal energy associated with the injected airstream is essentially stored in the solid rock

FIGURE 2-7. Radial Temperature Profile Based on a One-Dimensional Gas Flow Computer Simulation

constituents in a small zone around the borehole. Furthermore, if the storage zone is assumed to be totally dehydrated, then the only active transport mechanisms beyond the working air zone are solid-solid conduction and gaseous diffusion which dictate an exceedingly gradual outward migration of the temperature profile with time.

If one includes vaporization of the residual water, it can be deduced that the water acts as a heat sink, and further attenuates the temperatures within the storage zone. This will be discussed in more detail in Section 2.4.

FIGURE 2-8. Temperature Cycling After One Year of Operation

2.4 MAJOR POTENTIAL PROBLEM AREAS IN STORAGE OF COMPRESSED AIR

This section presents individual discussions of the major topic areas associated with reservoir design and stability criteria. The following areas are included:

- well casing and completion cement integrity
- liquid and vapor phase water
- caprock integrity
- geochemical reactions
- physical response of the storage matrix.

The following steps were followed in conducting this state-of-the-art survey:

- 1) all of the topics perceived as even remotely pertinent to the underground storage component of the CAES concept were listed, 2) available literature corresponding to this list of topics was collected and reviewed, 3) preliminary analytical and numerical studies were conducted to better define the

physical conditions within the storage zone, 4) the complete list of topics was reviewed and discussed by a panel of reservoir engineering experts, 5) preliminary determination of the relevancy and priority of each topic was made, 6) a list of topics requiring further attention was drafted, and 7) preliminary design and stability criteria, based on these analyses, were synthesized. The topics requiring further study are biased towards high temperature storage due to the associated uncertainties and paucity of historical experience. Potential problems with the storage reservoir are considered in this report. Criteria are established that will mitigate these problems and yet minimize unnecessary restrictions on the design and operation of a CAES facility.

2.4.1 Well Casing and Completion Integrity

One of the most important problems to be addressed is the thermo-mechanical response of the metal well casing and the cement grouting sheath when exposed to elevated temperatures and thermal cycling.

Casing failures in the steam-drive oil recovery industry are extensively documented. Thirty such failures have been verified in California alone. Casing failure occurs initially when temperature-generated compressive stresses exceed the yield strength of the casing. This causes the casing material or joints to permanently deform during the fluid injection period. Subsequent cooling while the well is closed or producing relieves the compressive stress. However, the induced deformation creates a tensile stress if the casing returns to a lower temperature level. Often this tensile stress results in joint failure by fracture or pullout.⁽⁴⁾ Figure 2-9 illustrates this general concept.

The physical principles governing casing failure are well known. The uncertainty resides in the precise temperature limits at which this failure is likely to occur. This temperature is a function of casing material properties, lateral deformation or buckling capacity, and joint performance under high compressive and tensile loads.

FIGURE 2-9. Stress History of Casing During Steam or Hot Air Injection(5)

To lend perspective to the problem, the following general rules are given: 1) unrestrained stainless steel casing will expand 0.8 in./100 ft of length/100°F temperature rise (1.2×10^{-3} cm/m/°C), and 2) restrained casing will experience compressive and tensile stresses on the order of 200 psi/1°F temperature variation (24.6 bars/°C).

Table 2-5 reveals how this stress-temperature relationship defines allowable temperature changes for compressive loading for some typical casings. Any temperature increases beyond this will generally result in inelastic deformation. For CAES projects it is assumed that completion practices will preclude buckling due to lack of radial confinement.

TABLE 2-5. Allowable Temperature Changes
for Compressive Loading⁽⁴⁾

<u>Material Grade, spec</u>	<u>Minimum Yield Stress, psi</u>	<u>Allowable Temperature Change (ΔT), °F</u>
J	55,000	275
N	80,000	400
S	95,000	475

Referring again to Figure 2-9, permanent compressive deformation occurs at temperatures exceeding ΔT_{yp} . Any additional degree of overstressing will determine the magnitude of permanent deformation and subsequent induced tensional stress upon cooling. This temperature range is ΔT_t and the stress leading to failure will be equal to 200 psi (ΔT_t). Table 2-6 reveals the range of these stresses on J type casing for various temperatures.

So far the analysis has assumed that the casing is totally restrained and that thermal response is manifested in high compressive stresses. The potential for casing expansion and shearing off of wellhead and surface pipes is also very real. Given a 1000-ft (305-m) casing string at 650°F (343°C) and totally unrestrained conditions, the top of the casing can be expected to expand out of the ground approximately 4.3 ft (1.3 m).

Superimposed upon the problem of temperature induced overstressing and/or linear elastic strain response is the concept of fatigue due to thermal cycling. An example of magnitude of anticipated temperature fluctuations for a 450°F (232°C) charging temperature is demonstrated in Figure 2-8. Very little experimental data on casing fatigue is available at the elevated temperatures in question. However, an example of thread failure after 20 to 40 cycles on a steel similar to N-80 casing has been documented.⁽⁵⁾ When stress corrosion was included, this level dropped to 10 to 20 cycles.

Naturally, tensile failure during the first cycle or fatigue failure during subsequent cycles is not a problem if the compressive yield point of the casing in question is never exceeded. Therefore, the following design criteria is recommended:

TABLE 2-6. Temperature Changes/Tensile Forces Resulting from Cooling Over-Stress Pipe

Casing Temperature, °F	$\Delta T_{\max}$, °F	ΔT_{yp} , °F	ΔT_t , °F	Tension when Cooled, psi
500	400	275	125	25,000
550	450	275	175	35,000
600	500	275	175	45,000
650	550	275	275	55,000

- The compressive stress generated by the change in casing temperature during initial hot air injection should not exceed the yield strength of the particular casing material in question.

There are two basic methods available to permit injection of air at elevated temperatures:

1. Design and build thermal protection into the initial well completion:
  - prestress the casing in a tensional mode prior to completion,
  - anchor the casing only at the bottom to allow for expansion, and
  - rely on casing steel with a greater yield strength
2. Attenuate the effective casing temperature by annular insulation and/or multiple strings.

The prestressed completion is based on the theory that enough tension (up to 80% of minimum yield strength) can be placed on the casing prior to final cementing to prevent the casing from exceeding the yield point in compression during heating. This technique certainly appears viable for a CAES project. Stress-free completion (bottom anchoring only) does not appear applicable to the problem since a good cement completion through at least the full extent of the caprock is required to maximize air containment potential. Utilization of upgraded casing materials and the various insulation and multiple strings techniques is certainly possible from an engineering standpoint. However, the cost may be prohibitive.

The problems of casing failure by joint pullout or fracture in wells have been extensively examined in the fields of steam and hot air injection for oil recovery. Design criteria have been successfully used to prevent casing failure in wells stimulated with 650°F (343°C) steam.⁽⁴⁾ Given this field experience and the rapid loss of carbon steel physical properties at or near 650°F (343°C), it is recommended that this temperature be considered as a maximum, at least from the standpoint of casing integrity.

The response of the cement grouting to elevated temperatures is another area requiring some thought. However, given the availability of good silica cements and completion practices, a 650°F (343°C) range should be attainable. There are two components to the thermal problem: 1) the elevated temperature itself and the potential for cements other than the silica-based ones to dehydrate and lose integrity, and 2) the establishment of a radial thermal gradient across the sheath. The first area appears to be manageable with the proper type of cement. The second problem may require that the injection temperature be raised gradually over many cycles. This would warm the cement sheath by conduction and possibly preclude the establishment of high thermal stresses within the sheath.

In conclusion, the upper temperature limit for casing materials and completion cements should currently be considered as 650°F (343°C).

2.4.2 Liquid and Vapor Phase Water

The humidity within the storage zone has been previously identified as an important parameter for both low and high temperature injection. This section is devoted to a discussion of: 1) the sources of the liquid and vapor phases of water, 2) the zones within the storage region where control of the humidity conditions is most vital, 3) the potential adverse consequences associated with the presence of the two phases, and 4) a mechanism for eliminating the water in the vital areas. Table 2-7 presents the various topics covered in this section.

TABLE 2-7. Components of the Humidity Problem

<u>Potential Fluid Sources</u>	Residual water subsequent to initial air bubble development. Water vapor associated with the injected air mass. Leakage through grout seal or caprock.
<u>Air Storage Zones (Figure 2-5)</u>	Critical (near-wellbore) zone. Working air zone. Cushion air zone.
<u>Potential Adverse Consequences</u>	Reduction in air deliverability for a given pressure gradient. Introduction of liquid and vapor to surface facilities. Geochemical reactions (permeability changes, corrosion, scaling). Reduction in available thermal energy. Increased thermal diffusivity.
<u>Dehydration Mechanism</u>	Cycle undersaturated air.

2.4.2.1 Sources of Liquid and Vapor Phases

The first source of liquid is the residual content that will be present after initial development of this air bubble. Prior to air injection, the porous media is totally saturated with liquid water and some concentration of dissolved solids. If air is injected at a pressure in excess of the local interstitial fluid pressure, then a certain percentage of the pore liquids will be displaced away from the injection point and ideally will no longer be of concern. However, in regions that: 1) support only a single communication channel (throat) with the remainder of the matrix, 2) support a capillary retention force in excess of the imposed air pressure gradient, or 3) are hydraulically isolated, the interstitial liquids will not be displaced by the advancing air front. This volume of water is known as the residual liquid saturation. This residual water content is typically measured in the laboratory by imposing a pressure gradient between the gas and liquid phases in capillary contact with a sink and measuring the volume of water displaced

after equilibrium has been attained. The test is then repeated with an incrementally higher imposed pressure gradient. Figure 2-10 demonstrates the results of several such experiments. Note the majority of the liquid is displaced by a very small ΔP (<5 psi) in these specific examples, but regardless of further pressure increases the liquid saturation levels remain relatively constant. This is termed the irreducible or connate saturation level and is defined in terms of the percentage of the available pore volume occupied by liquid constituents. Figure 2-11 demonstrates how the irreducible saturation might vary as a function of sample permeability. This limited data reveals that for 300 millidarcy media, the irreducible levels vary from 10 to 25%. Figure 2-12 demonstrates a 35% level for a specific 170-millidarcy sample.

FIGURE 2-10. Miscellaneous Capillary Pressure-Saturation Curves(2)

FIGURE 2-11. Permeability Versus Connate Water by Capillary Pressure⁽²⁾

FIGURE 2-12. Comparison of Capillary-Pressure Results with Mercury and Air/Water⁽²⁾

Similar core tests are conducted to yield relative permeability curves as a function of interstitial liquid saturation (S_w). Figure 2-13 shows that even for a 40% S_w level, the specific permeability to gas in the given sandstone sample is still on the order of 90% of the permeability with the sample totally dewatered. Unfortunately, the empirical scatter over the full spectrum of sandstone samples is such that the permeability to gas can be reduced somewhat more significantly, but the point is that the relative permeability curves are quite nonlinear and in general the permeability to gas is not drastically perturbed by a saturation level of 20% or less. Unfortunately, extrapolation of these results to field applications is not without added complexity.

FIGURE 2-13. Relative Permeability for Consolidated and Unconsolidated Sands(2)

In the field, the irreducible saturations tend to be somewhat higher than measured in the laboratory because a significant volume of water remains trapped in porous regions that do not support or rapidly lose hydraulic continuity before the applied capillary pressure gradient is sufficient to effect drainage.⁽¹⁰⁾ Therefore, it appears that in the field, the magnitude of the irreducible wetting phase saturations are somewhat controlled by the variability of the porous structure and that this heterogeneity cannot be reproduced in the small laboratory specimens. Figure 2-14 demonstrates in a conceptual manner how the laboratory results can be in error, and Figure 2-15 portrays the concept of hydraulic isolation. Note that as the applied capillary pressure due to the injected air mass is increased to P_1 , the region P_1 is drained and the air pressure completely equilibrates around the region P_2 . Even as the air injection pressure is increased so that a gradient in excess of P_2 might be imposed across the region P_2 , equilibration will occur far too

FIGURE 2-14. Pore Space Saturation⁽¹⁰⁾

FIGURE 2-15. A Heterogeneous Porous Mass Which Upon Drainage Retains Wetting Liquid in Region P_2 ⁽¹⁰⁾

rapidly in region P_1 to support the pressure gradient and displace the water from P_2 . Thus P_2 will remain saturated with the liquid phase. Similarly, region P_3 will remain saturated if the imposed pressure gradient does not exceed that necessary to drain P_4 even though it is great enough to drain P_3 . Region P_4 might represent a mini-layer shale boundary. The point is that a significant amount of water is going to remain in the reservoir subsequent to initial development of the air bubble and that this level will be in excess of that measured in the laboratory.⁽¹⁰⁾

The second potential source of water is associated with the injected air mass. Moisture injected with the air will condense when proper conditions are encountered in the reservoir. This is a function of temperature, pressure, and initial humidity levels. It is anticipated that the air will be undersaturated before it is introduced to the storage matrix. However, the degree of undersaturation will be economically determined. Solid desiccants and refrigeration systems may be uneconomical given the large air masses and flow rates. Therefore, cooling of the air stream to reduce its water carrying capacity, removal of the condensate, and subsequent reheating of the air may be the only realistic alternative.

To lend perspective, surface ambient air at 30% relative humidity contains approximately $6.0 \times 10^{-3} \text{ lb}_{\text{H}_2\text{O}}/\text{lb}_{\text{Air}}$. Air at 50 atm is totally saturated at $3.0 \times 10^{-4} \text{ lb}_{\text{H}_2\text{O}}/\text{lb}_{\text{Air}}$ for the same surface ambient temperature. If this mass of compressed air is heated in a heat exchanger to 450°F it can contain as much as $8.0 \times 10^{-1} \text{ lb}_{\text{H}_2\text{O}}/\text{lb}_{\text{Air}}$ before it is saturated. Figure 2-16 reveals the solubility of water in air at various temperatures and pressures. Assuming the air is heated and then injected, its temperature will be reduced as it proceeds into the storage zone and the water carrying capacity will be similarly reduced. If the air contains sufficient moisture, it will begin to condense within the storage zone. The quantity and resulting saturation profile will depend on the degree of undersaturation of the injected air and the reservoir temperature and pressure profiles. Thus, there are two primary sources of liquid and vapor phase water that must be investigated. A third source, leakage around the grout seal, should be noted, but will not be addressed in this section.

FIGURE 2-16. Solubility of Water in Air at Various Temperatures and Pressures

2.4.2.2 Air Storage Zone

Before discussing the potential consequences associated with liquid phase water, it would be instructive to subdivide the air storage zone into three components. Figure 2-5 presents a conceptual model of the system. The critical zone is defined as the cylindrical (ideal) volume around a wellbore that exhibits high velocity airflow and elevated temperatures. The working air zone is the cylindrical (ideal) zone that contains the mass of air used in a weekly cycle. In other words, this air mass will be expanded through the turbine at least once during the week. The critical zone is naturally encompassed within the working air zone. The third division is the cushion air zone. This is defined by the volume of air that perpetually remains in the reservoir. The caprock represents an additional region susceptible to the effects of humidity and is considered in the next section. Before specifying humidity criteria for each of these zones, some insight into the potential adverse consequences associated with the liquid and vapor phases of water is required.

2.4.2.3 Consequences Associated with the Wetting Phase Saturation

The presence of interstitial liquids, especially near the wellbore, may result in a reduction of air deliverability for a given pressure gradient. For example, water saturations of 50% can reduce the specific permeability to gas by some 30% of the dry value. Field operations frequently show a reduction of gas flow of 50% or more when liquid water reaches the wellbore.⁽¹⁾ Under the high airflow conditions associated with CAES, the residual water may be mobile to some extent. Some of this liquid may accumulate in the wellbore or be produced with the airstream. Although the conditions are not totally analogous, water infiltration in the natural gas storage industry is often considered a significant nemesis.

The interstitial water will reduce the effective permeability to air according to the empirical relative permeability curves. In addition, it will tend to increase the turbulent flow factor (β). This is a secondary effect, however, and may account for less than 5 to 10% of the anticipated air deliverability reduction. Unfortunately, few data are available describing two-phase flow in porous media with liquid saturation under high velocity conditions.

Liquid phase water reaching the wellbore could impact normal operation in the following ways: 1) significantly increase the flowing fluid column density and thus create a severe pressure drop penalty, 2) initiate casing corrosion especially if chlorides or alkali metals are involved, 3) enter the turbines and combine with sulfur compounds in the fossil fuel to create adverse corrosion conditions, and/or 4) accumulate in the bottom of the well and gradually reduce airflow capacity. In general, if the fluid flow rate is greater than 5 ft/sec (1.5 m/sec), the liquid will be produced with the airstream and the pressure drop, and corrosion effects will result. Below this velocity, the water will gravity drain out of the fluid column and will collect in the wellbore. It is anticipated that a CAES well would support a velocity in excess of the general threshold value and, therefore, water reaching the wellbore should be produced with the airstream.

Geochemical effects associated with the presence of the liquid phase are included in the next section and will not be further discussed at this time. Thermal development of the reservoir will be affected by the interstitial saturation conditions. The vaporization of the liquid will represent a heat sink and the thermal diffusivity, both real and apparent, is a function of saturation conditions.

Given 540 kcal/kg as the latent heat of vaporization of water, a cylindrical volume of radius 5 m and axial length 30 m, an interstitial porosity of 0.20, and 0.20 of that porosity saturated with liquid, it would require on the order of 5×10^7 kcal of energy to achieve a total state of dehydration within the zone. Only the process of evaporation is considered in this example.

The ability to disperse this quantity of thermal energy into the storage zone depends in part on the thermal diffusivity characteristics. The effective thermal diffusivity is strongly a function of liquid phase saturation. As with all characteristics of porous media, this characteristic is extremely site specific and the scatter in results from specimen to specimen and from laboratory to the field can be dramatic. The pertinent parameters affecting the thermal diffusivity include the degree of liquid saturation, the porosity,

and the conductivities of the liquid and, to a lesser extent, the solid constituents. Furthermore, temperature and confining pressure have limited effects. Here we are primarily interested in the dominant parameter, that of liquid phase saturation. Figures 2-17 and 2-18 reveal how the thermal conductivity of two specific oil sands varies as a function of brine saturation S_w . Analysis of these data results in the media-specific correlation⁽¹¹⁾:

$$\tau_{sw} = 0.735 - 1.30 \phi + 0.363 \tau_s S_w^{1/2}$$

where

τ_{sw} = thermal conductivity of the system

τ_s = thermal conductivity of the solid

ϕ = porosity

S_w = brine saturation

It can be seen that in one case the thermal conductivity increases by a factor of six in going from the totally dry to the totally saturated conditions.

It appears that in some cases an order of magnitude variation is not unrealistic. In our own laboratory, thermal conductivity for sandy sediments has increased by a factor of five in going from a dry to a 35% saturated condition.

For the consolidated sandstone samples that were tested a similar analysis resulted in a fitted curve defined by:

$$\tau(s_w) = \tau(s_w = 0) + [\tau(s_w = 1) - \tau(s_w = 0)] S_w^{1/3}$$

where

$\tau(s_w)$ = thermal conductivity at liquid saturation S_w

$\tau(s_w = 0)$ = thermal conductivity of the dry sample

$\tau(s_w = 1)$ = thermal conductivity of a fully brine-saturated sample

S_w = fractional brine saturation

FIGURE 2-17. Thermal Conductivity of Kern River Oil Sands⁽¹¹⁾

FIGURE 2-18. Thermal Conductivity of Partially Brine-Saturated Quartz Sand⁽¹¹⁾

Unfortunately, no numerical coefficients were reported for consolidated specimens. It must be reiterated that these results are very site and media specific. Sandstone chemical and physical properties are dispersed over a broad spectrum. However, in general brine-air saturation systems, thermal conductivity is related to the cube root of brine saturation for consolidated media. For unconsolidated sands saturated with air and brine, the trend was as the square root of the wetting phase saturation.^(a)

All of the consequences mentioned above are primarily concerned with the critical or near-wellbore zone. In the remainder of the working air zone and in the cushion air zone, the adverse effects associated with residual liquid saturation should be limited to a reduction in the available air storage capacity. This conclusion is based on the following observations: 1) away from the wellbore region air mass flow rates are low through any given unit volume of rock, and 2) the temperature should be radically attenuated in relation to that in the region near the wellbore. These observations do not take into consideration the influx of liquid water due to forced-flow migration and the condensation of vapor that was evaporated from regions nearer the wellbore. In addition, the impact of anisotropy and gravity drainage barriers is also unexplored. These topics should be further addressed during subsequent investigations.

2.4.2.4 Dehydration Mechanism

So far the discussion has centered around the fluid sources, the different air storage zones, and the consequences of the residual water in each zone. Since dehydration of the near-wellbore zone has been identified as necessary, it is instructive to explore a potential mechanism by which this state can be attained. Figure 2-19 conceptually portrays the evaporation process.

(a) Note that if the temperature is raised to near the in-situ boiling point of the fluids at the given pressure, then the effective heat transfer is drastically increased by the heat pipe effect. In other words, the water is vaporized, the vapor travels down the thermal gradient, condenses, and then the liquid is drawn back along the capillary pressure gradient. A somewhat less dramatic version of this process may occur if one considers liquid migration in response to a temperature gradient.

FIGURE 2-19. Conceptual Presentation of the Evaporation Process

Note that the presence of the thermal gradient in itself does not induce liquid or vapor migration. There may be some vertical density stratification, but there is no density instability process driving radially oriented convective transport. What the temperature near the wellbore does affect is the vapor carrying capacity of the flowing air (Figure 2-16). Evaporated water will be swept out into the storage matrix whereupon it will condense due to the decreasing temperature. This condensate will not be part of the residual water and will be free to migrate due to gravity drainage and/or capillary forces.

When the air is then produced, it will be swept back through the near-wellbore region whereupon it will be heated and thus able to carry more water vapor. This air-vapor mixture will then be produced in the wellbore. Thus, if one begins by injecting undersaturated air, the residual water near the wellbore will be in part displaced in the vapor state both during the injection and withdrawal parts of the cycle. It is this dehydration process with initially undersaturated air that will enable the near-wellbore region to be free of the interstitial liquid phase.

Obviously, the length of time to effect this dewatering is of extreme importance. The time is a function of: 1) the degree of undersaturation of the injected air, 2) the temperature and pressure of the injected air, 3) the temperature and pressure profiles within the storage zone, and 4) the mass flow rate and the air vapor contact area.

Two phase thermal/fluid flow numerical models and experimental efforts are necessary to address this complex problem. However, a simple computer simulation was devised to address the problem on a preliminary basis. Totally dehydrated air was injected into a storage zone that contained 20% residual water. The radial temperature profile was assumed, even initially, to be that shown in Figure 2-7. Thus, the temperature varied as a function of radial distance from 450°F (232°C) to reservoir ambient over a radial distance of approximately 75 ft (25 m). Reservoir pressure was assumed to follow a weekly injection-production schedule cycled around a 50 atm (50 bar) mean. All other parameters were identical to the one-dimensional air phase simulation program described earlier. The air mass was allowed to equilibrate

(totally saturate) at the given temperature and pressure, and was then withdrawn from the reservoir. This rough calculation ignored: 1) the thermal energy utilized in the evaporation of the liquid phase water, 2) the associated attenuation of the storage temperatures, 3) the potential for the air to remain undersaturated due to high flow rates or poor contact with the water, and 4) the displacement of vapor down the thermal gradient. Although gross assumptions, they appear to be conservative in terms of the rate of dehydration that can be expected within the working air zone. One additional assumption necessary for the rough calculation was that the drying front be constrained to advance as a rigid boundary. This would clearly not be the case under actual conditions.

The results reveal that with 450°F (232°C) dehydrated air being injected, the storage zone would be dehydrated to a radial distance of 22 ft (7 m) after the first year. However, because of the temperature decreasing radially within the zone, it will require approximately 9 years to dehydrate a total distance of 40 ft (15 m). Similar calculations for 150°F (66°C) injected air demonstrated that it would take decades to dehydrate the same 40-ft (22-m) zone.

These calculations were merely designed as a guide and prelude to the sophisticated simulation efforts that will be required to properly address the problem. However, they do demonstrate that a minimum operating temperature criterion may be necessary to ensure that the critical zone is dewatered in an expedient manner.

The loss of storage capacity, air deliverability, and available thermal energy, as well as the large quantities of water vapor being produced have been advanced as potential problems associated with liquid phase water. An additional adverse impact involves liquid phase water as a catalyst for geochemical reactions. The result may be degradation of interstitial and/or fracture permeability, well casing material, and surface facilities. These reactions and consequences will be discussed in detail in Section 2.4.4 of this report.

In conclusion:

- As much as 10 to 30% of the available porosity will be occupied by residual water after initial air bubble development.
- The wellbore and critical zone must be dehydrated and perpetually maintained in that state.
- Consequences associated with liquid water include: loss of air deliverability, introduction of liquid and vapor to surface facilities, geochemical reactions, and significant changes in the thermal development of the reservoir.
- The remaining part of the working air zone and the cushion bubble zone need not be dehydrated. The residual water will be essentially immobile in its liquid state.
- A minimum injection temperature may be required to ensure that dehydration of the critical zone be accomplished in an expedient manner.
- The degree of undersaturation of the injected air and the temperature profile within the storage reservoir must be such that the net transport of water vapor is out of the working air zone into the cushion zone or up the wells.
- Evaporation of residual water may result in a significant thermal energy loss and a source of vapor that may be transported up the wells.
- Thermal diffusivity and, therefore, reservoir thermal development is strongly dependent on the presence of liquid water.
- Numerical modeling is required to characterize the anticipated conditions within the reservoir. Also, the impact of reservoir heterogeneity and anisotropy must be addressed.
- Laboratory and field scale testing will ultimately be required.

2.4.3 Caprock Integrity

Figure 2-20 demonstrates two different mechanisms for exposing a shale caprock to elevated temperatures, and these will be assessed independently. First, there can be thermal losses in a radial direction from the well as the high temperature air flows downwards. Conduction of this thermal energy will result in elevated temperatures in the cement sheath and an interfacing cylindrical zone of shale caprock. If the temperature so attained is sufficient to induce physical and chemical degradation, loss of containment capacity may result. The second area requiring analysis is the thermal interaction between the storage zone and the overlying caprock. In general, this is considered to be a comparatively minor problem for reasons that will be discussed subsequently.

Heat losses in the radial direction associated with the injected air mass are reasonably well understood and are amenable to analytical calculations.⁽⁶⁾ The primary mechanism for heat transfer will be transient radial conduction. The unsteady state nature comes from the fact that the cylindrical zone will increase in temperature and therefore decrease in terms of thermal conductivity. This will attenuate further heat loss magnitudes with time. The important point is that although energy losses are insignificant in themselves, exposing a segment of shale to excessive temperatures over the full vertical extent of the caprock could have adverse consequences. Therefore, this maximum permissible temperature level must be established.

Ramey postulates and derives the solution for the following heat transmission problem.⁽⁶⁾ A fluid is injected down a tubing of known characteristics in a well which is cased to the top of the injection interval. It is assumed that the fluid is injected at known rates and surface temperatures. The problem is to determine the temperature of the injected fluid as a function of depth and time. The solution results in quantification of the amount of thermal energy lost in transit down the borehole. The solution for single phase air injection^(a) is:

-
- (a) If liquid either condenses or vaporizes in the well, the effective heat capacity of the air will change appreciably and the above solution is no longer valid.

FIGURE 2-20. Mechanism for Exposing the Caprock to Elevated Temperatures

$$T_1(z, t) = aZ + b - A \left(a + \frac{1}{778c} \right) + [T_0 - b + A \left(a + \frac{1}{778c} \right)] e^{-z/A}$$

where

$$A = \frac{Wc[k + r_1 U f(t)]}{2\pi r_1 U k}$$

T_1 = temperature of fluid in the tubing, °F

Z = depth below the surface, ft

t = time from start of injection, days

a = geothermal gradient, °F/ft

b = surface geothermal temperature

c = specific heat at constant pressure of fluid, Btu/lb-°F

A = time function, ft

T_0 = surface temperature of the injected fluid, °F

W = fluid injection rate, lb/day

k = thermal conductivity of the earth, Btu/day-ft-°F

r_1 = inside radius of tubing, ft

$f(t)$ = transient heat conduction time function for earth, dimensionless

U = overall heat transfer coefficient between the inside of the tubing and the outside of the casing based on r_1 , Btu/day-sq ft-°F.

This solution is based on the assumption that physical and thermal properties of the rock and wellbore materials are static, that heat will transfer only radially into the earth, and that heat transmission in the immediate vicinity of the borehole is rapid enough to be considered steady state.

This approximate analytical calculation replaces the requirement for numerical evaluation of a set of two simultaneous, linear partial differential equations and is relatively straightforward with the possible exception of the overall heat transfer coefficient U . This coefficient considers the effect of thermal resistances in the wellbore which can be very important in certain cases.

Figure 2-21 presents a comparison of measured and computed temperatures for injection of hot natural gas down insulated tubing.⁽⁶⁾ During the year and a half this test was operated, the temperature of the injected gas was increased to almost 500°F (260°C) and the gas injection rate varied from 0.8 to 16.0×10^6 lbm/day (0.4 to 7.2×10^6 kg/day). Gas was injected down 3-in. (8-cm) tubing. The annulus between the tubing and the 7-in. (18-cm) casing was filled with Perlite insulation. This example illustrates the magnitude of potential wellbore heat losses during hot, noncondensable gas injection.

Figure 2-1 reveals the liquid/vapor relationship for water as a function of pressure and temperature. If the air is not highly undersaturated and the wellbore heat losses are of sufficient magnitude, the potential for condensation in the wellbore exists. This would tend to increase the heat transfer coefficient and, therefore, increase subsequent heat losses.

The primary concern is not the loss in energy available to the system for useful work, since this will attenuate rapidly with time. What is of concern is that a cylindrical zone of shale caprock interfacing with the wellbore may be exposed to elevated temperature due to solid-solid conduction of the thermal energy. Dehydration of the interstitial fluids and/or cracking due to thermal stresses may result in the loss of containment capacity.

FIGURE 2-21. Measured and Computed Temperature-Depth Profile for Hot Natural Gas Injection Down an Insulated Tubing⁽⁶⁾

A proposed operating criterion might be that the combination of high injection temperatures and radial heat conduction into the shale zone must be such that the rock materials are not heated beyond the levels that would induce dehydration and that gradients sufficient to cause cracking be avoided.

Assuming that interstitial water vaporization is avoided, one must still address the potential for adverse chemical (hydrolytic and redox) reactions that could conceivably lead to degradation of this cylindrical caprock zone, the casing material, and surface facilities. A laboratory experimental

program is currently being initiated to investigate this potential problem and the operating restrictions it could impose on a CAES project. Some of the pertinent reactions are discussed in the geochemical section of this report.

The second mechanism for potential caprock degradation involves vertical heat losses from the storage zone into the overlying caprock. At this interface zone, elevated temperatures, liquid phase water, and free oxygen and carbon dioxide may all be present to some degree. Under these conditions, migration of the water/air interface zone, adverse chemical reactions, and some physical degradation will probably occur. However, the following argument is presented to suggest that these conditions can be expected to terminate after a distance of a meter or so into the caprock.

The permeability in the storage zone is on the order of hundreds of millidarcys. It is overlain by a caprock-zone graduating down to 10^{-4} to 10^{-6} millidarcys (10^{-19} to 10^{-21} m²). It is this caprock storage zone permeability contrast that is important. This fact, coupled with a relatively small delta pressure, results in the air flowing within the storage horizon (path of least resistance) and not within the caprock zone.

This concept suggests that there are no advective mass or heat transfer mechanisms operating within the majority of the caprock. The heated air mass has far less resistance to flow in the radial direction and, therefore, is primarily confined to the storage zone. As a result, the only significant heat and mass transfer mechanisms in the caprock are solid-solid conduction and gaseous diffusion.

Thus, it appears that the temperature profile in the caprock will be reduced essentially to ambient after a meter or so. Various geochemical reactions will occur in the 1- to 2-m zone and a certain percentage of the generated products may get back to the borehole via gaseous diffusion. However, there will be a finite source of these products, specifically in the elevated temperature zone near the borehole, and once the source material has been depleted the reactions will essentially cease. In other words,

degradation of the caprock and production of adverse geochemical products is limited. This "flow by" concept can be extrapolated to any macroscopic fracture flow system as well, so no steady state degradation of the shale material bounding a preferential flow path (fracture) should occur.

One additional point that should be addressed with analytical techniques is the effect of differential expansion. If the expansion of the storage zone relative to the cold caprock is large enough to induce tensile and shear stresses in the caprock, then fracturing might result.

These conclusions are based solely on experience and judgment of the research team and the panel of consultants. To validate this important concept, computer modeling and laboratory experimentation are required.

In conclusion:

- There are no apparent problems associated with the caprock for low temperature storage.
- The potential for physical and chemical degradation of the cylindrical caprock zone interfacing with the wellbore cannot presently be dismissed for high temperature storage.
- At the interface between the storage horizon and the caprock, shale material may experience physical and chemical degradation with elevated temperatures over a small vertical span, but significant deterioration beyond this should not occur.

2.4.4 Geochemical Reactions

The potential for cospatial existence of elevated temperatures, readily available free oxygen and carbon dioxide, liquid phase water, and sandstone or shale deem it necessary to address geochemical reactions and potential consequences to a CAES facility. In essence this is a perfect environment for classical chemical weathering reactions. From a purely chemical standpoint, elimination of the liquid phase water and/or reduction of the temperature to a level below 70 to 90°C would result in an uninteresting system. In other words, the temperature and saturation conditions are key parameters.

The following items are presented as motivation for conducting an experimental geochemical investigation:

- Thermal/chemical alterations could perturb matrix permeability, corrosion potential and/or scaling potential.
- The near-wellbore (critical zone) must be dehydrated to preclude the occurrence of thermal/chemical alterations. To do this, there is a tradeoff between temperature and time, as was previously discussed. As one increases the temperature to dehydrate, the chemical reaction rates also increase.
- During the evaporation process, the concentration of dissolved solids will increase and ultimately all of the constituents will be deposited within the matrix. Compound descriptions and anticipated quantities should be predicted.

This section is devoted to a discussion of some of the potential reactions anticipated in sandstone and shale and the associated consequences.

2.4.4.1 Silicate and Carbonate Hydrolysis

Silicate and carbonate hydrolysis is one of the most important mineral reactions to be considered. It is not uncommon for sandstone to contain silicate minerals composing 20% or more. Hydrogen ions in solution are exchanged for alkali (Na, K) and alkaline (Ca, Mg) cations in the silicate rock minerals. For example, forsterite, a magnesium silicate, can be hydrolyzed to yield free magnesium cations, hydroxide ions and silicic acid.

In addition, the rapid transformation of siliceous minerals to mobile and potentially swellable and dispersive smectite (clay) species may be of concern. This may result in permeability reduction by the plugging of interstices. For example, kaolinite (clay) is produced from a potassium silicate by the following simplified reaction:

These hydrolysis reactions are strongly pH dependent. During compressed air storage, oxygen, carbon dioxide and nitrogen will be introduced. Resulting reactions, such as

will increase the hydrogen ion concentration which in turn increases the degree of silicate hydrolysis.

Hydrolysis reactions are also strongly temperature dependent. In general, the reaction rate doubles for every 10°C temperature increment. In essence, the elevated temperatures tend to greatly accelerate natural chemical weathering reactions. In summary, hydrolysis reactions will result in: 1) an alkaline or at least a less acidic solution, 2) potentially swellable clay minerals and other residual solids, and 3) cations and weak silicic acid in solution.

2.4.4.2 Oxidation/Reduction Reactions

Most geothermal environments tend to be reducing in nature. In a CAES aquifer facility, on the other hand, free oxygen will be readily available. Silicate, carbonate, and sulfide oxidation reaction may thus occur. This can result in the production of insoluble compounds that may plug the reservoir and increased quantities of silicic and carbonic acid. For example, the iron silicate (fayalite) will oxidize to the insoluble ferric oxide and will also produce silicic acid.

In a similar fashion, the manganese carbonate (rhodochrosite) will oxidize to yield insoluble manganese oxide and carbonic acid.

Of special concern is the oxidation of sulfide minerals such as lead sulfide (galena) and iron sulfide (pyrite). Pyrite often occurs in shale material. The oxidation reaction produces sulfate ions which can result in the production of sulfuric acid. It is not unusual to go from a pH of 6.0 to a pH of 1.0 to 2.0 if this reaction takes place.

In summary, oxidation reactions can result in: 1) precipitation of insoluble oxides and hydroxides, 2) production of silicic, carbonic, or sulfuric acid, and 3) further acid production by hydrolysis of any free metal ions.

2.4.4.3 General Corrosion and Scaling

Stress corrosion due to heated chloride solutions and the severe scaling problems associated with silica and calcite are well known in the geothermal industry. How pertinent these processes might be to a CAES facility is not as yet certain. The obvious keys are the liquid saturation and mobility properties within the air bubble where the elevated temperatures occur. In other words, these reactions are highly temperature and saturation dependent. Figure 2-22 shows how the equilibrium constant for quartz (most common sandstone constituent) and amorphous silica dissolution vary with temperature.

2.4.4.4 Smectite (Clay) Swelling

The generation of clay minerals has already been discussed. Some further attention should be given to clay minerals that may exist in the reservoir at the time of initial air bubble development. A property of these compounds is their tendency to swell as the formation water is decreased in salinity. Laboratory tests, utilizing extreme conditions, have resulted in as much as 88% reduction in permeability to water in a sand matrix containing as little as 5% interstitial clay.⁽⁹⁾ In this experiment, the water salinity was varied from the near saturation level to a level approaching that of distilled water. This, therefore, represented a worst case. In a

FIGURE 2-22. Silica Solubility in Water⁽⁸⁾

CAES aquifer a great deal of water will be displaced radially into the saturated zone. Also, any water vapor condensed in the storage zone will be essentially fresh water. Theoretically, this could introduce permeability reduction due to clay swell or dispersion if the smectite constituents are present. However, it must be noted that the CAES aquifer will in most cases already contain water relatively low in dissolved solids. Furthermore, the zone of condensation of fresh water should be sufficiently removed from the borehole and, therefore, a reasonable permeability reduction could be accepted without significant impact. The axially symmetric nature of the problem and the fact that the bottleneck is around the wellbore region accounts for this flexibility. Furthermore, clay swell generally tends to reduce permeability by blocking of the interstices and thus eliminating effective flow paths. It will not significantly reduce porosity because of its low occurrence percentage. In general, smectite production and/or swelling with subsequent reduction in permeability in a zone well removed from the borehole is not considered a major concern at this point.

2.4.4.5 Residual Hydrocarbons

An obvious oxidation reaction is one that includes residual hydrocarbons. Two cases have been considered. First of all, depleted oil fields should be considered with caution. There appears to be no effective way to flush out the residual hydrocarbons. The consequences associated with an explosion in the wellbore or in surface facilities may be sufficient to severely penalize these reservoirs in siting considerations. On the other hand, insitu combustion of the residual oil would be advantageous from the standpoint of reservoir thermal development. Furthermore, it is possible that the combustion products could be flushed from the working air zone during weekly storage cycles. Therefore, additional study is warranted before abandoned oil reservoirs are dismissed as potential CAES sites. Depleted natural gas fields should seriously be considered. It is possible to air-flush such a reservoir, and the oxidation products so generated can be effectively expelled. Monitoring of the gas/air ratio would still be recommended, however, during operation of a CAES facility.

In conclusion:

- The potential for geochemical reactions and the magnitude of the associated consequences cannot be adequately determined based on judgment and the available literature.
- The elevated temperatures and the introduction of gases, such as O_2 and CO_2 , to the storage matrix will result in a change of solid/liquid composition and concentration. Some new compounds may swell or may be insoluble and result in a certain degree of permeability and porosity reduction. Some reaction products in the presence of liquid phase water may result in severe corrosion problems. Finally, solids originally in solution will be deposited within the pores or in the borehole as the water is evaporated from the critical zone. Porosity and permeability degradation due to: 1) deposition of solid constituents, 2) matrix consolidation subsequent to material dissolution, and

3) destruction of casing material or surface facilities by corrosive aqueous solutions must be quantified to some extent. It is clear that the critical zone must be dewatered. For the CAES concept to be viable, it must be demonstrated that one does not suffer an unacceptable penalty in the form of adverse geochemical reactions in the process.

- The reactions are strongly dependent on temperature and the presence of liquid phase water.
- The most interesting reactions are: hydrolysis and/or oxidation of silicates, carbonates, and sulfides, chloride stress corrosion, and silica and calcite scaling.
- Any siting criteria based on chemical composition of the storage zone or the caprock must be identified, i.e., cement should be silica, not calcite for elevated temperature air storage.
- The response of shale containing sulfides, carbonates and organic material should be determined.
- As potential CAES sites, depleted liquid hydrocarbon reservoirs should be considered with caution. Abandoned gas reservoirs appear attractive however.

2.4.5 Physical Response of the Porous Rock

Some attention has been given to the potential for microscopic level spalling and the subsequent production of mobile fine particles. These particulates could potentially block constrictions in the available pore space and lead to decreased porosity and effective permeability. Differential thermal expansion, deterioration of cement bonds between grains, and fragmentation of grains at sharp (high stress) grain contacts could result in collapse of the granular structure itself as well as the production of particles. Conversely, the high mass flow rates and cyclic nature of a CAES facility might clean out the matrix and improve porosity and permeability.

As a result of this concern, any laboratory efforts should address the following potential problems: 1) differential thermal expansion, 2) grain microfracturing and disintegration, and 3) dehydration of integranular cements

with subsequent disintegration and matrix compaction. Elevated temperatures and associated thermal and pressure cycling were initially postulated as driving mechanisms.

Calculations show that thermal expansion of quartz in a sandstone matrix is on the order of 1 to 3%. Therefore, the thermal expansion of grains into pore throats is not considered to be critical. Microcracking resulting from anisotropic thermal expansion might be a problem, however. Elevated temperatures and cycling near the wellbore could conceivably result in creep rupture and material disintegration to a certain degree, however. This particulate problem could have an adverse impact on surface facilities if it were allowed to continue. Fortunately, particulate production is well known to the natural gas industry and engineering countermeasures are available.

The storage matrix will be undergoing rapid (daily and weekly) effective stress cycling at elevated temperatures, and therefore some consideration has been given to the potential for material fatigue failure. The general consensus is that this is not an area for concern. The daily pressure swing will only be on the order of 20 to 80 psi. This type of daily cycling has been experienced on a limited basis in the natural gas storage industry without adverse effects. It is not clear that the matrix could withstand large scale daily swings (hundreds of psi), but the question is basically an academic one since a CAES porous media facility would never be designed for such a large daily pressure variation at a single well.

Pore solutioning, or the removal of cementing material and subsequent matrix compaction, in the presence of a gross nonhydrostatic stress does not appear to be a concern. Unless there is extremely poor communication between zones of preferential flow, no large magnitude nonhydrostatic conditions should be established. However, there is insufficient information to totally dismiss this process.

Finally, inelastic pore closure due to significant reductions in pore pressure and associated increases in effective stress should not take place. A mechanism leading to drastic reductions in pore pressure is not apparent. Due to the relative flow rates of air and water, the air mass will dynamically respond to a pressure gradient faster than the water, but as was

préviously discussed, the air/water interface zone should not physically migrate more than a meter or so in response to daily and weekly pressure cycling. Most of the response will be compression and dilation of the air, water and rock components. In reference to effective stress levels, air injection rates may have to be limited initially to ensure that the pore pressure in the immediate vicinity of the wellbore is not raised to the level of the lithostatic pressure. This negative effective stress coupled with the presence of water could result in hydrofracturing. This may or may not be beneficial.

Although judged not to represent significant problems, it is recommended that the following receive some laboratory experimental and modeling effort:

- the impact of pore pressure and thermal cycling, i.e., grain and cement microfracturing and disintegration,
- the potential for pore solutioning in the presence of a gross nonhydrostatic stress,
- the inelastic deformation of pore geometry due to pore pressure decreases and creep rupture, and
- the potential for thermally induced fracturing of the caprock.

3.0 NUMERICAL ANALYSIS

The objective of the mathematical modeling phase of this study is to establish preliminary stability and design criteria for CAES porous rock reservoirs based on theoretical investigations. Computer codes that incorporate both flow and thermal effects are being used in conjunction with inputs from laboratory testing and literature surveys to define expected reservoir pressure, temperature, and humidity profiles, and to examine the effects of reservoir parameter variation on reservoir performance. Section 3 presents the results of preliminary investigations of flow and thermal effects on the operation of a dry, one-dimensional porous reservoir.

3.1 SUMMARY OF RESULTS

Preliminary investigations of flow and thermal effects on the operation of a dry, one-dimensional (radial) aquifer reservoir were performed. Several reservoir parameters were examined to determine their influence on reservoir operation. Injection of hot air was shown to reduce well deliverability as the reservoir is heated. The influence of well bottom diameter was shown to become important only for high flow rates. The need for moderately high (~ 500 md) reservoir permeability was demonstrated, but the diminishing importance of very high permeability was also observed. It was shown that for a fixed number of wells and given permeability, the deliverability of a reservoir is about the same whether the total storage volume is spread out over a large area or concentrated within a smaller, more porous region. The potential for error in assuming Darcy flow throughout a reservoir was also demonstrated.

Thermal development of a CAES porous rock reservoir subjected to cyclic hot air injection was also examined and shown to occur very slowly. After one year of cycling, the temperature wave did not extend beyond about 100 ft, with high temperatures remaining fairly localized around wells. Temperature cycling is fairly pronounced near the wells but becomes negligible as close as 10 ft from the wellbore. Changes in reservoir properties have little effect on thermal development with the minor exception of the thermal conductivity of the reservoir rock.

3.2 GENERAL EQUATIONS

The most general equations governing the flow of compressible gases in a dry porous solid may be written as follows (see Appendix A for a more detailed discussion of equations and Nomenclature List for symbols):

a. conservation of mass

$$\phi \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \bar{v} = 0 \quad (3-1)$$

b. conservation of momentum

$$\rho \left[\frac{\partial \bar{v}}{\partial t} + \frac{\bar{v}}{\phi} \cdot \nabla \bar{v} \right] + \phi [\nabla P - \rho \bar{g}] = \bar{F} \quad (3-2)$$

c. conservation of energy (fluid phase)

$$\rho \left(\phi \frac{\partial h}{\partial t} + \bar{v} \cdot \nabla h \right) - \left(\phi \frac{\partial P}{\partial t} + \bar{v} \cdot \nabla P \right) - \phi \nabla \cdot K \nabla T - \mu \phi = H_V (T_S - T) \quad (3-3)$$

d. conservation of energy (solid phase)

$$(1 - \phi) \left(C_S \rho_S \frac{\partial T_S}{\partial t} - \nabla \cdot K_S \nabla T_S \right) = H_V (T - T_S) \quad (3-4)$$

3.3 SIMPLIFIED EQUATIONS

Several simplifications were made to obtain more tractable forms of the governing equations. These simplifications are listed below. The validity of these assumptions are discussed in some detail in Appendix A.

1. Viscous dissipation of energy was assumed negligible.
2. Gas kinetic energy was disregarded.
3. Ideal gas behavior was assumed.
4. Darcy or Forchheimer flow was assumed, depending on velocity.
5. Rapid fluid-solid local thermal equilibrium was assumed.
6. Properties of reservoir solid were assumed stepwise constant.
7. Flow was constrained to be one-dimensional radial.

Incorporation of these simplifying assumptions allows the conservation equations to be rewritten in the following forms:

a. conservation of mass

$$\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{P}{T} r v \right) = 0 \quad (3-5)$$

b. conservation of momentum

$$\frac{\mu}{\kappa} v + \beta \left(\frac{P}{RT} \right) |v| v + \frac{\partial P}{\partial r} = 0 \quad (3-6)$$

c. conservation of energy (includes fluid and solid)

$$\frac{\partial T}{\partial t} = \frac{1}{(1 - \phi) \rho_s C_s} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(k_e r \frac{\partial T}{\partial r} \right) + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \frac{1}{r} \frac{\partial}{\partial r} (r P v) \right] \quad (3-7)$$

This one-dimensional radial flow model was used to analyze the dynamics of flow of air injected or produced by a single well in porous rock.

3.4 BOUNDARY CONDITIONS

The number of wells in an aquifer air storage field may reach several hundred and will probably be arranged in a uniform pattern. Since a single well is likely to be surrounded by other wells being pressurized or depressurized at about the same rate, interference between these wells would have the effect of essentially no flow across the boundaries of the cylindrical regions fed by the individual wells (located halfway between adjoining wells, as illustrated in Figures 3-1 and 3-2). Consequently, the outer perimeter of the analytical reservoir model was assumed to represent a no-flow boundary.

During the power production phase, the flow to a CAES system turbine requires throttling to an essentially constant inlet pressure to produce constant power. The air mass flow rate required is approximately proportional to the power produced. Therefore, a constant flow boundary condition at the well was chosen for the analytical model during reservoir discharge (power production phase) to approximate constant power production.

FIGURE 3-1. Single Well Reservoir Within CAES Reservoir

FIGURE 3-2. One-Dimensional Radial Reservoir

Although air inlet conditions to a CAES compressor train are fixed at ambient, the compressor back pressure rises as the reservoir pressure builds during periods of air injection. If the available compression power is fixed, then the mass flow rate will decrease as reservoir pressure rises, assuming that compressor efficiency remains constant. This fact is shown graphically in Figure 3-3, where the ratio of mass flow rate to compression power is plotted as a function of compressor back pressure. From this figure it can be seen, however, that although the mass flow rate decreases with increasing

FIGURE 3-3. Power of Air Compression

back pressure (assuming constant power input), the rate of decrease becomes less for increasingly higher back pressures, with the slope of the curve approaching the horizontal. At storage pressures being contemplated for CAES application, relatively large changes in reservoir pressure (or compressor back pressure) cause relatively small corresponding changes in air mass flow rates. In addition, if a given CAES design maintains a large cushion air mass in the reservoir, total reservoir pressure swings will be small so that a constant mass flow rate corresponds even more closely to a constant power input. The constant flow rate wellbore boundary condition was therefore assumed to reasonably represent a CAES plant during the reservoir charging phase, and was incorporated into the model. During the idle periods of CAES operation there is no flow into or out of the reservoir. Therefore, a no-flow boundary was assumed at the well during these periods.

3.5 LIMITATIONS OF THE MODEL

Many of the complexities of actual underground porous rock air storage reservoirs obviously cannot be treated with the simplified reservoir model presented in this report. Heat and mass flow in real reservoirs will occur in three dimensions and will be influenced by the geometry, rock structure, and moisture conditions prevailing at any given site.

This model best represents a single well located in a relatively shallow, horizontal region of an aquifer air storage field, in which wells reach to the bottom rock and where the effects of gravity on flow are minimal. Some aquifer fields may have sizable regions that fit this description (Figure 3-1) although almost all reservoirs will also have inclined regions to provide closure for trapping the air. Wells on the outer edges of reservoir fields will function differently from those in the center and will not have the symmetrical boundary assumed in the model. If the porous layer is so deep that aquifer water is not expelled from the region between the caprock and bottom rock, but instead the air bubble is trapped between the domed caprock and a water "floor", the vertical mass flow becomes important, and this one-dimensional model less applicable. Air still enters and leaves the wells in

a radial manner, however, and temperature and pressure profiles in the near vicinity of the wells can be reasonably predicted by this simplified model.

Rock structures found in actual reservoirs are not likely to exhibit the homogeneity assumed in this model, but reservoirs will more typically exhibit varying degrees of non-uniformity. There may be regions containing fractured rock (such as joints, faults, fissures, etc.) and/or regions containing inclusions of impermeable materials which perturb or block the flow of fluids. The storage regions may consist of layers of rock of differing porosities and permeabilities, perhaps with impermeable layers sandwiched in between. Reservoir properties, such as permeability, porosity, thermal diffusivity, etc., may vary considerably from region to region throughout the reservoir. These conditions cannot be treated in detail with the symmetrically homogeneous model used here. The model can, however, be viewed as somewhat of an "average" of the many possibilities that exist, and is useful for examining the overall influence and relative importance of parameters influencing reservoir behavior.

Because only one dimension was included in the model, heat transfer through the caprock and bottom of the reservoir are not accounted for. Conduction of heat through these rock formations is very slow, however, and the effects on porous reservoir temperatures will be noticeable only after a relatively long period of time. In addition, this is a boundary effect that is of diminishing importance for thicker porous reservoirs.

The most serious deficiency of this model is its assumption that the reservoir is totally dry. This will never be the case for air storage reservoirs developed within aquifers. Although the bulk of the water is pushed out as the air bubble is developed, as much as 20-25%⁽²⁾ of the water originally in the rock remains within the air zone trapped by capillary forces and in dead-end pores. As discussed in detail in Section 2, the presence of this residual water will significantly affect the flow and thermal development of an aquifer storage field.

In view of the limitations mentioned above, the results presented in this report must be recognized as a first-cut analysis of porous rock air reservoir flow dynamics. They serve primarily to predict the relative influence of various reservoir parameters as well as to provide experience and direction for the development of more realistic analytical and experimental models.

3.6 NUMERICAL MODEL

The development of the finite-difference model for the governing mass and energy transport equations is summarized in this section. Additional details of the development of the difference equations are presented in Appendix B.

3.6.1 Finite-Difference Equations

The difference equations are developed from Equations 3-5 and 3-7 which represent the transport of mass and energy, respectively. The governing equations are written in difference form using an upstream difference technique. The one-dimensional difference equations are fully implicit.

The grid system for the difference equations is presented in Figure 3-4. Variable node spacing is available. Pressures and temperatures are defined at the node points j . A volumetric flux based on the product of a flow conductance and the pressure difference between adjacent nodes is the basis for evaluating transported quantities. Node $NR+1$, located beyond the reservoir boundary, is a "mirror" of node NR . The result is that there is no transport of either mass or energy across the outer reservoir boundary. All computations are based on a vertical grid thickness of one unit.

The development of the difference equation for the mass transport begins from Equation 3-5.

$$\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{P}{T} r v \right) = 0 \quad (3-5)$$

FIGURE 3-4. Finite Difference Grid

A weighted volumetric flux, F , is defined from the product of the radius and velocity, rv . The flux between nodes j and $j+1$ is written as

$$F_j = -C_j (P_{j+1} - P_j) \quad (3-8)$$

The flow conductance, C_j , is based on the difference cell geometry, the viscosity of air, and the permeability of the porous material. The flow calculation can be based on either the Darcy or Forchheimer momentum model by the appropriate calculation of C_j .

Substitution of the flux term transforms Equation 3-5 into

$$\frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \frac{1}{\phi r} \frac{\partial}{\partial r} \left[\left(\frac{P}{T} \right) F \right] = 0 \quad (3-9)$$

The implicit upstream difference form of Equation 3-9 is

$$P_{j,n+1} + \frac{\Delta t T_{j,n+1}}{\phi r_j \Delta r_j} \left[C_{j-1} \left[\left(\frac{P}{T} \right)_{j-1,F+} + \left(\frac{P}{T} \right)_{j,F-} \right] (P_j - P_{j-1}) \right. \\ \left. + C_j \left[\left(\frac{P}{T} \right)_{j,F+} + \left(\frac{P}{T} \right)_{j+1,F-} \right] (P_j - P_{j+1}) \right]_{n+1} = \frac{T_{j,n+1}}{T_{j,n}} P_{j,n} \quad (3-10)$$

where Equation 3-8 has been used for the flux. If the flux at a cell interface is radially outward (i.e., a positive flux), the density terms designated with the subscript F+ are used while the terms identified with the subscript F- are zero. If the flux is negative, the inverse of this convention applies.

The advected property in Equation 3-10 is the density, P/T . The pressures associated with the flux term represent the driving force for the mass transport. For the solution to be conservative in mass and energy, it was necessary to distinguish the two pressures from one another in the model.

The development of the difference equation for the energy transport begins from Equation 3-7.

$$\frac{\partial T}{\partial t} = \left[\frac{1}{r} \frac{\partial}{\partial r} \left(K_e r \frac{\partial T}{\partial r} \right) + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \frac{1}{r} \frac{\partial}{\partial r} (Prv) \right] \frac{1}{(1 - \phi) \rho_s C_s} \quad (3-7)$$

Using a method similar to that for the development of the volumetric flux, Equation 3-8, a heat flux, $K_e r \frac{\partial T}{\partial r}$, is defined from the conduction term. The heat flux between nodes j and $j+1$ is written as

$$H_j = K_j (T_{j+1} - T_j) \quad (3-11)$$

The last term on the right hand side of Equation 3-7, the spatial derivative of Prv , represents the advection of energy and is the dominant term for energy transport. The product of radius and velocity results in the same form as Equation 3-8. In this case, however, the transported quantity is thermal energy rather than mass.

Inclusion of the flux terms transforms Equation 3-7 into

$$\frac{\partial T}{\partial t} = \left[\frac{1}{r} \frac{\partial H}{\partial r} + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \frac{1}{r} \frac{\partial}{\partial r} (PF) \right] \frac{1}{(1 - \phi) \rho_s C_s} \quad (3-12)$$

In finite difference form, Equation 3-12 becomes

$$\begin{aligned}
 T_{j,n+1} = T_{j,n} + \frac{\Delta t}{(1-\phi)\rho_s C_{s,r}} & \left[\frac{1}{r_j \Delta r_j} \left(K_{j-1} T_{j-1} - (K_{j-1} + K_j) T_j + K_j T_{j+1} \right)_{n+1} \right. \\
 & + \left(1 - \frac{C_p}{R} \right) \phi \left(\frac{P_{j,n+1} - P_{j,n}}{\Delta t} \right) \\
 & \left. - \frac{C_p}{R} \frac{1}{r_j \Delta r_j} \left(P_j F_{j,F+} - P_{j-1} F_{j-1,F+} - P_j F_{j-1,F-} + P_{j+1} F_{j,F-} \right) \right] \quad (3-13)
 \end{aligned}$$

The subscripts F+ or F- on the last terms have the same implication as described in the discussion following Equation 3-10.

The method used for solving the coupled Equations 3-10 and 3-13 is outlined in Appendix B.

3.6.2 Code Verification

A computer code (described in Appendix B) was written to simultaneously solve the finite difference Equations 3-10 and 3-13. To promote confidence in the accuracy of the model, several problems were analyzed and the results compared to known solutions. These test problems were of three types:

1. isothermal airflow: pressure profile solution
2. non-isothermal airflow: temperature and pressure profile solutions
3. heat flow: temperature profile solution.

For isothermal flow through a porous medium (assuming Darcy flow) the describing equations can be reduced to the single equation

$$\frac{\partial P^2}{\partial t} + \frac{\kappa}{\mu \phi} \nabla^2 P^2 = 0 \quad (3-14)$$

Except for the non-linearity which appears as the pressure P, this equation has the same form as the conventional heat equation. If the pressure is not changing too rapidly, then the degree of non-linearity will be small and the

equation can be made linear (with minor effect on the results) by making the term $\frac{\kappa P}{\mu \phi}$ constant at some average or representative pressure. In this way the equation becomes analogous to the heat equation for which the solution is well known.⁽¹²⁾ Figure 3-5 compares the linearized analytic (heat analogy) solution to the non-linear numerical computer model solution for the problem of a constant pressure applied to the wellbore of a one-dimensional radial reservoir with isothermal flow. As can be seen, the results are very close.

In one phase of this study, Intercomp Resource and Development, Inc. was given a contract to establish temperature and pressure profiles for certain reservoir conditions. Comparisons of solutions obtained with the PNL model to some of Intercomp's results show good agreement for non-isothermal flow behavior.

The thermal model was also verified by comparison with solutions of heat conduction through a cylindrical wall. To do this, an effectively zero mass flux situation was applied with the temperatures at the inner and

FIGURE 3-5. Comparison of Numerical Solution with Linear Heat Flow Solution

outer boundaries specified. Again, agreement with the known solution was excellent.

3.7 ANALYSIS OF CAES RESERVOIRS

The computer program described in the last section was used to examine the influence of various parameters on CAES reservoir operation. A reference reservoir geometry was specified and analysis was performed by varying reservoir properties and boundary parameters to observe the effects on reservoir operation. Two types of reservoir response were examined: 1) flow response, which relates to reservoir deliverability and can be examined within relatively short time intervals; and 2) thermal response, which is the growth of heated regions around reservoir wells when high temperature air is injected on a weekly CAES cycle over long periods of time. The results of these analyses are presented in the sections that follow.

3.7.1 Flow Analysis

The influence on the flow behavior of a CAES porous rock reservoir was examined for several parameters, including permeability, well diameter, reservoir diameter and porosity, and air injection temperature. In addition, results obtained assuming Darcy flow were compared to results obtained using the more exact Forchheimer momentum equation (Appendix A).

3.7.1.1 Reference Reservoir

A reservoir geometry was established to provide a reference condition from which to observe the effects of changes in reservoir parameters. To approximate flow into a single well within a well field, a cylindrical reservoir 400 ft (122 m) in diameter was chosen (to simulate well spacing of approximately 400 ft (122 m), Figure 3-1) with one-dimensional radial flow from a 7-in. (18-cm) casing. The reference case porosity was set at 20 percent, and the permeability at 500 md. The reservoir temperature was assumed to be initially uniform at 100°F (38°C), and reservoir pressure initially uniform at 735 psi (5070 kPa, 50 atm). Air charging temperature was set at

450°F (232°C) to approximate the highest allowable temperatures from presently available centrifugal compressors.^(a) To simulate daily CAES charging, air was injected for 10-hour periods at constant values of mass flow rate per foot of reservoir thickness, ranging from 0.05 to 0.5 lbm/sec-ft (0.07 to 0.74 kg/sec-m). Figure 3-6 shows the typical behavior of the reservoir as it is charged for a 10-hour period. The top curve plots the well pressure as it increases with time from the initial reservoir pressure of 735 psi (5070 kPa) with a constant mass injection rate of 0.5 lbm/sec-ft (0.74 kg/sec-m). The bottom curve plots the pressure at the outer boundary of the single well reservoir (midpoint between wells if the well is within a large reservoir well field). When flow reaches quasi-steady state, the difference between the well pressure and reservoir boundary pressure remains constant as these two pressures increase at the same rate. If air were being extracted instead of injected, the resulting curves would be approximately mirror images about the reservoir initial uniform pressure level.

3.7.1.2 Permeability

The quasi-steady state difference between the well pressure and the reservoir boundary pressure (as depicted in Figure 3-6) is the driving force necessary to maintain constant flow into a given reservoir. Permeability is the characteristic of a reservoir which quantifies the inverse of resistance to fluid flow; low permeability indicates high flow resistance. Thus, high well pressures are required to inject air into low permeability reservoirs. Figure 3-7 presents the pressure profiles after injection of 0.10 lbm/sec-ft (0.15 kg/sec-m) for a 10-hour period into the reference reservoir for various values of permeability. Figure 3-8 shows the well pressure as a function of time. Similar curves are presented in Figure 3-9 for a flow rate of 0.05 lbm/sec-ft (0.07 kg/sec-m). Although not shown in these figures, the reservoir boundary pressure behaves similarly to that of the lower curve of Figure 3-6, rising at a rate to parallel the well pressure after a short transient.

(a) Axial compressors can withstand higher temperatures on the order of 600°F (315°C), but are generally pressure limited.

FIGURE 3-6. Typical Reservoir Pressure Behavior

FIGURE 3-7. Reservoir Pressure Profiles for Various Permeabilities After 10 Hours of Charging

FIGURE 3-8. Well Pressures During Injection
for Various Permeabilities
[$m = 0.10 \text{ lbm/sec-ft}$
($m = 0.15 \text{ kg/sec-m}$)]

FIGURE 3-9. Well Pressure During Injection
for Various Permeabilities
[$m = 0.05 \text{ lbm/sec-ft}$
($m = 0.07 \text{ kg/sec-m}$)]

It can be seen from these curves that increases in reservoir permeability eventually bring diminishing returns in terms of lowering the required well pressure for a given injection rate. This is shown more dramatically in Figure 3-10 where the quasi-steady state difference between the well pressure and reservoir pressure is plotted as a function of reservoir permeability for several values of air mass flow rate per foot of reservoir depth. Beyond about 2000 md the curves become quite flat, indicating little benefit for increases in permeability.

The merits of at least reasonably high permeability are readily evident, however, from these same curves. For example, suppose it were required that 2000 lbm/sec (900 kg/sec) of air be injected into (or produced from) a CAES reservoir, with a maximum pressure drop between well bottom and reservoir of 20 psi (140 kPa). If the available reservoir has a permeability of 500 md, then, according to Figure 3-10, the flow rates must be less than 0.10 lbm/sec-ft (0.15 kg/sec-m). If the reservoir is 50-ft (15-m) thick, then the required number of wells is

$$2000 \frac{\text{lbm}}{\text{sec}} \times \frac{\text{sec-ft}}{0.10 \text{ lbm}} \times \frac{\text{well}}{50 \text{ ft}} = 400 \text{ wells} . \quad (3-15)$$

If the reservoir thickness were 100 ft (30 m), the number of required wells would be reduced to 200. If, however, the permeability were only 250 md, then the maximum flow rate would be 0.05 lbm/sec-ft (0.07 kg/sec-m) (from Figure 3-10), and the number of wells required for a 100-ft (30-m) thick reservoir would increase to 400. Conversely, if the permeability were 1100 md, the flow rate could be as high as 0.20 lbm/sec-ft (0.30 kg/sec-m) and only 100 wells would be required for the 100-ft (30-m) thick reservoir.

Although prevailing economic factors will determine the optimum number and spacing of wells for a specific CAES installation, the need for reasonably high permeability underground structures is evident, particularly if the reservoir is thin. But the diminishing importance of very high permeability (>2000 md) structures should also be noted.

FIGURE 3-10. Driving Pressure Difference Versus Permeability for Various Mass Flow Rates

3.7.1.3 Well Diameter

Figure 3-11 is a plot of well pressure versus time for injecting 0.1 lbm/sec-ft (0.15 kg/sec-m) of air for 10 hr into the reference reservoir through wells of various diameters. After a relatively short transient, quasi-steady state injection conditions are reached, and pressure rises at a constant rate. Figure 3-12 shows the final quasi-steady state difference between well pressure and reservoir boundary pressure as a function of well diameter and for several mass flow rates. As can be seen, the well diameter has little effect on the required injection pressures at low flow rates but becomes of increasing importance as flow rates rise. This is another factor to be considered in optimization of a CAES plant design, although the effect of well shaft diameter on frictional losses through the shaft to the surface may be more constraining on design than its effect on flow resistance to the reservoir.

3.7.1.4 Porosity and Reservoir Diameter

The volume available for air storage in a radial porous rock reservoir is (neglecting well volume):

$$\text{Volume} = \phi \pi \frac{D^2}{4} s \quad (3-16)$$

where ϕ is porosity, D is reservoir diameter, and s is thickness. The storage volume fed by a single well thus consists of an areal extent of pore space within the solid medium, and can be increased by increasing porosity, thickness, or the effective single well reservoir diameter (well spacing). Figure 3-13 shows the effect of changing porosity (and thus volume) on the pressure required to inject 0.1 lbm/sec-ft (0.15 kg/sec-m) of air into the reference reservoir (assuming all other reference parameters constant). The effect on injection pressure is obvious: as the porosity (volume) is decreased the pressure rises at an increased rate as a constant mass flow is maintained.

FIGURE 3-11. Well Pressure During Injection
for Various Well Diameters
[$m = 0.10 \text{ lbm/sec-ft}$
($m = 0.15 \text{ kg/sec-m}$)]

FIGURE 3-12. Driving Pressure Difference Versus Well Diameter for Various Mass Flow Rates

FIGURE 3-13. Well Pressure During Injection
for Various Porosities
[$m = 0.1$ lbm/sec-ft
($m = 0.15$ kg/sec-m)]

Very similar curves are shown in Figure 3-14, where porosity is held constant at 20% and reservoir diameter is varied to obtain reservoirs having total volumes exactly equal to the 400-ft (122-m) diameter reservoirs with the various porosities represented in Figure 3-13.

The difference between these two sets of injection curves is very small. This indicates that the driving pressure difference between the well and the reservoir outer boundary necessary to maintain a given flow rate is about the same, whether the total storage volume is spread out in a large diameter reservoir or concentrated within a higher porosity region closer to the well. For example, the quasi-steady state difference between the well pressure and the outer boundary pressure of the 282-ft (86-m) diameter (20% porosity) reservoir is 18.78 psi (129.5 kPa), compared to 19.38 psi (133.6 kPa) for the 400-ft (122-m) diameter (10% porosity) reservoir having the same total volume. Since the permeability is the same for both cases, the additional flow resistance in the larger diameter reservoir is due only to the larger radial distance through which some of the flow must travel. Pressure gradients in this outer region are very small and velocities are very low, so that the effect of increased resistance is almost negligible on the overall operation of the reservoir.

3.7.1.5 Injection Temperature

Air charged into a reservoir at high temperatures is more viscous than cooler air (see Appendix D) and hence a higher pressure difference between well and reservoir is required to maintain a desired flow rate. It is true that hot air injected into a cooler porous rock reservoir will rapidly cool to very near the rock temperature, and, for the most part, flow will be nearly isothermal. However, as shown in Figure 3-15, injection of hot air does require higher pressure differences between well and reservoir, even if the reservoir is initially cool, as is the case for the bottom four curves of the figure. If hot air is cycled into the reservoir over long periods of time the rock temperature will gradually rise so that high temperature flow occurs in an increasingly larger region growing away from the well. The top curve of

FIGURE 3-14. Well Pressure During Injection for Various Reservoir Diameters
 $[m = 0.1 \text{ lbm/sec-ft}]$
 $[m = 0.15 \text{ kg/sec-m}]$

FIGURE 3-15. Well Pressure During Injection for Various Injection Temperatures
 $[m = 0.1 \text{ lbm/sec-ft}]$
 $(m = 0.15 \text{ kg/sec-m})]$

Figure 3-15 shows the well pressure required to inject 450°F (232°C) air into the reference reservoir after it has "aged" for a period of several years (see section on thermal response). It is seen that injection of hot air will reduce deliverability as the reservoir is heated. This is due to the higher air temperatures and, thus, higher viscosities that influence larger regions of the flow field. This continuous increase in flow resistance must be accounted for when designing CAES facilities which utilize hot air storage.

3.7.1.6 Darcy Versus Forchheimer Flow

The Darcy flow assumption stipulates that flow velocity increases proportionally with increased pressure drop. The simplicity of this assumption has led to its widespread use in simulation of porous reservoir flow, and its accuracy in many instances is well documented. It has been found, however, that at high flow rates inertia effects become important and increases in velocity cease to be proportional to changes in pressure drop (see Appendix A). Pressure drop instead becomes a quadratic function of velocity (Forchheimer flow).

The relative importance of the inertia effects is best expressed by the local Reynold's number defined as $Re = (\rho|v|)(\beta\kappa)/\mu$ in which $\beta\kappa$ may be interpreted as a characteristic length of the porous medium. The magnitude of the Reynold's number is a direct indication of deviation from Darcy flow. It arises directly from writing the Forchheimer momentum equation (Equation 3-6) in the following form:

$$\frac{\partial P}{\partial r} = - \frac{\mu v}{\kappa} \left[1 + \frac{\rho|v|(\beta\kappa)}{\mu} \right] = - \frac{\mu v}{\kappa} [1 + Re] \quad (3-17)$$

As the Reynold's number becomes small, the flow behaves according to Darcy's Law, $\frac{\partial P}{\partial r} = - \frac{\mu v}{\kappa}$.

The error that may occur by assuming Darcy flow is evidenced in Figure 3-16, where well pressure is plotted for a 10-hour period of charging into the reference reservoir. It is seen that for low injection rates (below about 0.1 lbm/sec-ft (0.15 kg/sec-m) for the reference reservoir), the Darcy assumption

FIGURE 3-16. Comparison of Darcy and Forchheimer Flow for Various Mass Flow Rates

produces results closely matching the curves obtained from inclusion of Forchheimer's quadratic term in the momentum equation. For higher flow rates the error of the Darcy assumption may become important.

The Darcy and Forchheimer curves match reasonably well for a flow rate of 0.1 lbm/sec-ft (0.15 kg/sec-m) into the reference reservoir. However, Figure 3-17 indicates that, for this same flow rate, the Darcy and Forchheimer results will disagree if the value of the reservoir permeability is decreased. Similar trends can be shown for decreases in well diameter, as in Figure 3-18. Thus, if more accurate results are desired, care must be taken to include the Forchheimer assumption whenever flow conditions warrant.

3.7.2 Thermal Response

To observe the process of heating a CAES porous rock reservoir subjected to hot air injection, a weekly injection-production cycle was applied to the reference reservoir for a period of 10 years. In addition, the effects of changing various reservoir parameters on the thermal response of the reservoir were examined by varying the individual parameters (including permeability, porosity, well spacing, rock thermal conductivity, rock thermal capacity, air storage pressure, and percentage of air mass cycled) one at a time from the reference condition, and applying the weekly air cycle for a period of one year. Thermal response of the reservoir was slow, and in most cases even a year was insufficient time to show significant deviation from the reference solution for reasonable changes in reservoir parameters. The trends, however, were observable. The results are discussed in the following sections.

3.7.2.1 Weekly CAES Cycle

The system load characteristics of any given electrical utility are unique, and design of a CAES system would be specific to the needs of the system it would serve. A schedule of power generation mix for a typical utility might be as shown in Figure 3-19, where the peak regions of the curve could represent that power to be supplied by CAES installations. It has been predicted that a CAES plant to serve a typical midwest utility might

FIGURE 3-17. Comparison of Darcy and Forchheimer Flow for Various Permeabilities
 $[m = 0.1 \text{ lbm/sec-ft } (m = 1.5 \text{ kg/sec-m})]$

FIGURE 3-18. Comparison of Darcy and Forchheimer Flow for Various Well Diameters
 $[m = 0.1 \text{ lbm/sec-ft } (m = 0.15 \text{ kg/sec-m})]$

FIGURE 3-19. Typical Power System Weekly Load

have approximately a 10- to 12-hour daily power generation period and would derive about 40% of its energy from the power grid over the weekends.⁽¹³⁾

These criteria were used to specify a hypothetical weekly CAES air cycle to examine the long-term effects changing various parameters might have on reservoir performance and thermal development.

This idealized weekly cycle is shown in Figure 3-20 for a reservoir with a maximum air mass content of $M_{\max}$. Already specified for the cycle is $\psi = 0.40$, which is the fraction of energy supplied to the CAES plant on the weekend. The other variable, λ , is the fraction of the total air mass which is cycled. This fraction, like any other specified variables, would be determined for a particular site from economic and operational considerations. Bush, et al.,⁽¹³⁾ found that for a CAES plant conceptually designed for a site near Brookville, IL, cycling about 12% of the total stored air mass in the reservoir was optimum. Katz and Lady⁽³⁾ designed cycling to be about 9% if a Michigan reef (Belle River Mills) were used. A value of less than 7% was calculated for a site designed using the Galesville Aquifer near Media, IL. Although this is a function of several site-specific factors, 12% cycling ($\lambda = 0.12$) was chosen as a reasonable reference case value for this study. Equal daily charging and discharging times of 10 hours each were specified. In developing this weekly cycle, an assumption was made that the air temperature in the reservoir was uniform so that the air mass in the reservoir was directly proportional to the spatial average of reservoir pressure. The term $M_{\max}$ in Figure 3-20 could therefore be replaced by $P_{\max}$ (representing the maximum average reservoir pressure) to convert the figure to a representation of the spatial average reservoir pressure throughout the week. Although injection of hot air into the reservoir will affect the accuracy of this uniform temperature assumption, the bulk of the air within the reservoir will remain cool due to the very high thermal inertia of the rock mass, and any deviation from the original average pressure cycle will be small and gradual.

FIGURE 3-20. Idealized Weekly CAES Cycle

- In order to prevent continued growth or shrinkage of a developed aquifer reservoir, it is necessary that

$$\int_{t=0}^{t=1 \text{ week}} [P(t) - P_0] dt \approx 0 \quad (a) \quad (3-17)$$

where $P(t)$ is spatial average reservoir pressure, P_0 is initial (before bubble growth) aquifer pressure, and t is time. Integrating the weekly pressure cycle curve (Figure 3-20) and solving for P_0 yields

$$P_0 = (1 - 0.6275 \lambda + 0.0466 \frac{\lambda}{\psi}) P_{\max} \quad (3-18)$$

For the weekly cycle reference case, P_0 was arbitrarily chosen as 50 atm (5070 kPa), or 735 psi. This results (for $\lambda = 0.12$ and $\psi = 0.40$) in a maximum reservoir pressure on Monday morning of $P_{\max} = 783$ psi (5400 kPa), and a minimum reservoir pressure on Friday evening of 689 psi (4750 kPa).

The reference geometry of the single well reservoir for weekly cycling is the same as that for short term studies, i.e., a cylindrical reservoir 400 ft in diameter with one-dimensional radial flow from a 7-in. (18-cm) well. The reference case porosity is 20%, permeability is 500 millidarcys, and the reservoir temperature is assumed to be initially uniform at 100°F (38°C). The rock thermal conductivity is assumed constant at 1.25 Btu/hr-ft-°F (216 W/m-°C). Rock density and specific heat are 165 lbm/ft³ (2643 kg/m³) and 0.22 Btu/lbm-°F (921 J/kg-°C), respectively (see Appendix C).

In order to follow the designated weekly cycle within the maximum and minimum pressures of 783 psi and 689 psi, the air injection and production rates were calculated to be 0.119 lbm/sec-ft (0.177 kg/sec-m) and 0.158 lbm/sec-ft (0.235 kg/sec-m), respectively. The final weekly reservoir pressure cycle used as reference case for examining long-term effects of reservoir thermal development is given in Figure 3-21.

(a) In the natural gas storage industry, where cycles are annual rather than weekly, this criterion is known as the pound-day concept and integration is for one year.⁽³⁾

FIGURE 3-21. Reference Weekly Cycle (Neglecting Heating Effect)

3.7.2.2 Thermal Development

As the weekly CAES cycle is applied to the reference reservoir, the well pressure and the reservoir pressure at the outer perimeter respond according to Figure 3-22 during the first week. The maximum well pressure occurs on Sunday at 4:00 p.m. and reaches a value of 816 psi (5630 kPa). The minimum well pressure, 660 psi (4550 kPa), is reached at the end of the final production period on Friday at 6:00 p.m. The reservoir pressure responds according to the cycle described in the last section ($P_{\max} \approx 783$ psi (5400 kPa), $P_{\min} \approx 689$ psi (4750 kPa)).

The reservoir temperature is initially uniform at 100°F (38°C). Air is injected at 450°F (232°C) and extracted at whatever temperature is available after heat exchange with the reservoir rock. Figure 3-23 shows the first weekly cycle of temperature at the well-reservoir boundary in addition to various reservoir locations within the vicinity of the well. Large temperature swings characterize the well-reservoir boundary. Injection air heats the rock next to the well to 450°F (232°C), but the temperature drops quickly as air is produced. The temperature of the extracted air reaches a minimum of 244°F (118°C) at the end of the last weekly extraction period on Friday evening.

This large amplitude temperature cycling damps out rapidly as one moves away from the well, and at a radius of less than 10 ft (3 m) is almost completely damped, with temperature rising slowly but with little daily cycling.

After one year of cycling the temperature curves are those shown in Figure 3-24. Temperature swings at the well have decreased and average reservoir temperatures have risen. The minimum extraction temperature (occurring again on Friday evening) has increased to 336°F (169° C). Ten years of cycling produces the curves of Figure 3-25, with the minimum extraction temperature having risen to 365°F (185°C).

If the minimum air extraction temperature is plotted as a function of time, Figure 3-26 results, showing that the greatest increase occurs within the first year. Further increases in minimum extraction temperature are very gradual.

FIGURE 3-22. Weekly Pressure Cycle

FIGURE 3-23. Reservoir Temperature Cycle at Various Locations for First Week

FIGURE 3-24. Reservoir Weekly Temperature Cycle at Various Locations After One Year (52 Consecutive Weeks)

FIGURE 3-25. Reservoir Weekly Temperature Cycle at Various Locations After Ten Years (52 Consecutive Weeks)

FIGURE 3-26. Minimum Air Extraction Temperature
(Initial reservoir temperature =
100°F, air injection temperature =
450°F)

Temperature profiles in the reservoir are shown in Figure 3-27 after cycling for the time periods shown. Due to the direct contact between hot injected air and the porous rock, and the large thermal capacitance of the rock, the thermal energy carried into the reservoir by the hot air is absorbed in the rock close to the well and transmission into the outer regions is slow. Because of the relatively low thermal conductivity of the rock, temperatures in the regions away from the reservoir rise very slowly, and the higher temperatures remain fairly localized around the wells.

FIGURE 3-27. Thermal Growth of Reservoir

One more result is observed as the average reservoir temperature rises. Since the reservoir volume of the one-dimensional model is held constant, and the amount of air mass injected is equal to that produced, the rise in average reservoir temperature causes a corresponding increase in reservoir pressure. Figure 3-28 shows the increase in maximum and minimum well pressure for constant injection and production flow rates over the 10-year period. In actual practice, the average pressure could not be allowed to increase in an aquifer without causing further growth of the reservoir. This could be easily controlled, however, by lowering the amount of air injected into the reservoir during one cycle. In actual operation, a CAES plant would be required to follow the system peaking load with adjustments, such as reservoir pressure level, being continually made.

FIGURE 3-28. Pressure Rise Due to Thermal Development

3.7.2.3 Response to Parameter Variation

The sensitivity of the thermal behavior of the reservoir to adjustments in several reservoir parameters was examined by changing parameters one at a time from their reference value and applying the weekly air cycle for a period of one year. The results were then compared with those of the reference reservoir after one year. The temperature and pressure profiles are so similar to those of the reference case discussed in the preceding section that for most cases they are not given here. The minimum extraction temperature (an indication of thermal growth) and the maximum and minimum average reservoir pressures after one year are presented in Table 3-1 for various parameters. It is seen that the only parameters having any noticeable effect on extraction temperature after one year are mass flow rates and the rock thermal conductivity. As might be expected, increasing the flow increases the rate of thermal growth in the reservoir. Increased thermal conductivity causes energy to dissipate away from the well more rapidly so that temperatures near the well are decreased and extraction temperatures are lower.

Only a small change in minimum extraction temperature occurred when the rock thermal capacity was lowered 25%. Figure 3-29 shows that the rock temperature throughout most of the reservoir was higher for the lower thermal capacity rock reservoir. The well boundary temperature was slightly less. Temperature gradients were reduced.

The temperature wave did not reach the outer radius of even the smallest diameter reservoir in the one-year period studied. Thus all of the included reservoirs are, in effect, infinite with regard to thermal growth. Extraction temperatures remained unaffected by changes in reservoir diameter.

Changes in porosity and reservoir diameter are direct changes in reservoir volume and, thus, the reservoir pressure. Their effects (as well as those of simply changing the average storage pressure) on the minimum extraction temperature are small. Also, the permeability of a given rock reservoir has no effect on the thermal growth rate.

TABLE 3-1. Minimum Extraction Temperatures and Reservoir Pressures After One Year of CAES Cycling for Various Parametric Conditions

Parameter with Reference Value	Off-Reference Condition	Minimum Extraction Temperature, °F(°C)	Maximum Reservoir Pressure, psi (kPa)	Minimum Reservoir Pressure, psi (kPa)
Reference Solution	--	337.12 (169.51)	791.5 (5457)	696.3 (4801)
Permeability	200	337.11 (169.51)	791.5 (5457)	696.3 (4801)
500 md	2000	337.13 (169.52)	791.5 (5457)	696.3 (4801)
Porosity	0.10	336.69 (169.27)	839.3 (5787)	649.2 (4476)
0.20	0.30	337.82 (169.90)	776.3 (5352)	712.6 (4913)
Average Storage Pressure	20 (2030)	337.13 (169.52)	345.7 (2384)	250.7 (1729)
50 atm (5070 kPa)	80 (8100)	337.09 (169.49)	1237.2 (8530)	1141.9 (7873)
Reservoir Diameter	282 (86)	338.36 (170.20)	849.4 (5856)	656.5 (4526)
400 ft (122 m)	490 (149)	336.96 (169.42)	772.6 (5327)	709.4 (4891)
Mass Flow Rates	0.050; 0.066 (0.074; 0.098)	330.66 (165.92)	759.9 (5239)	720.4 (4967)
Inject 0.119 lbm/sec-ft; Produce 0.158 lbm/sec-ft (0.177 kg/sec-m; 0.235 kg/sec-m)	0.298; 0.395 (0.443; 0.588)	341.89 (172.16)	863.7 (5955)	621.1 (4282)
Rock Thermal Conductivity	0.313 (0.542)	342.09 (172.27)	790.4 (5450)	695.3 (4794)
1.25 Btu/hr-ft-°F (2.16 W/m-°C)	3.13 (5.42)	328.30 (164.49)	793.3 (5470)	697.9 (4812)
Rock Thermal Capacity ($\rho_s C_s$)	30 (2.01)	336.93 (169.41)	794.0 (5474)	698.4 (4815)
39.1 Btu/ft ³ -°F (2.62 MJ/m ³ -°C)				

FIGURE 3-29. Reservoir Temperature Profiles After One Year for Two Values of Rock Thermal Capacity

Changes in most parameters, within reasonable limits, did not significantly change the minimum extraction temperature within one year, except to indicate the direction of change. The thermal capacitance of the rock is so large in comparison to the air that the effects of changes in most parameters are masked.

3.8 RECOMMENDATIONS FOR CONTINUED STUDY

Due to the limited nature of the one-dimensional dry reservoir model, the results presented in this report are considered to be preliminary to more detailed studies presently underway or planned. Among the problems which will be addressed in the next phases of analytical study are the following:

1. The dynamics of non-radial heat and mass flow. Extension of the flow model to more than one dimension will permit examination of such things as:
  - natural convection within the reservoir,
  - the interaction of wells in a multiple well field,
  - heat and mass losses through the reservoir bottom and caprock,
  - performance (deliverability, thermal development, etc.) of asymmetric reservoirs, and
  - the effects of directional permeability on reservoir operation.
2. The effects of porous structure heterogeneity on flow dynamics. Non-uniformities in reservoir rock may cause preferential airflows (fingering and/or wafering) affecting well deliverability as well as reservoir heating profiles and thermal and mechanical stress development in the rock structures.
3. Bubble development and movement of the water front surrounding the air bubble. The optimal rate and manner of bubble growth will directly affect the economics of compressed air storage. Cyclic movement of the developed air bubble/water front interface could conceivably affect well deliverability (depending on reservoir properties) as well as contribute to possible geochemical reactions and undesirable product generation and transmission.
4. Effect of hot air injection on well integrity. The thermo-mechanical response of steel air storage well casings and cement grouting exposed to possible elevated and cyclic air temperatures is important because it affects the suitability of porous underground media for hot compressed air storage. For the same reason, the problem of heat transfer into the surrounding earth between the reservoir and the surface is also important.
5. Heat and mass transfer through the caprock. This will affect not only the thermal development of the heated reservoir, but may also damage caprock impermeability.

6. The presence of water vapor and liquid phases in the reservoir and their effects on flow dynamics and thermodynamics. Rough computer calculations indicate that the presence of moisture left in the air storage zone after bubble development may substantially retard the development of the heated region around the well when hot air is injected. Incorporation of moisture effects in the reservoir flow model will be necessary to more carefully and completely analyze this problem.
7. Drying of the air storage zone. Preliminary calculations indicate that drying of the air storage zone (which may be necessary from a geochemical standpoint if air is stored hot, as well as a flow standpoint) may take several years to accomplish, possibly requiring large scale surface dehydration equipment, such as refrigeration facilities or cooling towers. There is certainly motivation for more detailed study of this issue.
8. Stresses and stress fluctuations in the rock matrix due to temperature and pressure gradients and cycling. Mechanical damage to the reservoir structure due to severe stress conditions may result in serious flow obstructions, or to carryover of sand particles to surface machinery with harmful results. This is an important problem which will require thorough analysis. Computer codes are presently available which, when coupled to the flow models, are capable of performing this stress analysis work.

These are not meant to represent all of the problems that may arise in the use of porous media reservoirs for CAES. They do, however, represent current thinking as to those of most importance which will require thorough analysis in order to solve. All of the analytical studies are being integrated, when possible, with the experimental studies of CAES aquifer reservoirs.

4.0 LABORATORY TESTING

The work done on this project in FY-1977 is the first step toward determining the effects of cyclic ventilation with heated, compressed air on rocks. The rocks of chief interest are porous sandstones and their associated cap-rocks. Some of the latter may also be suitable hosts for cavern storage.

Work is directed toward establishing procedures and criteria for identifying suitable sites for compressed air energy storage, and toward identifying geological parameters to be monitored in field tests and in operating systems.

The testing program for FY-1977 has sought to determine the effects of compressed air cycling on physical properties and microstructure of porous rocks, without the axial or confining loads prevailing underground. This, then, has been an effort to determine some baseline effects.

The main purpose of the 1978 work will be to determine the effects of compressed air cycling under confined compression, to simulate in-situ conditions. Work from both FY-1977 and -1978 will produce useful information on property changes that could adversely affect long- and short-term storage and flow of compressed air, mechanical stability of the aquifer and caprock, and the integrity of the rock enclosing the drill. Some of the data on cap-rock will be applicable to cavern storage.

4.1 EQUIPMENT DEVELOPMENT

Three systems for pumping air through rock specimens of NX diameter (2-1/8 in. and 54 mm) were developed:

- manual cycling system
- automatic cycling system
- simple blow-through system.

4.1.1 Manual Cycling System

The first, a modified triaxial test chamber for manually cycling jacketed NX cores with heated air, is shown in Figure 4-1. In the figure, air input is to the right and air outlet is to the left. The upper diagram

FIGURE 4-1. Manual Cycling Equipment

(forward flow) shows airflow in specimen from right to left. The lower diagram (reverse flow) shows airflow in the specimen from left to right. This setup accepts specimen cores up to 6 in. long. The specimen is circumferentially encased in an impermeable jacket on which confining pressure acts. Specimens shorter than 6 in. can be ventilated by inserting tubular spacers of suitable length and diameter.

Air at the heater is at 200 to 240°F and up to 115°F in the specimen chamber. Blown sediment can be collected at the air outlet. Confining pressure up to 100 psig has been used. Input air pressure is 45 psig. Flow rates up to 80 scfh through 1/4-in. tubing have been measured. Cycling is accomplished with a simple four-way valve.

This system, built as a backup to the automatic cycling system, is relatively simple to operate. Although it does not use air pressures as high as those that will be used in an operating system in-situ, pressure gradients and flow rates are probably comparable. The chamber will take up to 10,000 psi, so the heart of the system is not the limiting factor. Relative changes in permeability can be monitored continuously. With a few refinements, this system will be capable of determining absolute permeabilities with fairly good precision.

Specific details of the manual cycling equipment are shown in Figures 4-2 through 4-7. All major components and most tubing are wrapped in glass-wool insulation.

The manual cycling system was used to generate the data discussed in this section.

CONTROL PANEL WITH PRESSURE GAUGES
SHOWING PRESSURES AT EACH END OF
SPECIMEN AND CONFINING PRESSURE
(CENTER). VALVES CONTROL FLOW AT
EACH END OF SPECIMEN; SWITCHING
VALVE FOR REVERSING FLOW IS BEHIND
"D" CARD.

AIR HEATER (COPPER TUBING WRAPPED
IN HEATING TAPE), WITH THERMOMETER
AND PRESSURE RELIEF VALVE.

FLOW
METER

AIR TANK FOR PROVIDING CONFINING
PRESSURE. THIS IS RECHARGED WITH
THE BICYCLE PUMP IN THE LEFT REAR.

SPECIMEN CHAMBER. PYROMETER
TO RIGHT, ON TABLE, SENSES AIR
TEMPERATURE AT ONE END OF SPECIMEN

FIGURE 4-2. Manual Cycling System

FIGURE 4-3. Close-Up of Manual System Heating Unit (B)

FIGURE 4-4. Close-Up of Manual System Control Panel (D)

FIGURE 4-5. Close up of Manual System Specimen Chamber (C)

FIGURE 4-6. Close-Up of Specimen Jackets for Manual System

FIGURE 4-7. Close-Up of Air Tank (E) for Providing Confining Pressure, Manual System

4.1.2 Automatic Cycling System

The automatic cycling system is schematically represented in Figure 4-8. Airflow is from the bottled air source on the left to the manifold, right-center. Alternating flow through the specimens is controlled by the differential pressure monitor. The temperature sensor of the heat chamber interrupts the cycle when temperature drops to minimum permissible level and restarts the cycle when a pre-set upper temperature is reached. Specimens are circumferentially encased in impermeable jackets on which confining pressure acts. The test chamber can accommodate one to four specimens. Specimens shorter than 5 in. and be ventilated by inserting tubular spacers of suitable length and diameter.

All major components of this system were constructed by the researchers. These include the sample chamber, back-pressure chamber, manifold and heating chamber, as well as the control panel. However, the system was not completed in time to generate data for this report; the vendor has still not provided the differential pressure sensor or automatic valves. Fortunately, almost all and perhaps all of this system can be used as is in FY-1978 work; in fact, confining pressure will be comparable to horizontal stresses in many aquifers. When this system is actually completed, it will be used to generate FY-1977 data as well as FY-1978 data, without impeding FY-1978 progress. Figures 4-9 through 4-12 provide close-up details of the automatic cycling system.

4.1.3 Simple Blow-Through System

The third system consists of a short piece of tubing, with pressure gauge attached, into which NX core is inserted, secured by a washer and bolts at the outlet end. Shown in Figure 4-13, this system uses the lab compressed air (45 psig). Plastic tape is wrapped around the specimen's circumference to ensure end-to-end flow.

FIGURE 4-8. Automatic Cycling System

FIGURE 4-9. Automatic Cycling Equipment During Construction.
A - Heating chamber
B - Manifold
C - Specimen chamber
D - Back-pressure chamber

FIGURE 4-10. Specimen Chamber, Automatic System

FIGURE 4-11. Specimen Jacket with 5-in. NX Specimen,
Automatic System

FIGURE 4-12. Heating Elements for Heat Chamber

FIGURE 4-13. Simple Blow-Through System.

- A - Pressure gauge
- B - Washer and bolts
- C - Specimen

This system is simple and permits observation of the downstream rock surface as air moves through it. Specimen length is not critical, so this setup is useful for working with stubs unsuitable for other work. Very high flow rates can be achieved with short specimens of high permeability. Specimens can be quickly checked here for pore contaminants imbibed during their preparation. However, this system cannot provide flow property data. It can be used to quickly study microstructure changes resulting from unidirectional flow. Cyclic flow can be simulated by reversing the specimen inside the tube.

4.2 SPECIMENS

The rock specimens studied to date are:

- Bedford (Salem, Spergen) Limestone. Mississippian; generally massive, medium- to fine-grained, fossiliferous, oolitic limestone; white to light-gray to buff. Indiana, Illinois, Kentucky, Missouri and Iowa. Material used from standard ARPA-USBM rock suite.

- Berea Sandstone. Mississippian; light gray to drab, medium- to fine-grained sandstone with silica and clay cement. Ohio, Michigan, Pennsylvania, Kentucky, West Virginia. Material used from standard ARPA-USBM rock suite.
- Jordan Sandstone. Cambrian; Unfossiliferous sandstone; light gray to buff. Minnesota, Wisconsin, Iowa, Illinois. Collected north of Black Earth, Wisconsin.
- Platteville Limestone. Ordovician. Blue to gray to buff limestone, with some shaly layers at base. Wisconsin, Minnesota, Iowa, Illinois. Collected near Verona, Wisconsin.
- St. Peter Sandstone. Ordovician. White to yellow red sandstone, very clean, soft to hard. Minnesota, Michigan, Iowa, Illinois, Missouri, Indiana, Ohio, Kentucky, Kansas, Arkansas, Oklahoma. Collected near Verona, Wisconsin.

The Bedford and Berea were cored from 1-ft cubes from the ARPA-USBM standard rock suite. These were selected partly because the properties of these rocks have been studied intensively and good base data are available for comparison.

Between 500 and 600 lb of St. Peter, Platteville, and Jordan were collected in blocks weighing from 30 to 80 lb. Figure 4-14 shows St. Peter and Platteville specimens cut parallel to bedding (parallel to the ruler) and perpendicular to bedding. In the figure, the two specimens at the left include the contact between the St. Peter and the overlying Platteville. The two of St. Peter specimens at the right show conspicuous iron oxide banding, which undoubtedly results in anisotropic permeability.

Specimens exemplifying contrasting appearances from differences in composition and orientation are shown in Figure 4-15. From left to right in the foreground are Berea sandstone, Bedford (Salem) limestone, St. Peter sandstone, and St. Peter sandstone and Platteville limestone (contact parallel to cylinder axis).

FIGURE 4-14. Typical Specimen Cuts

FIGURE 4-15. Specimens Illustrating Contrasting Appearances

The St. Peter and Platteville, especially the shaly base of the latter, provide a good example of an aquifer-caprock pair.

ASTM specifications were used for both specimen preparation and mechanical property testing.

4.3 PROPERTY TEST RESULTS

The results presented in Tables 4-1 through 4-3 convey all of the numerical experimental data developed as of mid-September 1977. More data are currently being generated.

Table 4-1 shows results of property tests obtained at UWM, compared to results obtained elsewhere. Two members of the ARPA-USBM standard rock suite were used for this purpose. The UWM tests were run blind; that is, the operators were unaware of the data from other sources.

There seems to be fairly good agreement throughout. Some of the larger discrepancies merit further study. For example, although the mean USBM value for Young's modulus of the Bedford is notably smaller than the three UWM values, one of the three USBM values used to compute their mean is very close to the three UWM values and slightly larger than any.

The heat capacity data were obtained using a calorimeter retired from freshman physics labs. A precision drop calorimeter will be purchased for this work in the future.

The results of manual cycling are presented in Table 4-2. Perhaps the most important conclusion to be drawn from this work is that no relative changes in permeability were detected.

Specimen temperatures and absolute pressures were not as high as desired; this situation will be remedied when the automatic cycling system becomes operational. However, this cycling did induce other changes in specimens. Table 4-3 shows decreases with cycling in the values of Young's modulus and compressive strength for the Bedford, Platteville, and St. Peter, and increases for the Berea. The decreases for the St. Peter are substantial. The increases for the Berea may be the consequence of its clay content.

TABLE 4-1. Results of UWM Property Tests
on Bedford and Berea Specimens

			Data from Other Sources
<u>Bedford (Salem) Limestone</u>			
Heat Capacity, cal/g	0.206		Range 0.255-0.23 ⁽¹⁵⁾
	0.207	Mean 0.208	
	0.207	S.D. 0.002	
	0.210	C.V.(a) 1.0%	
Specific Gravity	2.35		Mean 2.34 ⁽¹⁴⁾ C.V. 0.2%
	2.35	Mean 2.35	
	2.34	S.D. 0.01	
	2.36	C.V. 0.3%	
Posity	11.6%	Mean 11.7%	Mean 12.5% ⁽¹⁴⁾ C.V. 4.4%
	11.6%	S.D. 0.01	
	11.8%	C.V. 0.8%	
Young's Modulus, 1/2 Tangent	5.62×10^6 psi ^(b)		Mean 3.66×10^6 (14) C.V. 59%
	5.24×10^6 psi ^(c)		
Compressive Strength	6.36×10^3 psi ^(b)		Mean 6.37×10^3 (14) C.V. 21.1%
	5.71×10^3 psi ^(c)		
<u>Berea Sandstone</u>			
Heat Capacity, cal/g	0.193		Quartz - 0.200 ⁽¹⁵⁾
	0.198	Mean 0.200	
	0.202	S.D. 0.006	
	0.208	C.V. 3.0%	
Specific Gravity	2.16		Mean 2.11 ⁽¹⁴⁾ C.V. 0.6%
	2.12	Mean 2.14	
	2.12	S.D. 0.02	
	2.15	C.V. 0.9%	
Porosity	19.8%		Mean 19.1% ⁽¹⁴⁾ C.V. 2.7%
	20.1%	Mean 20.0	
	20.1%	S.D. 0.2	
	19.9%	C.V. 0.8%	
Young's Modulus, 1/2 Tangent	1.61×10^6 psi ^(c)		Mean 2.00×10^6 (14) C. V. 12.3%
	1.75×10^6 psi ^(b)		
	2.20×10^6 psi ^(b)		
Compressive Strength	5.20×10^3 psi ^(c)		Mean 6.7×10^3 (14) C.V. 7.9%
	4.64×10^3 psi ^(b)		
	6.50×10^3 psi ^(b)		

(a) C.V. = coefficient of variation = standard deviation/mean.

(b) Axis parallel to bedding.

(c) Axis perpendicular to bedding.

TABLE 4-2. Summary of Experiments with Manual Cycling Equipment
(8/12/77 to 9/14/77)

Dates	Duration of Test, hours	Rock Type	Description	Average Pressure at High End, psi	Average Δ Pressure/Length of Specimen, psi/in.	Cycling	Air Temperature at Heater, °F	Air Temperature in Chamber, °F	Flow rate Input to Heater, scfh	Change in Permeability (relative) ^(a)	Remarks
8/12/77 to 8/15/77	69	St. Peter	1.6-in. long; gray-white, well-cemented sandstone, with one diagonal crack.	35	1.9 ^(b)	No	N/A	N/A	N/A	N/A	ODA #2362 and 2363. Water used for confinement. Some air bypassing specimen.
8/17/77 to 8/23/77	48	Bedford	6-in. long; 3 places.	40	1.2 ^(b)	Yes	N/A	N/A	N/A	N/A	ODA #2364 and 2365. Water used for confinement at 65 psi. Air bypassing specimen.
	15	Dolomite	Dolomite.	45	7.5 ^(c)	Yes	N/A	N/A	N/A	None detected	ODA # 2364 and 2365. Air confinement at 85 psi; no bypassing.
8/24/77 to 9/8/77	163	St. Peter	3-1/2 in. long; red, moderately-cemented sandstone.	34	2.6	Yes	N/A	N/A	N/A	None detected	ODA #2371. No bypassing here or for any subsequent tests.
	139	Dolomite	Dolomite.	32	2.6	Yes	200	92	80	None detected	Dolomite. Air temperature at air outflow 115°F.
9/10/77 to 1/12/77	36	Berea	5-in. long; axis perpendicular to bedding (Specimen #2B).	43	8.0	Yes	220-240	86-92	20	None detected	ODA #2372.
9/12/77 to 9/13/77	20	Berea	5-in. long; axis perpendicular to bedding (Specimen #2A).	44	8.6	Yes	220-230	86-91	4?	None detected	
9/13/77 to 9/14/77	26	St. Peter	5-in. long; axis parallel to bedding. Yellow, pink.	29	1.8	Yes	230	106-112	80	None detected	ODA #2373.
9/14/77 to 9/15/77	17	Platteville	5-in. long; axis perpendicular to bedding.	45	9.0 ^(c)	Yes	90	86	0?	None detected	Specimen moved to oven for baking at 200°F for 3 hours.

(a) Determined indirectly from pressure drops and flow rates.

(b) These are not valid measures of pressure gradients through the specimens because of bypassing.

(c) These are minimum figures. In each case the pressure at the low end of the specimen was psig.

TABLE 4-3. Comparison of Mechanical Properties of
Ventilated and Unventilated Specimens

	Unventilated		Ventilated	
	Young's Modulus, psi	Compressive Strength, psi	Young's Modulus, psi	Compressive Strength, psi
Bedford Limestone ^(a)	5.24×10^6	5.71×10^3		
Bedford Limestone ^(b)	5.62×10^6	6.36×10^3	5.16×10^6 (ODA #2375, 2376)	5.06×10^3
Berea Sandstone ^(a)	1.61×10^6	5.20×10^3	2.01×10^6 (ODA #2372)	8.38×10^3
			2.38×10^6	9.39×10^3
Berea Sandstone ^(b)	1.75×10^6	4.62×10^3		
	2.20×10^6	6.50×10^3		
Jordan Sandstone ^(a)	3.54×10^6	6.94×10^3		
Platteville Limestone ^(a)	5.04×10^6	9.39×10^3	4.66×10^6 (Also Baked)	4.34×10^3
St. Peter Sandstone ^(b)	1.64×10^6	1.73×10^3	0.72×10^6 (ODA #2373)	0.72×10^3

(a) Axis perpendicular to bedding.

(b) Axis parallel to bedding.

The results in Table 4-3 must be judged as tentative, because the number of specimens tested is small. Many more data points will be needed to provide a basis for reliable conclusions.

4.4 FABRIC ANALYSIS RESULTS

Fabric analysis of the specimen surfaces was accomplished by optical diffraction.

To improve contrast, specimen surfaces were treated with a white, wax-base paint. The surfaces were then photographed at the same scale on 35-mm high-contrast film. These transparencies were then used to generate two-dimensional optical transforms of the images; the transforms depict spatial frequencies along their radial coordinates, as well as orientations. Figures 4-16 and 4-17 convey the relationships between a rectangular input and its optical transform; these figures also provide scaling information for the entire series of figures in this section. In Figure 4-16 line spacing (spacing of 2 lines in bottom margin) is 0.4 mm in the original, or spatial frequency is 2.5 lines/mm. The print magnification is, therefore, 4.6X. Each of the input prints (even-numbered figures) has also been enlarged from its input negative by exactly the same amount, 4.6X, so Figure 4-16 can be used as a scale for each even-numbered figure. The input negatives are 1:1 replicas of the rock specimens, hence, each input print in the figures that follow is an exact 4.6X enlargement of the rock surface it represents.

Figure 4-17 is the two-dimensional Fourier amplitude transform of the calibration grid in Figure 4-16. The bar in the lower margin represents a spatial frequency of 2.5 lines/mm; the spatial frequency varies linearly in all directions from the intersection (D.C. spot) of the rectangular axes. The transforms (odd-numbered figures) were all prepared from inputs at identical scales under identical conditions; hence, Figure 4-17 can be used to scale spatial frequencies in each transform print, and these transforms can be compared directly with each other.

Table 4-4 summarizes the fabric work done.

FIGURE 4-16. Calibration Grid

FIGURE 4-17. Calibration Transform

TABLE 4-4. Fabric Analysis of Specimens by Optical Diffraction

ODA #	Rock Type	Specimen Description	Test	Figure Numbers	Remarks
2362	St. Peter	Gray-white, well-cemented sandstone.	In manual cycling equipment without cycling. No heating.	4-18 4-19	High pressure end.
2363	St. Peter	Gray-white, well-cemented sandstone.	In manual cycling equipment without cycling. No heating.	4-20 4-21	Low-pressure end.
2364	Bedford	White, fine-grained limestone; fossil fragments, colites.	Partly without and partly with cycling. No heating.	4-22 4-23	High-pressure end.
2365	Bedford	White, fine-grained limestone; fossil fragments, colites.	Partly without and partly with cycling. No heating.	4-24 4-25	Low-pressure end.
2366	St. Peter	Red, moderately cemented sandstone.	In simple blow-through system.	4-26 4-27	High-pressure end.
2367	St. Peter	Red, moderately cemented sandstone.	In simple blow-through system.	4-28 4-29	Low-pressure end.
2368	St. Peter	Red, moderately cemented sandstone.	No test.	4-30 4-31	Control specimen.
2369	Berea	Light gray sandstone, with some clay.	In simple blow-through system.	4-32 4-33	High-pressure end.
2370	Berea	Light gray sandstone, with some clay.	In simple blow-through system.	4-34 4-35	Low-pressure end.
2371	St. Peter	Red, moderately cemented sandstone.	Cycled with unheated and heated air.	4-36 4-37	From same block as 2366 and 2370.
2372	Berea	Light gray sandstone, with some clay.	Cycled with heated air.	4-38 4-39	From same block as 2369 and 2370.
2373	St. Peter	Yellow, pink sandstone, weakly cemented.	Cycled with heated air.	4-40 4-41	
2374	St. Peter	Yellow, pink sandstone, weakly cemented.	No test.	4-42 4-43	Control specimen.
2375	Bedford	White, fine-grained limestone; fossil fragments, colites.	In manual cycling equipment without cycling. Room temperature. Air bypassing.	4-44 4-45	High-pressure end. From same block as 2364 and 2365.
2376	Bedford	White, fine-grained limestone; fossil fragments, colites.	In manual cycling equipment without cycling. Room temperature. Air bypassing.	4-46 4-47	Low pressure end.
Calibration grid and transform.				4-16 4-17	

Examination of Figures 4-18 through 4-21, and 4-26 through 4-28 shows more low spatial-frequency components in high-pressure ends than in low-pressure ends of the St. Peter. Unventilated St. Peter (Figure 4-30) yields a pattern more like the high-pressure surfaces (Figures 4-18 and 4-26) than the low-pressure surfaces (Figures 4-20 and 4-28). Cycled St. Peter (Figure 4-40) shows more low spatial-frequency components than in the uncycled counterpart.

This could mean that, in the St. Peter, some fines are being dislodged from large pores and are being moved to smaller pores. Sample bags at the air outlet showed no accumulated fines.

Changes in the Berea are opposite to those in the St. Peter. Examination of Figures 4-32 and 4-34 shows more high spatial-frequency components in the high-pressure end than in the low-pressure end. The cycled Berea (Figure 4-38) yields a pattern closer to that of the high-pressure end (Figure 4-32) than to the low-pressure end.

This could be the result of readjustments in the clayey matrix of the Berea, with some of these materials being lost through the low-pressure end by blow-out. No accumulation of such materials was found in the sample bags at the air outlet, perhaps because the permeability of the Berea is low and only a tiny amount could have accumulated. This blow-out process would be consistent with the results reported previously for simple, unidirectional blow-through, with accumulation of fines on the plastic-tape wrappings. A higher accumulation was detected at the low-pressure end than at the high-pressure end.

No changes in the Bedford (Figures 4-22, 4-24, 4-44 and 4-46) were noted. This is to be expected, because flow through the rock was minute.

Again, in interpreting these results, the small number of specimens treated requires that the conclusions drawn be treated as tentative.

The method developed for highlighting specimen surfaces is useful, and probably could be used in boreholes for monitoring in-situ changes in fabric. Borescope photography would be required to record images.

Optical diffraction analysis appears to be well-suited to fabric studies of the type needed here.

The St. Peter sandstone specimen shown in Figure 4-18 was subjected to unidimensional (noncyclic) and bypassing flow of unheated air. The fine horizontal lines appearing in the figure are brush strokes. This view is of the high-pressure end of the specimen. The optical transform in Figure 4-19 shows more low spatial-frequency components out to about 2.5 lines/mm than appear in the counterpart transform in Figure 4-21.

Figures 4-20 and 4-21 are the low-pressure end of the same specimen shown in Figures 4-18 and 4-19. The transform (Figure 4-21) shows a more uniform distribution of spatial frequencies throughout the transform than in the counterpart in Figures 4-18 and 4-19.

The Bedford (Salem) limestone specimen was initially subjected to unidirectional (noncyclic) flow with bypassing, followed by cyclic pressurization without bypassing, with unheated air. Figures 4-22 and 4-23 show the high-pressure end of the specimen during the noncyclic phase. The low-pressure end of this specimen is shown in Figures 4-24 and 4-25. The transforms in Figures 4-23 and 4-25 are virtually identical in appearance, despite the difference in pressure to which the specimen ends were subjected.

The simple blow-through system was used to subject a moderately cemented St. Peter sandstone specimen to unidirectional flow. The results presented in Figures 4-26 and 4-27 show the high-pressure end of the specimen. Figures 4-28 and 4-29 show the specimen's low-pressure end. The high-pressure transform (Figure 4-27) shows conspicuously more low spatial-frequency components than appear in Figure 4-29, the low-pressure end.

For comparison, an untested (unventilated) specimen of the same St. Peter sandstone appears in Figures 4-30 and 4-31. The transform is intermediate to those shown in Figures 4-27 and 4-29, resembling the former more closely.

FIGURE 4-18. Gray-White, Well-Cemented St. Peter Sandstone (ODA #2362)

FIGURE 4-19. Optical Transform of Figure 4-18 Input (ODA #2362)

FIGURE 4-20. Gray-White, Well-Cemented St. Peter Sandstone (ODA #2363)

FIGURE 4-21. Optical Transform of Figure 4-20 Input (ODA #2363)

FIGURE 4-22. White, Fine-Grained Bedford (Salem)
Limestone (ODA #2364)

FIGURE 4-23. Optical Transform of Figure 4-22 Input (ODA #2364)

FIGURE 4-24. White, Fine-Grained Bedford (Salem)
Limestone (ODA #2365)

FIGURE 4-25. Optical Transform of Figure 4-24 Input (ODA #2365)

FIGURE 4-26. Red, Moderately Cemented St. Peter Sandstone (ODA #2366)

FIGURE 4-27. Optical Transform of Figure 4-26 Input (ODA #2366)

FIGURE 4-28. Red, Moderately Cemented St. Peter Sandstone (ODA #2367)

FIGURE 4-29. Optical Transform of Figure 4-28 Input (ODA #2367)

FIGURE 4-30. Red, Moderately Cemented St. Peter Sandstone (ODA #2368)

FIGURE 4-31. Optical Transform of Figure 4-30 Input (ODA #2368)

Light gray Berea sandstone containing some clay was subjected to unidirectional flow in the simple blow-through system. Figures 4-32 and 4-33 show the high-pressure end of an axial cut through the cylindrical specimen. The low-pressure end of the same axial cut appears in Figures 4-34 and 4-35. When comparing the two transforms, Figures 4-33 and 4-35, the latter shows fewer high spatial-frequency components and more low spatial-frequency components than the former.

Another specimen of red, moderately cemented St. Peter sandstone was subjected to cyclic flow of both heated and unheated air. The end view is shown in Figures 4-36 and 4-37. The appearance of the transform is similar to that of Figure 4-31, but is slightly elongated vertically. This results from a weak preferred orientation of grains and pores in the horizontal direction shown in Figure 4-36.

The Berea sandstone specimen shown in Figures 4-38 and 4-39 was subjected to cyclic flow of heated air. The transform (end view) resembles that in Figure 4-33 more closely than it does Figure 4-35.

Figure 4-40 shows the end view of a weakly cemented St. Peter sandstone specimen subjected to cyclic flow of heated air. The vertical elongation appearing in the transform, Figure 4-41, results from the preferred orientation in the horizontal direction of grains and pores in the input.

An untested (unventilated) specimen of the same St. Peter sandstone appears in Figure 4-42. The transform in Figure 4-43 shows slightly less low spatial-frequency components and somewhat weaker preferred orientation than its counterpart in Figure 4-41.

Fine-grained Bedford (Salem) limestone was subjected to unidirectional (noncyclic) and bypassing unheated airflow. Figure 4-44 presents the high-pressure end of the specimen. Its optical transform appears in Figure 4-45.

Figure 4-46 shows the low-pressure end of the same specimen. Its transform (Figure 4-47) is virtually identical to that of Figure 4-45.

The transforms in Figures 4-45 and 4-47 are noticeably brighter than those in Figures 4-23 and 4-25, because of different surface treatments of the two Bedford specimens prior to photography.

FIGURE 4-32. Light Gray Berea Sandstone, Containing
Some Clay (ODA #2369)

FIGURE 4-33. Optical Transform of Figure 4-32 Input (ODA #2369)

FIGURE 4-34. Light Gray Berea Sandstone Containing Some Clay (ODA #2370)

FIGURE 4-35. Optical Transform of Figure 4-34 Input (ODA #2370)

FIGURE 4-36. Red, Moderately Cemented St. Peter Sandstone (ODA #2371)

FIGURE 4-37. Optical Transform of Figure 4-36 Input (ODA #2371)

FIGURE 4-38. Light Gray Berea Sandstone Containing Some Clay (ODA #2372)

FIGURE 4-39. Optical Transform of Figure 4-38 Input (ODA #2372)

FIGURE 4-40. Yellow and Pink, Weakly Cemented
St. Peter Sandstone (ODA #2373)

FIGURE 4-41. Optical Transform of Figure 4-40 Input (ODA #2373)

FIGURE 4-42. Yellow and Pink, Weakly Cemented
St. Peter Sandstone (ODA #2374)

FIGURE 4-43. Optical Transform of Figure 4-42 Input (ODA #2374)

FIGURE 4-44. White, Fine-Grained Bedford (Salem)
Limestone (ODA #2375)

FIGURE 4-45. Optical Transform of Figure 4-44 Input (ODA #2375)

FIGURE 4-46. White, Fine-Grained Bedford (Salem)
Limestone (ODA #2376)

FIGURE 4-47. Optical Transform of Figure 4-46 Input (ODA #2376)

4.5 SUMMARY

No relative changes in permeability due to cyclic ventilation were observed in any specimens. Some changes in Young's modulus and compressive strengths were noted, as were some minor changes in microstructure. Any results must be judged as tentative, however, because of the small number of specimens tested.

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APPENDIX A

DEVELOPMENT OF DIFFERENTIAL EQUATIONS

DEVELOPMENT OF DIFFERENTIAL EQUATIONS

The governing equations of compressible flow through a dry porous rigid structure are developed in Appendix A. Starting from general forms of the conservation laws, simplifications applicable to flow regimes that may be encountered in CAES systems are made to develop the final forms of the equations used.

GENERAL CONSERVATION LAWS

In classical fluid mechanics, the conservation laws of mass, momentum, and energy can be written, respectively, as

$$\frac{\partial \rho}{\partial t} + (\nabla \cdot \rho \bar{v}_0) = 0 \quad (A-1)$$

$$\rho \left[\frac{\partial \bar{v}_0}{\partial t} + \bar{v}_0 \cdot \nabla \bar{v}_0 \right] = -\nabla P - [\nabla \cdot \underline{\tau}] + \rho \bar{g} \quad (A-2)$$

and

$$\rho \left(\frac{\partial h}{\partial t} + \bar{v}_0 \cdot \nabla h \right) = \nabla \cdot K \nabla T + \mu \Phi + \left(\frac{\partial P}{\partial t} + \bar{v}_0 \cdot \nabla P \right) \quad (A-3)$$

If the flow is within a porous solid, these equations become

$$\phi \frac{\partial \rho}{\partial t} + (\nabla \cdot \rho \bar{v}) = 0 \quad (A-4)$$

$$\rho \left[\frac{\partial \bar{v}}{\partial t} + \frac{\bar{v}}{\phi} \cdot \nabla \bar{v} \right] = \phi \left[-\nabla P - \frac{\bar{F}}{\phi} + \rho \bar{g} \right] \quad (A-5)$$

and

$$\rho \left(\phi \frac{\partial h}{\partial t} + \bar{v} \cdot \nabla h \right) = \phi \nabla \cdot K \nabla T + \mu \Phi_p + \left(\phi \frac{\partial P}{\partial t} + \bar{v} \cdot \nabla P \right) + H_v (T_s - T) \quad (A-6)$$

In these equations, the term ϕ is known as the porosity (open volume divided by total volume) and reflects the presence of the solid phase within the flow field. The velocity $\bar{v}$ in these equations is the superficial velocity (volume rate of flow through a unit cross-sectional area) averaged over a small region of space--small with respect to macroscopic dimensions of the flow system but large with respect to pore size. All fluid properties are averaged over a region available to flow that is large with respect to pore size.

The fluid phase viscous shear force term $-\nabla \cdot \underline{\tau}$ in the momentum equation has been replaced by the term $\frac{\bar{F}}{\phi}$ to include not only viscous shear forces, but also form drag forces imposed on the flowing fluid by the solid structure. Similarly, the viscous energy dissipation function ϕ in the energy equation has been replaced by ϕ_p to account for dissimilar viscous energy dissipation due to the effects of the porous medium. An additional term, $H_V(T_S - T)$, is added to register the heat transfer to the fluid from the solid phase.

One additional equation must be written for energy balance in the porous solid. In terms of the characteristic rock temperature T_S , it is

$$(1 - \phi) \left(C_S \rho_S \frac{\partial T_S}{\partial t} - \nabla \cdot K_S \nabla T_S \right) = H_V(T - T_S) \quad (A-7)$$

SIMPLIFYING ASSUMPTIONS

Equations A-4, A-5, A-6 and A-7 represent the general equations of flow in a porous medium. Several simplifications can be made to reduce these to forms more suitable for analysis of CAES porous rock air reservoirs. Simplifying assumptions incorporated into this study are discussed in the sections that follow.

Negligible Viscous Dissipation of Energy

It is well known that for gases (where Prandtl numbers are near 1) the velocity must approach the speed of sound before viscous dissipation terms become significant in comparison to other terms of the energy equation. CAES reservoir flow velocities will be several orders of magnitude below the sonic level so that neglect of the dissipation term $\mu \phi_p$ in Equation A-6 is perfectly warranted.

Kinetic Energy Disregarded

For the low velocities of CAES reservoir flows, the kinetic energy terms are also negligible in comparison to other forms of energy. In fact, calculations show that disregarding kinetic energy causes errors of only a very small fraction of a percent in the solutions to the flow equations. If kinetic energy is neglected, the term $\bar{v} \cdot \nabla P$ drops from the energy equation.

Ideal Gas Behavior

As can be seen from Figure A-1, air deviates only slightly from ideal gas behavior under conditions contemplated for compressed air energy storage. The ideal gas equation of state

$$\rho = \frac{P}{RT} \quad (A-8)$$

is therefore justified to relate air density, pressure and temperature.

The relationship between gas enthalpy and temperature is established from the thermodynamic relationship for an ideal gas,

$$dH = C_p dT \quad (A-9)$$

Thus, $\frac{\partial h}{\partial T} = C_p$, and $\nabla h = C_p \nabla T$.

Darcy or Forchheimer Flow Assumed

If the pore Reynolds number is small the inertial terms of the momentum equation (Equation A-5) may be neglected to yield

$$\frac{\bar{F}}{\phi} = (-\nabla P + \rho \bar{g}) \quad (A-10)$$

For flow in this velocity regime, the viscous forces have been shown experimentally to be proportional to velocity, i.e.,

$$\frac{\bar{F}}{\phi} = C \bar{v} \quad (A-11)$$

FIGURE A-1. Compressibility Factors for Air

where the constant of proportionality, C , should be expressed as the ratio $\frac{\mu}{\kappa}$. μ is the absolute viscosity of the fluid, and κ is the porous medium permeability. Thus, the momentum equation may be written as

$$\bar{v} = - \frac{\kappa}{\mu} [\nabla P - \rho \bar{g}] \quad (A-12)$$

which is known as Darcy's law for flow through porous media.

Darcy's law says that in the flow of a fluid through a porous medium, the flow rate increases proportionally with increased pressure drop. Data gathered by Fancher, Lewis and Barnes⁽¹⁾ (Figure A-2) show that, similar to the case for flow in pipes, this "viscous" flow occurs only over a range of flows. At some higher flow rate the increased rate no longer matches the increased pressure drop (in pipes this indicates the onset of turbulence)

FIGURE A-2. Flow Through Porous Media⁽³⁾

and the Darcy equation is no longer adequate. Forchheimer⁽²⁾ suggests the addition of a quadratic term to the Darcy momentum equation to more correctly match the nonlinear relationships between pressure drop and velocity. The Forchheimer momentum equation is expressed as

$$\frac{\mu}{\kappa} \bar{v} + \beta \rho [\underline{v}_a \cdot \bar{v}] = -\nabla P + \rho \bar{g} \quad (A-13)$$

where $\underline{v}_a = \begin{pmatrix} |v_r| & 0 & 0 \\ 0 & |v_\theta| & 0 \\ 0 & 0 & |v_z| \end{pmatrix}$

where the term β is traditionally called the turbulence factor, and has been correlated with reservoir permeability and porosity by Katz and others⁽³⁾ (Figure A-3). The Forchheimer equation is sometimes referred to as the modified Darcy equation, and, in fact, reduces to the Darcy equation when velocities are small.

Rapid Thermal Equilibrium Between Solid and Fluid Phases

Due to the intimate contact between fluid and solid, the assumption of local thermal equilibrium between solid and fluid ($T_s = T$) is commonly employed in porous media flow analyses. In reality, the temperatures of the solid matrix and fluid are coupled by the internal volumetric heat transfer coefficient H_v . An exact determination of this coefficient by theoretical analysis is not possible as a result of the complex flow patterns and geometric characteristics of porous media. Although correlation formulae have been developed (using dimensional analysis and experimental measurement) for specialized porous structures with varying degrees of success, experiments have upheld the validity of the local thermal equilibrium assumption for flow conditions similar to those expected in CAES reservoirs. This assumption simplifies the problem by reducing the number of energy equations from two to one.

Solid Properties Assumed Stepwise Constant

Already inherent in the conservation equations is the assumption that the reservoir properties of porosity, permeability, rock specific heat, and rock

FIGURE A-3. Correlation of Turbulence Factor β with Permeability(1)

density are at least stepwise constant. They are assumed independent of temperature and pressure, and to be adequately represented by appropriate stair functions of reservoir geometry.

FINAL EQUATIONS

Incorporation of the assumptions discussed in the preceding section reduces the conservation laws to the following:

Conservation of Mass

$$\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \nabla \cdot \left(\frac{P}{T} \right) \bar{v} = 0 \quad (A-14)$$

Conservation of Momentum

$$\frac{\mu}{\kappa} \bar{v} + \beta \left(\frac{P}{RT} \right) [\bar{v}_a \cdot \bar{v}] = -\nabla P + \bar{\rho} \bar{g} \quad (A-15)$$

Conservation of Energy

$$\frac{C_p P}{RT} \left(\phi \frac{\partial T}{\partial t} + \bar{v} \cdot \nabla T \right) - \phi \frac{\partial P}{\partial t} = \phi \nabla \cdot K \nabla T + (1 - \phi) \nabla \cdot K_s \nabla T - (1 - \phi) \rho_s C_s \frac{\partial T}{\partial t} \quad (A-16)$$

Since the porosity ϕ is constant (at least stepwise) the conductivity terms may be written

$$\nabla \cdot \phi K \nabla T + \nabla \cdot (1 - \phi) K_s \nabla T = \nabla \cdot [\phi K + (1 - \phi) K_s] \nabla T$$

Defining an equivalent thermal conductivity

$$K_e = \phi K + (1 - \phi) K_s \quad (A-17)$$

this reduces to $\nabla \cdot K_e \nabla T$.

It should be noted that although the thermal conductivity of air varies with temperature, its contribution to the equivalent matrix conductivity in porous rock is so small (less than 1%) that it can be assumed constant with negligible effect. The uncertainty of determining appropriate values for rock conductivity will have a much greater effect on the analysis of a given reservoir.

As written, the continuity and momentum equations are both in what are called "conservative forms" suitable for finite differencing for numerical solution. By "conservative" it is meant that no variables appear both outside as well as inside a differential. This is not the case for the energy equation as it appears in Equation A-16, but it can be put into a numerically conservative form by adding

$$\frac{C_p T}{R} \left[\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \nabla \cdot \left(\frac{P}{T} \right) \bar{v} \right] = 0$$

to Equation A-16 and simplifying to

$$\left(\frac{C_p}{R} - 1 \right) \phi \frac{\partial P}{\partial t} + \left(\frac{C_p}{R} \right) \nabla \cdot P \bar{v} = \nabla \cdot K_e \nabla T - (1 - \phi) \rho_s C_s \frac{\partial T}{\partial t}$$

Rearranged, the energy equation, including energy of both fluid and solid, becomes

$$\frac{\partial T}{\partial t} = \frac{1}{(1 - \phi) \rho_s C_s} \left[\nabla \cdot K_e \nabla T + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \nabla \cdot P \bar{v} \right] \quad (A-18)$$

which is a conservative form.

ONE-DIMENSIONAL RADIAL FLOW

Air entering or leaving a wellbore at the bottom of a well flows radially through the porous rock. Thus, a reasonable yet simple model for flow to and from a single well is the one-dimensional radial model depicted in Figure 3-2. Since there is no component of gravity in the horizontal direction, the term $\rho \bar{g}$ in the momentum equation disappears, and all equations can be rewritten in terms of the single radial coordinate r . The velocity vector $\bar{v}$ reduces to the radial component v .

Conservation of Mass

$$\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left[r \left(\frac{P}{T} \right) v \right] = 0 \quad (A-19)$$

Conservation of Momentum

$$\frac{\mu}{\kappa} v + \beta \left(\frac{P}{RT} \right) |v| v + \frac{\partial P}{\partial r} = 0 \quad (A-20)$$

Conservation of Energy

$$\frac{\partial T}{\partial t} = \frac{1}{(1 - \phi) \rho_s C_s} \left[\frac{1}{r} \frac{\partial}{\partial r} \left(k_e r \frac{\partial T}{\partial r} \right) + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \frac{1}{r} \frac{\partial}{\partial r} (r P v) \right] \quad (A-21)$$

These are the final forms of the one-dimensional conservation equations used in developing a numerical computer model for determining pressure and temperature gradients in air-filled porous rock reservoirs.

APPENDIX A REFERENCES

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APPENDIX B

DEVELOPMENT AND SOLUTION OF THE DIFFERENCE EQUATIONS

DEVELOPMENT AND SOLUTION OF THE DIFFERENCE EQUATIONS

In Appendix B the difference equations are derived from the governing difference equations. Details of the development of the difference Equations 3-10 and 3-13 are presented. The method of solution of the equations is subsequently developed.

MASS TRANSPORT DIFFERENCE EQUATIONS

The difference equation for the mass transport is developed from the continuity equation, Equation 3-5.

$$\phi \frac{\partial}{\partial t} \left(\frac{P}{T} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(\frac{Prv}{T} \right) = 0 \quad (3-5)$$

A weighted volumetric flux, F , is defined from the product of radius and velocity.

$$F = rv \quad (B-1)$$

For the Darcy flow assumption the velocity can be written as

$$v = - \frac{\kappa}{\mu} \frac{\partial P}{\partial r} \quad (B-2)$$

so that

$$F = - \frac{\kappa r}{\mu} \frac{\partial P}{\partial r} \quad (B-3)$$

The pressure and radius can be separated and the result integrated between two radial positions:

$$\int_{r_i}^{r_o} F \frac{\partial r}{r} = - \int_{P_i}^{P_o} \frac{\kappa}{\mu} \partial P \quad (B-4)$$

which yields

$$F = - \frac{\frac{\kappa}{\mu} (P_o - P_i)}{\ln (r_o/r_i)} \quad (B-5)$$

Since the flux from a node to the difference cell boundary is equal to the flux from the boundary to the adjacent node, then the flux across the boundary can be written as

$$F_{j+1/2} = \frac{-(P_{j+1/2} - P_j)}{\left(\frac{\mu}{\kappa}\right)_j \ln \left(\frac{r_{j+1/2}}{r_j}\right)} = \frac{-(P_{j+1} - P_{j+1/2})}{\left(\frac{\mu}{\kappa}\right)_{j+1} \ln \left(\frac{r_{j+1}}{r_{j+1/2}}\right)} \quad (B-6)$$

The boundary pressure, $P_{j+1/2}$, is eliminated to give

$$F_{j+1/2} = \frac{-(P_{j+1} - P_j)}{\left(\frac{\mu}{\kappa}\right)_j \ln \left(\frac{r_{j+1/2}}{r_j}\right) + \left(\frac{\mu}{\kappa}\right)_{j+1} \ln \left(\frac{r_{j+1}}{r_{j+1/2}}\right)} \quad (B-7)$$

A flow conductance between nodes j and $j+1$ is defined as

$$C_j = \frac{1}{\left(\frac{\mu}{\kappa}\right)_j \ln \left(\frac{r_{j+1/2}}{r_j}\right) + \left(\frac{\mu}{\kappa}\right)_{j+1} \ln \left(\frac{r_{j+1}}{r_{j+1/2}}\right)} \quad (B-8)$$

In this way the flux between nodes j and $j+1$ is defined as

$$F_j = - C_j (P_{j+1} - P_j) \quad (B-9)$$

For high velocity flows the Forchheimer equation was used to define the velocity:

$$\beta \frac{P}{RT} v |v| + \frac{\mu}{\kappa} v = \frac{\partial P}{\partial r} \quad (\text{B-10})$$

Define

$$\eta = -1 \text{ for } v < 0, \text{ i.e., } \frac{\partial P}{\partial r} > 0$$

and

$$\eta = +1 \text{ for } v \geq 0, \text{ i.e., } \frac{\partial P}{\partial r} < 0$$

so that

$$\eta \beta \frac{P}{RT} v^2 + \frac{\mu}{\kappa} v = - \frac{\partial P}{\partial r} \quad (\text{B-11})$$

and

$$v = \frac{-\frac{\mu}{\kappa} + \sqrt{\left(\frac{\mu}{\kappa}\right)^2 - 4 \eta \beta \frac{P}{RT} \frac{\partial P}{\partial r}}}{2 \eta \beta \frac{P}{RT}} \quad (\text{B-12})$$

The product $\eta \frac{\partial P}{\partial r}$ is always negative so that the velocity is written as

$$v = \frac{-\frac{\mu}{\kappa} + \sqrt{\left(\frac{\mu}{\kappa}\right)^2 + 4 \beta \frac{P}{RT} \left|\frac{\partial P}{\partial r}\right|}}{2 \eta \beta \frac{P}{RT}} \quad (\text{B-13})$$

From Equation B-10

$$v = \frac{-\frac{\partial P}{\partial r}}{\frac{\mu}{\kappa} + \beta \frac{P |v|}{RT}} \quad (\text{B-14})$$

or

$$v = \frac{-\frac{\partial P}{\partial r}}{\frac{\mu}{\kappa} + \eta \frac{\beta P |v|}{RT}} \quad (B-15)$$

Substituting Equation B-13 into Equation B-15 gives

$$v = \frac{-2 \frac{\partial P}{\partial r}}{\frac{\mu}{\kappa} + \sqrt{\left(\frac{\mu}{\kappa}\right)^2 + 4 \beta \frac{P}{RT} \left|\frac{\partial P}{\partial r}\right|}} \quad (B-16)$$

By treating $\left|\frac{\partial P}{\partial r}\right|$ as a constant, an integration similar to Equation B-4 can be made. Subsequently, the flux can be defined as

$$F_j = -C_j (P_{j+1} - P_j) \quad (B-17)$$

where the high velocity form of the flow conductance is written as

$$C_j = \left[\left\{ \frac{\mu}{\kappa} + \sqrt{\left(\frac{\mu}{\kappa}\right)^2 + 4 \beta \frac{P}{RT} \left|\frac{\partial P}{\partial r}\right|} \right\}_j \ln \left(\frac{r_{j+1/2}}{r_j} \right) + \left\{ \frac{\mu}{\kappa} + \sqrt{\left(\frac{\mu}{\kappa}\right)^2 + 4 \beta \frac{P}{RT} \left|\frac{\partial P}{\partial r}\right|} \right\}_{j+1} \ln \left(\frac{r_{j+1}}{r_{j+1/2}} \right) \right]^{-1} \quad (B-18)$$

With the flux terms properly defined, the donor cell differencing leading to Equation 3-10 is straightforward.

ENERGY TRANSPORT DIFFERENCE EQUATIONS

The difference equation for the energy transport is developed from Equation 3-7,

$$\frac{\partial T}{\partial t} = \left[\frac{1}{r} \frac{\partial}{\partial r} \left(k_e r \frac{\partial T}{\partial r} \right) + \left(1 - \frac{C_p}{R} \right) \phi \frac{\partial P}{\partial t} - \left(\frac{C_p}{R} \right) \frac{1}{r} \frac{\partial}{\partial r} (Prv) \right] \frac{1}{(1 - \phi) \rho_s C_s} \quad (3-7)$$

The only term for which a detailed development is considered necessary is the heat conduction term. In this case a heat flux is defined similar to the weighted volumetric flux of Equation B-1.

$$H = K_e r \frac{\partial T}{\partial r} \quad (B-19)$$

The temperature and radius can be separated and the result integrated between two radial positions.

$$\int_{r_i}^{r_o} H \frac{\partial r}{r} = \int_{T_i}^{T_o} K_e \partial T \quad (B-20)$$

yields

$$H = \frac{K_e (T_o - T_i)}{\ln(r_o/r_i)} \quad (B-21)$$

Since the heat flux between two nodes is constant, the flux at the cell boundary can be written as

$$H_{j+1/2} = \frac{K_{e,j} (T_{j+1/2} - T_j)}{\ln\left(\frac{r_{j+1/2}}{r_j}\right)} = \frac{K_{e,j+1} (T_{j+1} - T_{j+1/2})}{\ln\left(\frac{r_{j+1}}{r_{j+1/2}}\right)} \quad (B-22)$$

The temperature at the interface, $T_{j+1/2}$, is eliminated to give

$$H_{j+1/2} = \frac{T_{j+1} - T_j}{\frac{1}{K_{e,j}} \ln\left(\frac{r_{j+1/2}}{r_j}\right) + \frac{1}{K_{e,j+1}} \ln\left(\frac{r_{j+1}}{r_{j+1/2}}\right)} \quad (B-23)$$

A heat conductance between nodes j and $j+1$ is defined as

$$K_j = \frac{1}{\frac{1}{K_{e,j}} \ln\left(\frac{r_{j+1/2}}{r_j}\right) + \frac{1}{K_{e,j+1}} \ln\left(\frac{r_{j+1}}{r_{j+1/2}}\right)}$$

In this way the heat flux between the nodes is defined as

$$H_j = K_j (T_{j+1} - T_j)$$

From this point the donor cell differencing leading to Equation 3-13 is straightforward.

SOLUTION METHOD

This section of Appendix B provides the details of the solution of Equations 3-10 and 3-13. A flow chart of the computer solution is given in Figure B-1.

In the solution there are essentially three levels of time distinguished during each time step. Properties to be evaluated are designated as new time values by the subscript $n+1$ in Equations 3-10 and 3-13. The properties from which the solution is achieved are designated as old time values by the subscript n . The third condition is a result of the nonlinearity of the mass transport equation as well as the coupling of the transport equations. To obtain a reasonably conservative solution it is necessary to distinguish the pressure in the advected density from the pressure of the flux term.^(a) This requires guessing the new time values of the density. The guessed values are iteratively improved until they converge with the new time solution.

-
- (a) Previous numerical investigations of mass flow through porous media have typically not distinguished between the pressure associated with the density and with the flux. This results in the continuity equation combining with Darcy's law to form

$$\phi \frac{\partial P^2}{\partial t} + \frac{\kappa}{\mu r} P \frac{\partial}{\partial r} \left(r \frac{\partial P^2}{\partial r} \right) = 0$$

The most significant assumption inherent in deriving this equation is that the temperature is constant. This form of the equation provides a good pressure solution for the isothermal problem but is not conservative when temperatures vary.

FIGURE B-1. Calculational Flow Chart

Designating pressure and temperature at old time with P_0 and T_0 , guessed values with P_G and T_G , and new time with P_N and T_N , Equations 3-10 and 3-13 are reconstructed to improve the visibility of these different levels of time.

$$P_{Nj} + \frac{\Delta t}{\phi} \frac{T_{Gj}}{r_j \Delta r_j} \left[C_{j-1} \left[\left(\frac{P_G}{T_G} \right)_{j-1,F+} + \left(\frac{P_G}{T_G} \right)_{j,F-} \right] (P_{Nj} - P_{Nj-1}) \right. \\ \left. + C_j \left[\left(\frac{P_G}{T_G} \right)_{j,F+} + \left(\frac{P_G}{T_G} \right)_{j+1,F-} \right] (P_{Nj} - P_{Nj+1}) \right] = \frac{T_{Gj}}{T_{0j}} P_{0j} \quad (B-24)$$

$$T_{Nj} = T_{0j} + \frac{\Delta t}{(1-\phi)\rho_s C_s} \left[\frac{1}{r_j \Delta r_j} (K_{j-1} T_{Gj-1} - (K_{j-1} + K_j) T_{Gj} + K_j T_{Gj+1}) \right. \\ \left. + \left(1 - \frac{C_p}{R} \right) \phi \left(\frac{P_{Nj} - P_{0j}}{\Delta t} \right) \right. \\ \left. - \left(\frac{C_p}{R} \right) \frac{1}{r_j \Delta r_j} (P_{Nj} F_{j,F+} - P_{Nj-1} F_{j-1,F+} \right. \\ \left. - P_{Nj} F_{j-1,F-} + P_{Nj+1} F_{j,F-}) \right] \quad (B-25)$$

The required sequence of the solution is now more obvious. All the pressures and the flux terms used in Equation B-25 are obtained from the solution of Equation B-24.

In Equation B-24 the pressures associated with the density are iteratively improved. The determination of the sign of the flux term is based on these guessed values of pressure.

In Equation B-25 the conduction terms on the right hand side could be transposed to the left side and thereby be designated as new time values. This would require a simultaneous solution technique such as a Gauss elimination. However, since the primary mode of energy transport is by advection which, computationally, depends only on the pressure solution, it is not necessary to solve exactly for the temperatures. Instead, the best prediction of the mass and energy transport is gained by the best possible solution of Equation B-24.

BOUNDARY CONDITIONS

The boundary conditions are applied in a direct manner except for the mass flux specified at the wellbore.

The outer reservoir boundary is insulated to the passage of either mass or energy. During mass injection the temperature of the injected air is specified at the wellbore. During extraction, the wellbore node is given the temperature of the second node at the previous time step. When there is no flow the wellbore node is disconnected from the solution by setting the mass conductance, C_1 (from Equation 3-8) and the thermal conductance, K_1 (from Equation 3-11) to zero. In this way there is no source or sink for mass or energy.

The forcing function for the advection of mass and energy is the pressure specified at the wellbore. Therefore, to apply a mass flux boundary condition it is necessary to specify a pressure. This presents difficulties because the new time pressure must be known. Since the pressure cannot be known until the solution is obtained, the application of the mass flux boundary condition is an iterative procedure. The procedure is included in Figure B-1.

APPENDIX C

AIR AND ROCK PROPERTIES

AIR AND ROCK PROPERTIES

PROPERTIES OF AIR

The gas constant for air used in this study is

$$R = \frac{1.987 \text{ Btu/lbm-mole}^\circ\text{R}}{28.97 \text{ lbm/lbm-mole}} = 0.06859 \text{ Btu/lbm-}^\circ\text{R} = 287.2 \text{ J/kg-}^\circ\text{K}.$$

The constant pressure specific heat of air was held constant at

$$C_p = 0.242 \text{ Btu/lbm-}^\circ\text{F} = 1013 \text{ J/kg-}^\circ\text{C}.$$

Air viscosity as a function of temperature and pressure is presented in Figure C-1.

FIGURE C-1. Viscosity of Air

PROPERTIES OF TYPICAL RESERVOIR ROCK

Since the original source of most sand grains, as pointed out by Landes,⁽¹⁾ is granite or granite gneiss, the solid, or sand grain, phase of the porous reservoir can be assumed to have physical properties similar to these substances.

The density of granite or gneiss is in the range of 165 to 175 lbm/ft³ (2640 to 2800 kg/m³).⁽²⁻⁴⁾ The specific heat, C_s , and thermal conductivity, K_s , of high SiO₂ rocks, including granite, are given as functions of temperature in Figures C-2 and C-3, respectively. Values of rock properties used in this study were assumed constant at the following values:

- density, $\rho_s = 165 \text{ lb/ft}^3$ (2643 kg/m³)
- specific heat, $C_s = 0.22 \text{ Btu/lb-}^\circ\text{F}$ (921 J/kg- $^\circ\text{C}$)
- thermal conductivity, $K_s = 1.25 \text{ Btu/hr-ft-}^\circ\text{F}$ (2.16 W/m- $^\circ\text{C}$).

FIGURE C-2. Specific Heat of Some High SiO₂ Rocks⁽⁵⁾

FIGURE C-3. Thermal Conductivity of Some High SiO₂ Rocks⁽⁴⁾

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