Geotechnical Factors and Guidelines for Storage of Compressed Air in Solution Mined Salt Cavities

R. D. Allen
T. J. Doherty
R. L. Thoms

May 1982

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

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

DISCLAIMER

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

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 7830

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

NTIS Price Codes
Microfiche A01

Printed Copy

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

GEOTECHNICAL FACTORS AND
GUIDELINES FOR STORAGE OF
COMPRESSED AIR IN SOLUTION
MINED SALT CAVITIES

R. D. Allen
T. J. Doherty
R. L. Thoms

May 1982

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

Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

The Compressed Air Energy Storage (CAES) Technology Program is funded by the Division of Energy Storage Technology (EST) of the U.S. Department of Energy (DOE). The program is charged with developing the advanced technology base necessary for the cyclical storage of compressed air in geologic reservoirs by electric utilities. Low cost baseload electricity, available during off-peak periods, is used to compress air and deliver it to the underground reservoir. The potential mechanical energy is utilized to generate electricity during peak-load periods. This storage technique reduces or eliminates the burning of fluid fossil fuels that currently power inefficient peaking turbine generators. The introduction of this technology requires effective liaison among the government sponsor, prime and subcontractors, electric utilities and their representative architect-engineering organizations, machinery manufacturers, and environmental specialists.

This document provides these organizations with the latest research on stability topics specific to CAES using solution-mined salt cavities for air storage. Currently, the only CAES operational facility in the world is located at Huntorf, West Germany. This CAES facility uses two solution-mined salt caverns for air storage and has been operating successfully for more than 2 years. Stability criteria for solution-mined salt caverns from the Huntorf facility and recent field and laboratory studies are included in this report.

SUMMARY

The state of knowledge about utilization of solution-mined salt cavities for CAES including laboratory experiments, numerical modeling, field characterization, solution mining experience, and operating parameters is outlined in this report. Salt caverns for CAES systems will undergo daily cycles of pressure, temperature, and humidity. Effects that could damage the cavern must be controlled. Topics evaluated in recent studies include:

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

Studies cited in this report have identified several criteria that could serve as guidelines for long-term stability of salt cavities:

Cavity floor depths to 1524 m may be acceptable depending on site conditions. For the anticipated maximum operating pressures of 9.0 MPa or less, optimal depth to cavern roof is about 800 m (Maximum air pressure is to be 1.639 MPa per 100 m of depth.)

Cavity wall temperatures should not exceed 80°C.

- Cavity separation (center-to-center) to diameter ratio (S/D) should be at least 4. Salt thickness between a cavern wall and the lateral salt dome boundary should be at least 3 times the cavern diameter.
- Minimum thickness of salt above a solution cavity should be 150 m. The ratio of overburden salt thickness to cavity span is to be at least 2.5. Cavern span should not exceed 60 m

Cavity height to diameter ratio (H/D) should be in the range of 1 to 5.

- Octahedral shear strength should lie between 3.8 and 5.2 MPa.
- In-situ horizontal stress should not exceed 120% of overburden pressure.
- Depressurization should not exceed 1 MPa/hr.
- Salt cavities must be protected against ground water encroachment.
- Surface subsidence in the region overlying a CAES cavity must not be significant.

Accessory minerals in salt reduce self-healing of fractures and contribute to irregular cavern shapes. Site selection will take this into consideration.

This document is not a general geotechnical engineering manual for solution mining and use of salt caverns for storage, but confines itself to those topics which will be of concern to cavern designers who are dealing specifically with the CAES application. Familiarity with the concepts of geologic engineering is assumed as is some knowledge of the compressed air energy storage technology.

ACKNOWLEDGMENTS

Technical direction of the overall CAES Program has been provided since inception by W. V. Loscutoff and L. D. Kannberg. Substantial technical contributions have been supplied by R. L. Thoms of Louisiana State University (also an author) and S. Serata of Serata Geomechanics in prior documentation. Susan J. Arey meticulously prepared the several drafts. Steven E. Farkas of Central Washington University developed the first compilation of salt CAES cavern guidelines while working at PNL under a National Science Foundation fellowship.

CONTENTS

FOREWORD	iii
SUMMARY	v
ACKNOWLEDGEMENTS.	vi
FIGURES	xiii
TABLES.	xiv
1.0 INTRODUCTION	1
2.0 STORAGE IN SALT CAVITIES	5
3.0 GEOLOGICAL ISSUES.	9
3.1 GENERAL REQUIREMENTS.	9
3.2 PETROLOGYANDMINERALOGY.	9
3.3 STRUCTURE	10
3.4 STRATIGRAPHY.	12
3.5 HYDROLOGY	13
3.6 SITE QUALIFICATION.	14
3.6.1 Initial Screening.	14
3.6.2 Geophysical Surveying.	15
3.6.3 Exploratory Drilling	15
3.6.4 Rock Characterization.	16
3.6.5 Hydrologic Characterization.	17
3.6.6 Huntorf Qualification.	18
4.0 SOLUTION MINING.	19
4.1 BASIC PROCESS	21
4.2 CIRCULATION METHODS	21
4.2.1 Direct Circulation	21
4.2.2 Reverse Circulation.	23
4.3 CAVERNDEVELOPMENT.	24
4.3.1 Conductor Casing	24
4.3.2 Surface Casing	28
4.3.3 Intermediate Casing.	28
4.3.4 Product Casing	28

4.4	HUNTORF EXPERIENCE.	29
4.5	BRINE DISPOSAL.	30
4.6	BRINE DISPOSAL WELLS.	32
4.6.1	Conductor Casing	32
4.6.2	Surface Casing	32
4.6.3	Product Casing	32
4.6.4	Injection Tubing	34
5.0	CAVERN STABILITY	35
5.1	MECHANICAL BEHAVIOR	35
5.1.1	Triaxial Compression Testing	38
5.1.2	Creep Behavior	40
5.1.3	Compressed Air Energy Storage Environment.	44
5.1.4	Loading Parameters	47
5.2	CYCLIC LOADING TESTS.	49
5.3	NUMERICAL MODELING OF MECHANICAL BEHAVIOR	49
5.4	VARIABLES OF NUMERICAL ANALYSIS	51
5.4.1	Cavern Depth	51
5.4.2	Cavern Air Pressure.	51
5.4.3	Excess Lateral Stress.	53
5.4.4	Octahedral Shear Strength.	53
5.4.5	Other Properties of Salt	53
5.4.6	Cavern Height/Diameter Ratio	55
5.4.7	Cavern Separation Distance	55
5.5	PARAMETRIC STUDIES OF SINGLE CAVERNS.	55
5.5.1	Cavern Depth	56
5.5.2	Cavern Air Pressure.	56
5.5.3	Excess Lateral Stress.	56
5.5.4	Octahedral Shear Strength of Salt.	56
5.5.5	Other Properties of Salt	57
5.5.6	Cavern Height/Diameter Ratio	57
5.6	TWO-CAVERN INTERFERENCE ANALYSIS.	57
5.6.1	Cavern Depth	58

5.6.2	Cavern Air Pressure	58
5.6.3	Excess Lateral Stress	59
5.6.4	Octahedral Shear Strength	59
5.6.5	Other Properties of Salt	59
5.6.6	Cavern Separation Distance	59
5.7	PRELIMINARY DESIGN CRITERIA	60
5.7.1	Basis of Criteria	60
5.7.2	Cavern Depth	60
5.7.3	Cavern Depressurization	60
5.7.4	Excess Lateral Stress	61
5.7.5	Octahedral Shear Strength	61
5.7.6	Other Properties of Salt	61
5.7.7	Cavern Height/Diameter Ratio	61
5.7.8	Cavern Separation/Distance Ratio	62
5.8	GENERAL CONCLUSIONS	62
5.8.1	Long-Term Stability	62
5.8.2	Design Criteria	62
5.8.3	Measure of Cavern Stability	62
5.8.4	Constitutive Equations	63
5.8.5	Cyclic Loading Tests	63
5.8.6	Temperature Effects	63
6.0	CAVERN DESIGN AND OPERATION	65
6.1	DESIGN GUIDELINES	65
6.2	GEOLOGIC FACTORS	66
6.2.1	Effect of Impurities on Mining	66
6.2.2	Caprock Instability	67
6.2.3	Creep Deformation	67
6.2.4	Surface Subsidence	68
6.3	CAVERN CHARACTERISTICS	69
6.3.1	Octahedral Shear Strength	69
6.3.2	Excess Lateral Stress	69
6.3.3	Depth to Cavern Top	70

6.3.4	Lateral Salt Thickness.	70
6.3.5	Vertical Salt Thickness and Span.	71
6.3.6	Height-to-Diameter Ratio.	71
6.4	INJECTION AND DECOMPRESSION PARAMETERS	72
6.4.1	Cavern Temperature.	73
6.4.2	Cavern Air Pressure	73
6.4.3	Depressurization Rate	74
6.4.4	Injection Parameters at Huntorf	75
6.5	COMPARISON OF NONCOMPENSATED AND COMPENSATED CAVERNS . .	75
6.5.1	General	75
6.5.2	Relative Effects on Cavern Stability.	76
6.6	CAVERN MONITORING.	78
7.0	DESIGN AND STABILITY CRITERIA	81
	REFERENCES	87

FIGURES

1	Major Salt Deposits and Mines in the United States	7
2	Casing Configuration for Sump and Cavity Construction.	20
3	Typical Cavern Construction Using Direct Circulation	22
4	Typical Cavern Construction Using Reverse Circulation.	25
5	Typical Development Concept.	26
6	Typical Cavern Development Well Configuration.	27
7	NWK Huntorf Cavern Shape Complying with Requirements of Rock Mechanics.	31
8	Typical Disposal Well Casing Configuration	33
9	General Response of Rock Salt to Load Applied at t_0	36
10	Brazilian Test Results for Salt from Different Sources	37
11	Typical Stress Strain Curves for Rock Salt	39
12	Strength of Rock Salt at 2% Deformation.	41
13	Strength of Rock Salt at 10% Deformation	41
14	Strength of Rock Salt at 20% Deformation	42
15	In Situ Representation by Triaxial Extension Test.	43
16	Triaxial Extension Creep Tests	45
17	Uniaxial Compression Creep Tests	45

TABLES

1	Geology of Major U.S. Salt Basins	8
2	Variables Considered in Analyzing CAES Cavern Design	52
3	Values and Ranges of CAES Cavern Parameters	53
4	Material Properties of Rock Salt at Room Temperature	54
5	Base Values and Ranges of Principal Parameters Used in Two-Cavern Analysis	58
6	Relative Effects for Compensated Versus Noncompensated CAES Caverns in Salt Domes	76
7	Design and Stability Criteria	82

GEOTECHNICAL FACTORS AND GUIDELINES FOR STORAGE OF COMPRESSED AIR IN SOLUTION-MINED SALT CAVITIES

1.0 INTRODUCTION

Compressed air energy storage (CAES) involves the reversible conversion of electrical to mechanical energy and effects the storage of low cost base load electricity for recovery during peak demand periods. Geologic space within a hard rock cavern, solution-mined salt cavity, or naturally porous, water-bearing formation is used to store the required large volumes of compressed air. Electrical energy is produced by heating the compressed air and passing it through staged surface turbines. Heat may be added by combustion of fossil fuel or by addition of the original heat of compression from a thermal storage reservoir.

Massive salt deposits exist in many locations throughout the world (Fenix and Scisson 1978). Many of these deposits have been used for constructing underground solution-mined caverns in which such diverse hydrocarbon fuels as natural gas, hydrogen, propane, butane, ethylene, and gasoline, have been stored. Because of its unique combination of characteristics, salt is an ideal rock for cavern construction. It is generally impervious to liquid or gaseous hydrocarbons, has a compressive strength comparable to concrete, moves plastically to seal fractures or voids, and can be easily mined by dissolution in water. Three basic conditions must exist at the location where storage facilities are needed if solution mining is to be used for cavern construction: 1) a sufficient thickness of structurally competent salt at a proper depth, without an excess of interbedded insolubles; 2) an adequate supply of raw water for leaching the salt; and 3) an environmentally acceptable and economical means of brine disposal.

In cavern storage (hard rock and salt) the compressed air reservoir may be either compensated or uncompensated (Chang et al. 1980). In a compensated reservoir the air pressure is determined by the height of a water or brine column extending from the cavern base to a surface pond.

This height and the air pressure will remain nearly constant, whereas the effective reservoir volume will vary considerably in accord with the compression-utilization cycle. In an uncompensated reservoir the air pressure will vary but the volume will remain constant. Because turbine performance is dependent upon maintaining pressure within a reasonably narrow band, the cavern must be sufficiently oversized to prevent catastrophic pressure drops during power generation. This over-sizing requirement is economically more attractive in salt cavern solution mining than in hard rock excavation.

During the proposed 30- to 50-year operational lifetime of a CAES cavern the subterranean system of containment and shafts could be subjected to between 15,000 and 20,000 loading/unloading cycles. The cyclic effects produced will result from pressurization/depressurization, temperature additions and subtractions associated with compression and expansion of the air, and water/humidity concentrations associated with pressure compensation and the presence of water vapor within the compressed air. Degradation of the exposed rock surface can be caused by fatigue from expansion/contraction and by accelerated weathering produced by heated oxygen/water contact with rock surface and crevices. To minimize the risk of either structural or air/water leakage instability, the geotechnical characteristics and material properties of any rock mass must be quantified before designing a cavern.

The primary objective of the studies reported herein was to compile preliminary criteria to ensure stability of CAES caverns solution-mined from domal or bedded rock salt. This report summarizes essential numerical modeling results, as well as laboratory work, and field-scale research. The material is based upon published and unpublished information relating to the geotechnical behavior of rock salt masses and describes the principal factors affecting CAES in solution-mined salt cavities. Most factors relate to cavern design, site geology, and operating conditions.

Section 2 presents background information about storage of natural gas and petroleum in salt caverns developed by solution mining. The Huntorf CAES plant caverns are described. The candidate salt deposits of the United States and prospects for their utilization are described.

Section 3 treats the geological factors and includes: 1) general (siting) requirements, 2) petrology and mineralogy, 3) structural features, 4) stratigraphy, 5) hydrology, and 6) site qualification (initial screening, geophysical surveying, exploratory drilling, rock characterization, hydrological characterization and Huntorf qualification).

Section 4 describes basic elements of solution mining. These include drilling, water injection and brine displacement. The solution mining experience at Huntorf is described.

Section 5 describes cavern stability based upon numerical modeling and laboratory studies of rock mechanics. The parameters addressed are cavern depth, cavern air pressure, excess lateral stress, rock salt strength, cavern height/diameter ratio, and cavern separation/diameter ratio.

Section 6 treats six aspects of cavern design and operation: 1) design guidelines, 2) geologic factors, 3) cavern characteristics, 4) injection and decompression parameters, 5) comparison of noncompensated and compensated caverns, and 6) cavern monitoring.

Preliminary design and stability criteria are tabulated in Section 7. Although many are assigned numbers, others are handled with qualitative statements. Reservoir properties such as rock salt strength, horizontal stress, temperature, pressure, depth, wall thickness, and rate of depressurization are specified in the light of previous storage or CAES experience, numerical modeling and rock mechanical experiments.

2.0 STORAGE IN SALT CAVITIES

Caverns have been solution-mined from both bedded and domal salt for storing natural gas and petroleum. The first cavity for natural gas storage was leached from bedded salt at Marysville, Michigan in 1948. Since then the majority of cavities have been solution-mined within Gulf Coast salt domes (Weinstein et al. 1978).

Both types of salt deposits have been studied to determine their feasibility for long-term containment of hazardous nuclear and chemical wastes. The results of these studies and experience with storing hydrocarbon fluids provide information germane to the storage of compressed air. However, CAES storage raises more concerns with stability than relatively static forms of storage (Thoms 1978).

The concept of utilizing surplus baseload electrical power to compress air for operating gas turbines to decrease conventional electrical production peaks can be credited to Professor Bozidar Djordjevitch of Yugoslavia (Weinstein et al. 1978). The CAES method was patented in the U.S. in 1948 (Gay 1948) and in the Federal Republic of Germany in March 1956. The Geological Survey of the Federal Republic of Germany recommended abandoned salt and potash mines as the most technically and economically feasible geologic containments for compressed air. The development of the solution-mined cavern concept permitted the CAES design to specify cavern depth, shape and wall quality.

In late 1978, the world's first CAES plant went on-line at Huntorf, West Germany. Two cavities of about 150,000 m³ each were solution-mined within a domal structure in the Zechstein salt. Air is stored at pressures up to 7.0 MPa (Quast and Lorenzen 1979). The top of the salt mass is about 500 m below ground and the cavity tops are at least 600 m below ground surface. The maximum cavity diameter is 60 m. Cavity height is 180 m. The salt pillar thickness between cavities is 160 m. The salt thickness above the cavities is 100 m. The maximum storage

pressure permissible is computed at 10.0 MPa. Design and development of the Huntorf facility is described in Sections 3 and 4 of this report.

Massive bedded salt deposits occur in sedimentary basins within the west-central, southern, and north-central United States (Figure 1). Diapiric salt domes, which are intrusions of relatively pure salt from their original beds into the overlying sediments, occur in the Gulf Coast region of Mississippi, Louisiana, and Texas. Bedded salt deposits occur in the Paradox Basin of Colorado and Utah. Depths and thicknesses of major U.S. salt basins are shown in Table 1 (Querio 1980). Many deposits have been or are currently being mined by both room-and-pillar excavation and solution extraction techniques.

The salt deposits are located mostly in areas of known low seismic risk and long term geologic stability. Faulting near salt domes is associated with their diapiric emplacement and is not attributable to large regional tectonic stresses. Some bedded salts have excellent structural properties, including high compressive strength (comparable to concrete) and plasticity, which under ideal conditions may passively relieve stress by deformation rather than fracture. Properties of salt domes that make them most compatible with controlled solution-mining of CAES chambers are:

- nearly homogeneous lithology consisting of about 95% halite with minor accessory minerals
- large deposits occurring at relatively shallow depths
- imperviousness to saturated, stagnant ground water
- chemical compatibility with oxygen.

The value of the U.S. salt dome resource is now being recognized. Development of salt domes for hydrocarbon storage, radioactive waste isolation, waste disposal, and other important uses requires a serious consideration of space utilization. Systematic planning is necessary to permit future accommodation of current and potential uses.

FIGURE 1 Major Salt Deposits and Mines in the United States (Aamodt et al. 975)

TABLE 1. Geology of Major U.S. Salt Basins (Querio1980)

<u>Location</u>	<u>Range in Depth</u>	<u>Maximum Thickness</u>
Sabin Basin		
Michigan	150 - 1920 m	550 m
New York	215 - 915 m	122 m
Ohio	245 - 1830 m	92 m
Pennsylvania	670 - 2750 m	61 m
Gulf Coast Basin	Over 300 salt domes at various depths	Not measured
Williston Basin	Generally 1525 m	92 m
Permian Basin	61 - 1220 m	150 m inter- stratified with shale
Paradox Basin	150 - 1220 m	65 m
Supai Basin	305 - 460 m	31 m

Early development of salt domes at shallow depths may preclude future deep development if allowances are not made for additional access space. For example, the Bayou Choctaw Salt Dome is extensively used for light hydrocarbon storage. Twenty-three cavities have been created in this dome with storage capacities ranging between 3,000 and 17,000 barrels. The current space utilization pattern of this dome may preclude some types of future development such as CAES systems. For example, hydrocarbon storage cavities usually are subjected to less severe loading environments than those expected for CAES systems. As a result, a system of cavities ideally spaced for hydrocarbon storage may disqualify the dome for safe containment of CAES cavities at an optimal depth (Martinez and Thoms 1977).

Geologic, operational, and institutional issues must be resolved at each potential site during the design, construction, and utilization of a solution-mined cavity for CAES. The remainder of this report concentrates on the geologic and operational issues revealed in the literature on rock salt cavities.

3.0 GEOLOGIC ISSUES

Geologic issues embrace all aspects of rock salt's natural occurrence. These include its mineralogic and petrologic characteristics, structure, stratigraphy, and interactions with vadose, saturated and confined aquifer zones.

3.1 GENERAL REQUIREMENTS

The salt deposit must be of sufficient diameter and thickness to accommodate one or more solution-mined openings at substantial distances from the top, bottom, and sides of the formation. If multiple cavities are to be mined the salt walls separating them must be sufficiently thick to prevent any cavern-to-cavern interaction. The salt quality should be adequate to contain compressed air without compromise due to extensive impure zones or solution channels. The salt deposit may be a dome, anticline or possibly a flat-bedded formation. The salt deposit should not exhibit effects of significant dissolution, e.g., saline plumes in normally fresh water aquifers. If the salt is considered, the ideal caprock would be impervious and tightly sealed to the underlying dome. The history of the salt deposit should not divulge uncontrolled brining, petroleum, or sulfur recovery operations that have compromised the salt's integrity.

3.2 PETROLOGY AND MINERALOGY

Rock salt formations consist dominantly of halite, often in coarse crystal sizes with individual orientations measuring up to many millimeters parallel to each crystallographic axis. Other saline minerals associated with rock salt deposits include gypsum, anhydrite, sylvite, and carnallite. More rarely, kainite and polyhalite may be associated (Hurlbut 1941). Calcite, clay minerals, and quartz are also found, usually within particular zones. These relatively insoluble minerals may represent indigenous impurities deposited due to interruptions in the evaporative process, e.g., an interim fresh water flood during prior sedimentation periods.

Weak salt, gas, brine, inclusions, and gas outbursts are known to occur in spatial trends or "zones" in some Louisiana salt domes mined by the room and pillar method (Kupfer 1976, Kupfer 1978, Thoms and Martinez 1978a). Such trends are possibly the chief concern with the integrity of salt domes for all kinds of storage. In the generally homogeneous and relatively light salt away from these zones, few problems are encountered relative to brine, gas, wall spalling, or roof falls. Furthermore, the salt in such areas is relatively impermeable. In the trend zones the salt is darker because of impurities and higher anhydrite content, and it may exhibit generally undesirable features of inhomogeneity, structural weakness, and relative permeability. Whether these features "die out" with greater depth remains to be investigated. In any case, the intersection of such zones with CAES caverns must be avoided; otherwise, the integrity of the air reservoir could be jeopardized. Establishing the locations of these trends or zones apparently can be accomplished only by thorough geologic investigations, including cored drill holes. It has been suggested that some indications of such zones may be obtained by mapping the dome surface with complementary shallow seismic methods. Other potential indirect methods include gravimetry, magnetometry and acoustic holography (Thoms and Martinez 1978b).

The Zechstein salt stock utilized for air storage at Huntorf is composed mainly of rock salt with 5 to 10% anhydrite and clay, as well as some thin layers of potash (Quast and Lorenzen 1979). Potash seams and anhydrite layers were identified also at the flanks of the dome.

3.3 STRUCTURE

The cores of salt domes in the U.S. are essentially circular in plan, and characteristically range in diameter from 0.8 to 3.2 km with some up to 8 km in diameter (Billings 1972). German salt domes are comparable in diameter. Russian salt domes on the northeast shore of the Caspian Sea range from 4.8 to 12 km in diameter. The cores of the Rumanian salt domes are elliptical in plan with the longer axes parallel to the trend of associated folds.

In many salt domes the walls dip steeply outward; the top may be flat or domed. Some cores are symmetrical, the walls dipping at essentially the same angle on all sides; other cores are asymmetrical, the walls dipping steeper on some sides than on others. In many American domes the upper core overhangs or "mushrooms". In other words, although in the uppermost levels the core diameter increases downward, at greater depth it narrows again. Adequate prospecting is necessary to prevent solution mining too close to a concealed overhung vertical contact (Thoms and Martinez 1978b).

In northern Louisiana, wells have been drilled more than 1500 m into salt domes, and in Germany wells have been drilled 1220 m through salt. The depths to the bottoms of these wells are conjectural.

Caprocks usually overlie salt domes and may be over 30 m thick, but in some domes they are absent. The caprock characteristically consists of limestone, gypsum, and anhydrite from top to bottom. Commercial deposits of sulfur and other minerals occur in some caprocks. For example, uranium minerals occur in caprocks found in southern Texas.

The domed sediments overlying the cores of some salt domes are transected by normal faults. These faults may be radial, but more commonly they tend toward parallelism in which one or more grabens are identifiable. These faults show that the sediments were subjected to tension during salt emplacement.

The depth of the core beneath the surface varies widely, and salt domes are sometimes classified on this basis (Billings 1972). Deep domes are those in which the top of the core is 1525 m or more beneath the surface; in some so-called deep domes, the evidence for their existence may be entirely geophysical. Intermediate-depth domes are those with core tops 1067 to 1525 m below surface. Shallow domes are those whose core tops are less than 1067 m deep. The shallow domes are most suitable for CAES.

The salt anticlines of the Paradox Basin in Colorado and Utah are folded rather than intrusive structures. This region probably has substantially higher horizontal stresses than the Gulf Coast region because it lies within an orogenic belt. However, significant strain is likely at depths of 915 m and greater in the Paradox Basin (Serata and McNamara 1980). When the salt becomes viscoplastic no vertical/horizontal stress differential can be maintained.

3.4 STRATIGRAPHY

The typical sedimentary sequence intruded by a salt dome shows vertically variable lithology due to diverse epochs of sedimentation and horizontally variable lithology due to facies changes. This variability is further compounded by faulting caused by the upward diapiric movement of the salt stock. The sediments surrounding a salt dome core are uplifted into an anticlinal dome (Billings 1972). The sediments in many instances are sharply truncated by the rock salt core, whereas in other occurrences the bedding planes are parallel to the salt contact. On this basis salt domes may be classified as "piercement" and "non-piercement" domes. Some domes may show both relationships; the cores may truncate the older formations on their flanks, but not the younger strata near their tops.

The sedimentary rocks adjacent to the cores have been dragged upward many thousands of feet. The exact measurements may be calculated by comparing the depth of a bed adjacent to a salt core with its depth where it has not been disturbed by the salt intrusion.

Materials derived tectonically from intruded formations may be incorporated within the peripheral regions of the salt. Such material may exist as gouge, breccia or larger horsts, reducing the contact definition between salt and country rock. Gouge zones have been discovered at salt-sedimentary contacts in the Gulf Coast domes. Thick breccias are reported locally surrounding Rumanian domes. The breccia fragments are embedded in matrices of halite and gypsum.

3.5 HYDROLOGY

The Gulf Coast Embayment is an hydrologic basin of considerable size with a thick sequence of southerly dipping sedimentary strata. Large volumes of ground water migrate or are contained in high permeability aquifers in these strata. Aquifer recharge takes place along the northern perimeter of the embayment as a result of annual rainfall in excess of 100 cm (Aamodt et al. 1975).

Natural hydrostatic pressure causes ground water to rise to the surface in areas of faulting or salt dome intrusion. Water-saturated strata surround the salt domes to considerable depths. The hydrologic regime of each salt dome is different, and information concerning hydrologic conditions is sparse, despite the great density of drilling.

Because salt is impermeable, it acts as a barrier to ground water. The rate of salt dissolution is dependent on the rate of flow, fractional saturation of the water, and solubility of the salt formation.

A water problem can occur when sinking shafts through very permeable and saturated strata or when large lenses of water-bearing sandstones are occasionally encountered during mining operations in either salt domes or bedded deposits (Aamodt et al. 1975). Drillholes that penetrate bedded salt deposits and connect aquifers above and below can serve as channels for the migration of water resulting in the dissolution of salt. Because some salt domes and some bedded deposits are surrounded by saturated strata, flooding of mines can occur if the impervious walls of the salt are penetrated. The potential also exists for the flooding of mined caverns by surface streams, lakes, and impoundments.

A detailed exploration program and analysis of hydrologic conditions must be carried out prior to and during mining. Excellent control must be exercised during mining operations. Leakage around the shaft pipe must be controlled by sealants (Weinstein et al. 1978).

3.6 SITE QUALIFICATION

The configuration of the system can be determined to varying degrees of detail by a combination of geophysical methods, e.g., seismic and gravity techniques, and by reference to drilling data. Drilling data are usually considered as control points for the seismic data; however, the sources of such logs should be carefully reviewed prior to weighing them with a high level of confidence. Slant drilling and more sophisticated (and expensive) geophysical methods can be employed **if** required to define salt boundaries (Thoms and Martinez 1978b).

3.6.1 Initial Screening

The site-specific utilization history of potential air storage structures should be researched to ensure that man-made effects will not threaten the integrity of the containing salt. A number of salt domes in the U.S. Gulf Coast have a history of sulfur mining, uncontrolled ("wild") brine operations, and other generally poorly defined early uses. There must be an absence of man-made hydraulic fracturing connections or solution channels through the salt, possibly due to early brine production, that could open under CAES operations (Thoms 1978). A good record of ability to maintain well casings through caprock (if any) into salt is also desirable. Any previous brine and/or sulfur operations in caprock should be checked to ensure that associated effects such as surface subsidence have essentially ceased and will not significantly affect CAES operation. Results of level recording surveys may be available. Careful study of all historical records of dome utilization and discussions with local area residents should be carried out to determine the current status of any particular potential CAES dome (Thoms and Martinez 1978a).

Illustrating the importance of careful site screening is the rapid creep that occurred within the Eminence dome in Mississippi. The natural gas storage cavities underwent a 40% volume reduction within several months after completion (Dreyer 1974). Roofs and floors of two cavities were at approximate depths of 1737 m and 2042 m, respectively (Allen 1972). Although the rock salt behavior around the Eminence cavities may have been anomalous for U.S. Gulf Coast domes, **it** would

not be prudent to propose preliminary long-term cavity stability criteria that ignore this field example of undesirable behavior (Thoms 1979).

3.6.2 Geophysical Surveying

Seismic prospecting using both refraction and reflection methods has been very successful in locating and delineating salt domes (Billings 1972). Gravitational methods have also been applied with success because salt domes are usually associated with gravity anomalies due to the low density of salt relative to adjacent rock formations. Resistivity methods depend upon the fact that salt domes appear as resistivity highs, probably because of the absence of ground water. In some instances, however, the dome may appear as a resistivity low because strata of low resistivity overlie the dome.

For three-dimensional mapping of a salt structure, seismic surveying is the most valuable geophysical method. The upper surface and surrounding sedimentary strata can be mapped by reflection, whereas the deeper relatively steep boundaries of the structure can be mapped by both refraction and reflection methods. Special techniques may be applied to mapping an overhanging type dome. Seismic reflection prospecting is most applicable to mapping salt anticline configurations.

3.6.3 Exploratory Drilling

A drilling program is developed to reach several objectives: 1) verify the salt structure divulged by geophysical results; 2) explore and sample the caprock for mineralogy, porosity/permeability, adherence to the salt dome, and presence of corrosive geochemical substances; 3) sample the salt dome for mineralogy, crystal size and boundary characteristics, presence of lesser quality zones or trends, and core procurement for mechanical property determination; 4) geophysical logging; and 5) in situ stress measurement.

Slant drilling may be required to accurately determine the steeply dipping lateral boundaries. Another possible approach to lateral boundary mapping would use a sonic source within a borehole coupled with geophones

(also in the borehole) to measure travel times of seismic waves from the hole to the salt boundary and back.

3.6.4 Rock Characterization

Mined salt deposits contain very pure sodium chloride with minor amounts of anhydrite, related salts, and shales. These contaminants usually do not exceed 5% of total composition. Minor amounts of interstitial water and gas (commonly CO_2 and methane) may also exist. Salt domes are generally more pure than bedded salt deposits, possibly because of a natural refining of domal salt during intrusion. Similarly, younger coastal domes generally are considered to be more pure than the older and more shallow interior domes (Aamodt et al 1975).

The inherent imperviousness of salt, whether bedded or domal, is often enhanced by associated impermeable rock, either as discrete intervals above, below, or within bedded deposits with the salt. Also, sometimes the caprock over a salt dome may be impermeable and form an effective seal. In some cases the caprock may be very permeable and cavernous and pose problems for cavern borehole development (Thoms and Martinez 1978b).

The purity of naturally occurring salt is responsible for its highly impermeable nature; thus, it is an important property when considering plastic deformation, which acts to close permeable openings. In general, minerals other than halite tend to reduce the self-healing properties of rock salt (Aamodt et al. 1975).

Rock characterization procedures will involve optical and electron microscopic analysis, x-ray diffraction, x-ray spectrometry, chemical analysis, and physical and mechanical property measurements. Accessory minerals and their distributions will be identified. Differential thermal analysis may be useful to identify saline hydrates.

Crystal diameters in polycrystalline rock salt are relatively large, often more than 6 mm. Scale effects may influence laboratory tests using relatively small specimens (Stickney 1977). Some test data imply that dependence on diameter of cylindrical salt specimens falls

off sharply for cylinders 10 cm or more in diameter with length to diameter ratios of 2 or slightly larger.

Microfracturing of rock salt may affect the degree of penetration of air and water along grain boundaries and internal fractures under cyclic CAES operating conditions. The quantitative importance of this effect must be determined in the laboratory. The damage zone thickness due to this mechanism must be quantified to establish optimal distances between CAES caverns and between caverns and the peripheries of salt domes surrounded by porous and saturated aquifers. Creep deformation of rock salt influenced by air penetration under CAES operations must also be quantified (Thoms and Martinez 1978b). In situ testing methods are receiving increased attention in geotechnical engineering. For rock salt mechanics in particular, where large crystal sizes are encountered, in situ testing is particularly appropriate as test specimens are likely to be damaged by sample coring methods (Thoms and Martinez 1978b).

In situ CAES field tests in the Jefferson Island salt mine in south Louisiana have included static and cycle loading (Thoms and Gehle 1981). Diametral hole displacements and acoustic emissions showed close correlation. Acoustic emission is a promising method for monitoring operational CAES reservoirs. The field experiments showed that salt permeability depends upon load history and confining pressure.

3.6.5 Hydrologic Characterization

The principal region requiring study lies above the salt dome or anticline. Unconfined or confined aquifers overlying the dome must be isolated from all exploratory boreholes and larger diameter penetrations. Other geologic structures containing water may consist of permeable sedimentary lenses within a salt formation, abutting sedimentary strata, fault zones adjacent to or above a salt formation and aquifers below a salt formation.

Stagnant water in contact with salt does not constitute an important hazard to the salt body's integrity because saturated water cannot dissolve sodium chloride. Existing stable salt formation/ground water relationships must not be perturbed by infusion of unsaturated ground water.

3.6.6 Huntorf Qualification

Before the startup of the NWK project, the Huntorf salt dome was thoroughly explored by four wells for a natural gas storage project within the same dome (Quast and Lorenzen 1979). The dome is located about 20 km east of Oldenburg in Lower Saxony. The salt dome is a nearly symmetrical zone of Zechstein salt with an elliptical cross-sectional area of 12 km² at 800 m below mean sea level. The Zechstein salt formation is generally very complex and shows ample evidence of complicated geologic and tectonic history. It is composed of rock salt from the Strassfurt series with impurities of 5 to 10% anhydrite and clay and some thin layers of potash. Potash seams and anhydrite layers were also identified at the flanks of the salt dome. In the central part of the dome, wells drilled to a depth of 950 m identified only salt layers of so-called "Zechstein III", which is eminently suitable for the construction of cavities. Wells have not been drilled deeper than 950 m to date. The bottom of the Zechstein mass, however, is probably approximately 3,000 to 4,000 m underground.

Each cavity well was designed for a maximum air throughput of 210 kg/sec at minimum friction losses. The last cemented casing had a diameter of 62.2 cm to allow installation of a 50.8-cm diameter production tubing. This tube can produce the necessary air flow rates at friction losses of less than 300 kPa in the design pressure range. Because of the high costs and geologic risks involved in large-diameter wells, each location selected was first probed by an exploratory well of a smaller diameter. Five exploration wells were drilled between November 1974 and June 1975. Three wells transected rock salt layers alternating with layers of anhydrite and potash salt. It was judged that the compressed-air cavities should not be established in any of these locations. The other two wells confirmed the presence of suitable rock salt layers with permissible fractions of insoluble components and potash salt. The cavity wells, designated NK1 and NK2, were drilled by combined rotary/air lift drilling 20 m from the exploration wells during the period from April to November 1975.

4.0 SOLUTION MINING

The basic technique of cavern development involves drilling a hole into the salt formation, injecting water, allowing time for dissolution of the salt, and displacing the resulting brine from the hole (Fenix and Scisson 1978). This section describes the basic process and the solution mining experience at Huntorf.

4.1 BASIC PROCESS

During initial injection, the pressure differential between the cavern's fluid entry point and its fluid exit point forces circulation. As the cavern grows, the density differential between injected raw water and brine causes gravity convection, which provides the necessary circulation during the remainder of the leaching process.

A so-called blanket material is a protective fluid that occupies the space in the uppermost interval of the cavern. The blanket fluid is lighter than water and does not dissolve salt. Its purpose is to prohibit leaching of salt from around the cemented casing and assure a pressure tight cavern. The blanket also prohibits development of high spots from which the stored product could not be removed. In addition, it protects the product casing from internal corrosion and can be used to restrict initial leaching to the upper limit of the interval selected for the sump. Typical blanket fluids are natural gas, propane, butane, diesel oil, and crude oil.

Relatively insoluble minerals common in ~~dome~~ salt include quartz, anhydrite, gypsum, and clay minerals. As leaching proceeds, insoluble minerals accumulate in the bottom of the cavern. This deposit may cause plugging of the wash string or restrict free circulation. If this occurs the wash casing must be raised to a new position before leaching continues. The problem can be solved by either physically removing the insoluble fraction (normally not economically feasible) or constructing a collection sump below the cavern interval as shown in Figure 2.

FIGURE 2. Casing Configuration for Sump and Cavity Construction

The direction of circulation, injection point of fresh water, and the control of contact surface between the blanket and the water are the principal factors influencing cavern shape. The final shape and size of a cavern also depend on leaching rate, overall leaching time, percentage of insolubles in the salt stock, and solubility of the salt stock.

During solutioning, interface logs are run periodically to determine the blanket-to-brine interface. These logs are needed particularly when the blanket and/or wash casing strings are moved to control the cavern shape. In addition, a sonar log may be run periodically during solutioning to track the shape of the cavern. The cavern shape may deviate from that desired due to erratic distribution of insolubles in the salt dome (Chang et al. 1980). A sonar log is always run at the end of solutioning to determine final cavern shape and volume. The cavern volume is also determined during solutioning by measuring the volume of water circulated and by monitoring the salinity of the returned brine.

The volume determined by sonar may vary from the calculated volume because all irregularities are not recorded by sonar. For this reason, the calculated volume is usually the final accepted figure. Dimensional limitations may be imposed by proximity of adjacent caverns and distance to the dome's boundary or property lines, as established by state rules.

4.2 CIRCULATION METHODS

Water may be introduced into a cavern by either direct or reverse circulation (Fenix and Scisson 1978). Direct circulation is more common.

4.2.1 Direct Circulation

With direct circulation, water is injected through the wash casing set near the bottom of the wellbore and brine is discharged through the blanket casing (see Figure 3). Direct circulation is usually used to develop the sump in the cavern floor. Leaching continues until the sump configuration, commonly cylindrical in shape, is developed. The wash casing is then repositioned for cavern development. The blanket

FIGURE 3. Typical Cavern Construction Using Direct Circulation (after Fenix and Scisson 1978)

string and/or interface is set at or near the location predetermined for the roof of the cavern.

Leaching is initiated by direct circulation of the water in the confined wellbore. Salinity increases not only radially outward from the centerline of the wash casing but vertically from the point of injection to the point of discharge from the cavern.

This pattern initially develops the typical "teardrop" cavern shape (see Figure 3). With continued direct circulation, the heavier brine solution tends to collect near the bottom of the cavern, forcing the inlet water to rise rapidly with decreasing exposure to lower portions of the cavern. Continued leaching usually develops the intermediate and upper portions of the cavern and results in the formation of a more cylindrical cavern.

Further leaching develops the upper cavern. As additional water is injected it tends to rise rapidly to the point of discharge. A rolling motion is produced that facilitates mixing and helps to distribute a nonsaturated solution below the blanket interface.

Upon contact with the interface some of the nonsaturated solution is discharged up the blanket casing; the rest is forced radially outward and dissolves salt exposed to the upper walls of the cavern. Thus, it is not uncommon for the brine discharge to be slightly undersaturated when this method is used. As the cavern enlarges, the solution becomes more saline and tends to sink to the bottom of the cavity. In actual practice, advancing upper cavern development to the cylindrical stage with direct circulation requires additional leaching time and the development of very large caverns.

4.2.2 Reverse Circulation

As in direct circulation, flow patterns for reverse circulation enable a variety of cavern shapes and sizes to be constructed. The position of the blanket casing is an important factor in determining the shape of the caverns.

The casing configuration for upper cavern injection is the same as for direct circulation but the flow is reversed. Because it is lighter than brine, water continuously injected into the cavity rises to or remains at the blanket interface. It is then displaced radially outward until it contacts and begins to dissolve the salt. As the solution increases in salinity and becomes heavier, it sinks to the bottom of the cavern where the discharge pipe is set. This results in the "morning glory" shaped cavern illustrated in Figure 4.

Reverse circulation is also used in cases where the blanket casing is positioned at any point in the cavern interval from the roof to near the bottom of the wash casing. These positions characteristically result first in an enlargement of the wellbore near the point of injection and later in a more cylindrical shape in the lower part of the cavern.

A cylindrical cavern can be constructed in several ways. One is to alternate the direction of flow with the blanket and wash casing in the same position. Another is to change the depth of the blanket and/or wash casing at selected time intervals.

4.3 CAVERN DEVELOPMENT

A procedure used to construct a typical cavern development well is discussed below (Fenix and Scisson 1978). Figure 5 shows a typical minimum surface installation for cavern development. Figure 6 illustrates the casing configuration used in a typical cavern development solution well.

4.3.1 Conductor Casing

A short section of casing called conductor casing is usually set before mobilizing the rotary drilling rig. This casing may be driven into place under swampy conditions or may be set in a hole dug with an auger drill. The conductor casing has two purposes. It prevents the loose soil and shallow unconsolidated sands and gravels from continually sloughing into the borehole as it is being drilled. Also, while the

FIGURE 4. Typical Cavern Construction Using Reverse Circulation (after Fenix and Scisson 1978)

FIGURE 5. Typical Development Concept (after Fenix and Scisson 1978)

FIGURE 6. Typical Cavern Development Well Configuration (after Fenix and Scisson 1978)

hole for the surface casing is being drilled by normal rotary drilling, drilling mud is directly circulated down the inside of the drillpipe and back up the drillpipe-borehole annulus. As mud containing formation cuttings return to the surface, the conductor casing "conducts" it to surface mud pits through an outlet connection near the top of the casing. After the well is drilled, the conductor casing is usually cut off at ground level.

4.3.2 Surface Casing

A somewhat longer string of pipe called surface casing (not shown in Figure 6) is required after the hole has been drilled through the potable water zones. This protects the water zones from mud contamination and from fluids or gases that might be encountered deeper in the hole. Cement is placed between this casing and borehole from the bottom to surface.

4.3.3 Intermediate Casing

Intermediate casing may be required to isolate very porous loss-of-circulation zones or intervals where formation caving occurs. These zones often are found in or near the eaprock. Mississippi and Louisiana state rules require two casing strings into the salt. One intermediate string is set after the well is drilled 15 to 30 m into the salt. The other casing string extends to the top of the cavern structure. Cement is placed between these casing strings and the borehole.

4.3.4 Product Casing

Product casing is the last casing to be cemented in the well and is set at the depth chosen for the top of the cavern. Before it is installed the borehole may be drilled to the planned depth of the bottom of the sump if suitable geologic conditions exist. The casing is cemented at least up into the intermediate casing or the surface casing if an intermediate string is not used.

In the specific case of compressed air storage, the air is conducted through another casing string suspended inside the product casing to 30 m below the bottom of the casing. For final design, consideration will be given to placing a packer on the suspended casing at the base of the cemented product string. This will also involve a possible expansion joint in the suspended string to allow for expansion while injecting heated air.

4.4 HUNTORF EXPERIENCE

Solution mining was used to develop two air storage caverns at Huntorf, Federal Republic of Germany. Logs run in exploration wells were correlated with the chemical and physical analyses of cores taken from the future cavern volume (Quast and Lorenzen 1979). A detailed solution-mining concept was prepared for each cavity using a three-dimensional numerical simulation program. This concept was used to achieve the cavern configuration required by rock mechanics calculations.

After 50,000 m³ cavity volume had been washed out by direct leaching, the cavity shape was checked by echo-logging. Subsequently, solution-mining was continued by indirect leaching to increase brine saturation and to reduce solution-mining time. Indirect leaching involves reverse circulation, i.e., opposite to that shown in Figure 2. The injected fresh water remains just below the blanket, moves radially to the salt boundary, dissolves salt, and eventually migrates toward the bottom from which it is pumped through the discharge pipe.

Rock salt taken from the NK1 cavity borehole contained substantial impurities, and when the cavity volume exceeded 55,000 m³, the potassium and magnesium fractions increased disproportionately in the brine. From this, it was concluded that salt layers of higher solubility were being leached. Interim surveys demonstrated steep layers in the southeast portion of the cavity, which extend over the total height. These layers dissolve more rapidly than rock salt. Horizontal sections, however, do not show any formation of "finger traps" in spite of very different

solution velocities; they show a shape which is still acceptable from a rock mechanics point of view. By reducing the solution mining rate, altering the suspended tubing depth, and frequently checking shape development, the cavity diameter could be controlled in such a way that it remained within the required limits as shown in Figure 7. However, the final roof shape deviated from the intended shape due to the more complicated and varied solution behavior in that area. The total volume of the cavity is about 150,000 m³.

The salt encountered in the NK2 cavity location is more uniform in solubility. A cavity was dissolved with total volume of 170,000 m³ whose shape is satisfactory from a rock mechanics standpoint. The solution-mining steps were the same for both cavities. However, the logging and tubing alteration work needed was less extensive than for the NK1 cavity. Figure 2 shows the actual cavity shapes (NK1 and NK2); both are within design limits.

The cavities were leached between October 1975 and January 1977. The maximum solution-mining rates were 300 m³/hr (NK2) and 200 m³/hr (NK1).

4.5 BRINE DISPOSAL

In some areas otherwise qualified for solution mining, the high cost of brine disposal may preclude cavern construction. The rates of cavity construction and brine disposal are interdependent. The brine must be disposed of in an environmentally acceptable manner.

In small-scale projects, it is sometimes possible to reclaim and sell the dissolved salt. However, the construction rates would then be controlled by extraction plant capabilities (Corcoran et al. 1974a). The most widely used method is to inject the brine into a saltwater aquifer (Medley 1978; General Electric 1976; Corcoran et al. 1974a). However, disposal may be restricted by governmental regulations or by the plugging of the aquifer due to the injection of brines (Corcoran et al. 1974a). Brine may also be pumped into the Gulf of Mexico or into another saline body if the necessary permits can be acquired. Another method is to

FIGURE 7 . NWK Huntorf Cavern Shape Complying with Requirements of Rock Mechanics

dispose of the brine in surface-lined pits, sumps, or in another cavity specifically constructed for that purpose. These latter methods would result in cost increases that might cause an otherwise acceptable site to become unattractive (Weinstein et al. 1978).

4.6 BRINE DISPOSAL WELLS

A typical procedure to develop a brine disposal well is discussed below (Fenix and Scisson 1978). Figure 8 illustrates the casing configuration used in a typical disposal well.

4.6.1 Conductor Casing

The first casing to be installed after the site has been selected for the brine disposal well is the conductor casing. As in the cavern development well, its purpose is to keep the wellbore open through the shallow surface formation and to conduct drilling mud to the mud pits while the hole for the surface casing is being drilled. After the hole for conductor casing is drilled and casing is installed, the space between the casing and hole is cemented to the surface.

4.6.2 Surface Casing

The hole for surface casing is drilled next and casing is installed and cemented from the bottom to the surface. This casing isolates all freshwater-bearing formations from the injected fluids.

4.6.3 Product Casing

After the surface casing is set, the hole for product casing is drilled to total depth. Casing is installed and cemented from the bottom to a point well above the zone to be perforated. The purpose of the casing and the cement is to prevent migration of fluids between the formations penetrated.

Following installations of the product casing, a perforating gun is used to make perforations through the casing wall and the cement sheath and into the disposal zone. Acid is then injected into the well

FIGURE 8. Typical Disposal Well Casing Configuration (Fenix and Scisson 1978)

and forced out through the perforations. The acid increases the size of the holes made by the perforations through the cement and cleans off drilling mud left on the face of the formation. In some instances, hydraulic fracturing may be necessary to increase injectivity.

4.6.4 Injection Tubing

An injection tubing string is required as additional protection of upper formations. A packer is installed on the lower end of the injection tubing and set inside the product casing at a point above the perforations to form a mechanical seal between the injection tubing and product casing. Hydrocarbons or treated fluids may be used in the injection tubing-product casing annulus to protect against corrosion.

5.0 CAVERN STABILITY

The state-of-knowledge about cavern stability embraces laboratory results of mechanical testing, numerical modeling, in situ field test data, and full-scale field results involving salt cavities used for both CAES and other storage technologies. The study of fundamental rock salt mechanics for CAES involves complicated loading conditions (Thoms 1978). An integrated mechanical model has so far eluded researchers. Nevertheless, CAES is operational at Huntorf where empirical relationships were used to design the dual salt cavities. Numerical models are described by Cundey and Serata (1978), Serata and Cundey (1979) and Serata and McNamara (1980).

Golder Associates (1979) has summarized the possible negative outcomes associated with cavern instability: 1) excessive closure without brittle failure which renders the cavern inappropriate for storage; 2) structural instability of the roof, walls, or floor of the cavern; 3) damage to the access well and associated equipment; 4) surface subsidence including major structural failure of the roof; and 5) loss of stored fluid.

This section presents the results of mechanical testing and numerical modeling. The combined data are used to develop design criteria and general conclusions.

5.1 MECHANICAL BEHAVIOR

Rock salt behavior may be typified using time as a general reference parameter. For a static creep test, a constant state of stress (load) is applied and maintained constant for the duration of the test. Strain is monitored and plotted as a function of time. A family of curves can be obtained for a set of loadings selected so as to span the stress state anticipated around a cavern.

With reference to Figure 9, application of an "instantaneous" load to a salt specimen at time t_0 results in 1) an "immediate" nonlinear displacement (or strain) response ϵ_0 , 2) a time-dependent creep response

FIGURE 9. General Response of Rock Salt to Load Applied at t_0 (after Thoms 1978)

ϵ_c , which accumulates with time t , and 3) a possible rupture at time t_f , provided the salt is in a loading mode permitting rupture. The time interval of the test, $t_0 \leq t \leq t_f$, is traditionally divided into three idealized subintervals or phases of material creep response, i.e., transient, steady-state, and tertiary. Rock salt typically exhibits a prolonged steady-state creep phase, provided the applied loading state is not so severe as to cause transient and tertiary phases to completely dominate specimen behavior. The steady-state phase of rock salt response is of particular interest to long-term stability concerns of storage caverns, provided of course, an acceptable phase of transient response can be accommodated (Thoms and Martinez 1978b).

Thoms (1980) has reported results of laboratory and in situ tests. First, rock salt apparently has good endurance to cyclic load effects within the modest ranges used to date. Second, under cyclic loads, rock salt exhibits short-term response (displacement) that is approximately linear with varying loads. However, the accumulated short term responses generate an envelope that trends along typical time-dependent salt

Currently, there is no general agreement among researchers as to the best method of characterizing long-term behavior of rock salt (Baar 1977; Thoms and Martinez 1978b). In considering laboratory versus in situ tests, the fundamental trade-off occurs between degree of specimen disturbance and extent of information on boundary conditions, respectively. Both types of test appear appropriate to rock salt mechanics, but with correlation of data ultimately required (Thoms and Martinez 1978b).

Laboratory testing programs have been conducted mainly with compression triaxial and uniaxial tests (Thoms 1978). Triaxial extension tests, which are more difficult to perform, permit a more comprehensive evaluation of creep-rupture, which is a significant effect in long-term behavior of openings in rock salt.

5.1.1 Triaxial Compression Testing

Test data to indicate time-independent behavior of rock salt is usually obtained by "quick" triaxial tests (e.g., stress rates on the order of 137.90 kPa per second resulting in plots of some stress measure versus a corresponding strain measure (Thoms 1978)). The measures plotted are usually preselected to be consistent with the adoption of some material model. The behavior of the salt is influenced by the loading history and environment, including stress state, crystal grain boundary state (e.g., wetness), temperature, and loading rate. Figure 11 depicts typical stress-strain curves from triaxial tests on Tatum dome salt (Boresi and Deere 1963). The ordinate of these curves is the difference in the principal axially and laterally applied stresses ($\sigma_1 - \sigma_2$) (also called effective stress). This stress measure is conventional in geotechnical engineering. Both temperature and loading rates should be included in data from rock salt testing.

If rock salt is unloaded and reloaded in a "quick" test, it exhibits strain-hardening characteristics. That is, it will unload along an approximately straight line and then reload along essentially the same straight line until the nonlinear original load-displacement curve,

FIGURE 11. Typical Stress Strain Curves for Rock Salt (after Boresi and Deere 1963)

similar to those depicted in Figure 11, is intersected. Thereafter, the nonlinear load-displacement curve is followed unless unloading again occurs. This material behavior implies that short-term cyclic pressure loading effects in rock salt associated with CAES cavern operations may be analyzed in part with effective linear reaction moduli.

Other data that can be obtained from "quick" triaxial tests include Mohr-Coulomb envelopes (Thoms 1978). The Mohr-Coulomb failure criterion is widely used in geotechnical engineering. As depicted in Figures 12 through 14, the format used for plotting test data frequently implies the adoption of certain material models to describe yield or strength behavior of salt.

The conventional geotechnical concept of time-independent strength is difficult to define for rock salt unless the loading rate is relatively high. Short-term strength will not be a principal criterion for long-term stability of storage caverns within salt stock. For example, in Figures 12 through 14, "strength" had to be defined in terms of percentage deformation (strain). The rock salt reportedly would not exhibit fracture or a rapid loss of load-carrying ability under compressive triaxial loading conditions if the confining stress exceeded 341 kPa. By contrast, long-term failure of rock salt, in a progressive spalling mode, can be associated with time-dependent extensional creep and related creep rupture.

5.1.2 Creep Behavior

The determination and/or description of time-dependent creep of rock salt has been treated fairly extensively in theory (Cruden 1971; Le Compte 1965). Various forms of creep "laws" have been proposed and used in numerical modeling (Morgan et al. 1981). Heard (1972) employs an exponential form of creep law dependent upon absolute temperature and differential stress along with appropriate material parameters and the universal gas constant.

FIGURE 12. Strength of Rock Salt at 2% Deformation (after U.S. Department of Interior 1962)

FIGURE 13. Strength of Rock Salt at 10% Deformation (after U.S. Department of Interior 1962)

FIGURE 14. Strength of Rock Salt at 20% Deformation (after U.S. Department of Interior 1962)

Power law formulations have been used perhaps most frequently to represent time-dependent rock salt behavior (Cruden 1971). Russell (1978) has noted that a power law formulation with a constant non-zero exponent for time cannot accommodate a steady-state creep phase. However, Dwyer and Thoms (1974) have suggested that creep can be handled by a combination of traditional power law, in the transient phase, followed by a degenerate form wherein the time exponent is set to zero, in the steady-state phase. This latter approach corresponds essentially to employing a spline fit in time for the material response of rock salt (Desai 1971). Additional study is required, particularly with verification by in situ tests, before a "best" creep model formulation is universally accepted. The analytical description of in situ polycrystalline rock salt behavior, including creep rupture, currently requires considerable additional research.

There are little long-term creep data for thousands of hours available from laboratory experiments on domal salt because such tests obviously require considerable time, i.e., months. Most existing laboratory test data in geotechnical engineering are based on axial compression tests (either uniaxial or triaxial). This is appropriate because such tests "track" the loading environments of prime interest in the majority of geotechnical engineering applications. However, the principal phenomenon involved in time-dependent cavern closure is best simulated with triaxial extension creep tests (Nair and Deere 1970). With reference to Figure 15, the loading environment associated with creep closure of a storage cavern would be most nearly attained in the laboratory by tests on cylindrical specimens with axes normal to the cavern surface and $|\sigma_3| > |\sigma_1|$, where σ_3 and σ_1 represent geostatic stress and cavern pressure, respectively.

Because test cylinders of salt are obtained from vertical holes it is necessary to assume material isotropy for data interpretation from triaxial extension tests relative to cavern creep closure in the horizontal

FIGURE 15. In Situ Representation by Triaxial Extension Test

direction. If sufficiently large cylinders can be obtained to machine horizontally oriented specimens without inducing scale effects, then this assumption is not necessary.

After a certain amount of strain has occurred in an extensional mode, the rock salt will "creep rupture". This phenomenon can be observed in south Louisiana salt mines where spalling of the walls occurs with the passage of time (Thoms 1978). As preventive maintenance measures, the mines are periodically "scaled" using a large machine with a metal pick that breaks off potential rock-fall material. In older and more shallow inactive mining levels, the spalling (creep rupture) phenomenon is particularly evident.

In laboratory testing of rock, clearly visible failure due to creep rupture can be observed in triaxial extension creep tests (Figure 16), but not in conventional uniaxial compression creep tests with moderate loads (Figure 17). This again points up the more appropriate loading environment of triaxial extension tests over compression tests for cavern closure studies.

5.1.3 Compressed Air Energy Storage Environment

Caverns used for CAES will be subjected to typical daily and weekly cycles of pressure and temperature variation. Thus, the "fatigue limit" of the rock salt in the cavern walls will be of primary concern. The Huntorf CAES cycle includes cavern pressurization over eight hours to 70 atm followed by unloading over two hours to 50 atm. Other operating cycles obviously can be suggested. An upper limit has been placed on operating pressure within hydrocarbon storage caverns in Louisiana; "The maximum operating pressure (gauge) at the casing seat or chamber ceiling, whichever is the shallowest, shall not exceed 0.9 psi per foot of overburden" (State of Louisiana 1977). This limiting pressure value was established mainly on the basis of extensive experience of storage cavern operators in Gulf Coast salt domes. Typical daily and weekly cycles therefore probably will be bounded approximately by this value. Limiting pressure values must be kept in mind in setting up a cyclic effects (fatigue) testing program.

FIGURE 16. Triaxial Extension Creep Tests (after Boresi and Deere 1963)

FIGURE 17. Uniaxial Compression Creep Tests (after Boresi and Deere 1963)

Following the concepts developed for metals, a site-specific rock salt can be typified as possessing the ability to withstand a certain number of load cycles, under specified loading conditions, based on laboratory tests (Thoms 1978). These test data can be interpreted in terms of years of service or engineering life of the cavern under operating cyclic loading conditions. If the life is not sufficient for the planned facility, then a different set of loading conditions or a site with "better" salt must be selected (Thoms 1978).

It is well known that rock salt behavior is strongly temperature-dependent. Thus all material strength properties determined in the laboratory should be qualified as typical for certain temperatures. In addition, the cyclic thermal stresses associated with the time-varying temperature gradients in the cavern walls must be taken into account (Howells 1977).

In testing for cycles or low frequency fatigue effects associated with CAES, it is possible that the influence of temperature and stresses will be strongly coupled (Wawersik 1978). Thus, testing for explicit effects on rock salt due to pressure and/or temperature cycling alone may not be adequate for CAES studies. Therefore, simultaneous pressure and temperature cycles should be simulated in at least one phase of a laboratory or bench-scale testing program to assess possible coupled fatigue effects. Furthermore, the surface of the salt specimens should be exposed to air with various degrees of water content to establish levels of possible deterioration in the exposed crystal fabric.

Other material properties affecting cavern stability considerations include unit weight, permeability, heat capacity, conductivity and thermal diffusivity, moisture content, and compressibility (bulk modulus) of the salt and other geologic materials. The unit weight of salt obviously influences the stress state in the cavern walls. Further, unit weight of salt possibly may be useful as an index number to characterize salt variability, including anhydrite content, within a dome or domes.

Heat transfer parameters obviously will enter into the analysis of the time dependent temperature field surrounding a storage cavern.

5.1.4 Loading Parameters

Loading parameters affecting cavern stability in salt domes are discussed individually in the following paragraphs. Loading parameters involve pressure, temperature and time.

Perhaps the most significant long-term loading parameter is the pressure difference, p_d ; i.e., $p_d = g - p$, where g corresponds to the magnitude of geostatic stress in surrounding salt due to overburden, and p corresponds to the magnitude of cavern pressure (Rohr 1974). The parameter, g , is a function of depth and unit weight of overburden material. Obert (1962) determined the geostatic stress state in Gulf Coast domal salt, at some distance from a mined opening, to be hydrostatic in character and equal in magnitude to overburden (lithostatic) pressure. This determination was made using the overcoring method, which requires assumptions about material behavior. The material behavior of rock salt is complicated; thus, other methods (e.g., flat jacks) also should be employed for stress determination in domes. The magnitude of cavern pressure is specified, for a noncompensated cavern simply by gauge pressure at the wellhead of the surface facility. The pressure along with the geometric configuration of a cavern and material properties of salt are primary input data for analyzing the associated stress and displacement fields and subsequently the stability of storage caverns in salt domes. A first-cut analysis of stress distribution around CAES caverns can be obtained with widely available axisymmetric finite element programs and assumed linear "effective reaction" moduli for material response. This analysis then can be used as a basis for selecting loadings for a laboratory testing program on rock salt response under simulated CAES conditions. Effective reaction moduli can be estimated, for example, from Figure 11, and anticipated loading histories and environments.

It is relatively well known that salt behaves as an elastic brittle-like material if loaded (or unloaded) at a rapid rate. In storage caverns the pressure unloading rate must be limited as roof falls apparently have been caused by rapid pressure drops. The transition loading (unloading) rate, above which rock salt behaves as a brittle material, has not been studied carefully. The transition rate should be established as part of a more complete investigation of long-term CAES cavern stability.

The temperature and rates of temperature change with time of the fluid (air and possibly brine) used as the pumping medium for CAES caverns in salt domes are significant loading parameters because rock salt becomes more plastic with higher temperatures. In addition, time-dependent thermal stresses will be incurred in the cavern walls because of varying temperatures (Howells 1977).

Lomenick (1968) performed a series of laboratory experiments in which he studied effects of elevated temperatures and different loads on the creep behavior of rock salt model mine pillars. Based on his model studies, he reported "...temperature is the single most important parameter that affects cavity closure in salt mines". His empirical relation for vertical creep rate of pillar models utilizes temperature ($^{\circ}\text{K}$) with an exponent of 9.5. He further concludes "...at 200°C severe structural stability problems will occur in subsurface salt excavations, even at superincumbent loads as low as 2000 psi".

For Lomenick's results, an upper bound on salt temperature around storage cavities should be less than 200°C . However, an even lower upper limit for temperature is desirable for CAES reservoirs where relatively stable storage volumes are required for approximately 35 years (Thoms 1978). Thus, a maximum salt temperature of 80°C in the reservoir wall is postulated as an upper bound for CAES. It should be noted that maximum air temperatures could be higher during injection periods. Rock salt, as a geologic material, has relatively large values of heat capacity and thermal conductivity (Clark 1966). Furthermore, air, with relatively low heat capacity, will

be injected and withdrawn into a large CAES reservoir away from the immediately surrounding rock salt "walls". Heat from the air will be transferred into the salt by convection. Temperature rise can be analyzed with an appropriate film coefficient that should incorporate effects of seasonal variations in temperature. Thermal effects probably will not be manifested by the salt (Thoms and Martinez 1978a). Instead, salt temperatures probably will be close to mean values of operating CAES cycles even relatively close to the cavern wall surfaces, and will decay rapidly to ambient temperatures in the salt stock away from the caverns. It is probable that cyclic temperature and pressure loadings may couple to accelerate deleterious effects within the salt around CAES caverns.

5.2 CYCLIC LOADING TESTS

Cyclic loading test results reported by Serata and McNamara (1980) include:

- Under a confining stress of 17.25 MPa, large strains occur without either material property or granular deterioration. Even at an octahedral shear strain above 25%, the shear modulus remains constant. This indicates ductile behavior under cyclic loading.
- Cyclic loading may cause strain-hardening, which would reduce viscoelastic deformation. This would assure general CAES cavern stability except near the immediate air-rock interface.
- The condition of salt close to the cavern boundary is not revealed by cyclic loading tests because confinement was not accurately simulated. Direct exposure to compressed air may also affect this region (Serata and Cundey 1979).

5.3 NUMERICAL MODELING OF MECHANICAL BEHAVIOR

Serata and McNamara (1980) have stated that rock salt exhibits generally consistent behavior under particular geomechanical conditions, and therefore the behavior can be mathematically modeled. However, the behavior is complex and no standard method has been accepted by the

research community. Serata Geomechanics adopted the FEM finite element computer simulation method, which identifies brittle fracture and ductile yield as simultaneous and distinct deformation modes that operate upon salt cavity walls. The FEM method also includes basic behavioral components of rock salt. These include elasticity, viscoelasticity, viscoplasticity, compressibility, and property deterioration. The HEAT finite element heat transfer code was also used to model long-term behavior of CAES salt caverns (McNamara et al. 1981). The material presented herein and through Section 5.8 is based on work performed by Serata Geomechanics, Inc. It should be noted that there are a wide variety of methodologies for modeling rock salt and, as with many areas of developing research, there is much contention among researchers in the field on the correctness of various methods and even on the theoretical basis for the models. The method used here was one of the methods used to confirm the Huntorf rock mechanics design.

Rock salt is subject to changes in stress distribution due to cavern excavation. The stress-strain relationship can be expressed in terms of four quantities: octahedral stress and strain and mean stress and strain. Material characteristics have been defined as follows (Serata and Cundey 1979; Serata and McNamara 1980):

- Rock salt exhibits a strong strain-hardening effect. (a)
- Compressibility is affected by both viscoelastic and viscoplastic mechanisms.
- Ultimate octahedral shear strength is between 3.45 and 5.18 MPa.
- Brittle failure takes place along grain boundaries.
- Ductile yield (viscoplastic creep) occurs along crystal glide planes.
- Predominantly brittle fracture occurs at mean stresses below 6.9 MPa.
- Ductile yield is dominant above 6.9 MPa and exclusive above 13.8 MPa.

(a) Not accepted by all investigators of rock salt behavior.

5.4 VARIABLES OF NUMERICAL ANALYSIS

Variables affecting the feasibility of compressed air energy storage in salt caverns may be grouped under three headings: operational, geological, and geometrical (Serata and McNamara 1980). These are summarized in Table 2. Among them are seven parameters representing the critical variables for the numerical analysis. The base values and ranges of these parameters are summarized in Table 3.

Two important parameters, cavern air temperature and salt property deterioration, are not included in this analysis because of absence of detailed information. Cundey and Serata (1978) has found that temperatures up to 150°C have little effect on the elastic and viscoelastic behavior of salt, but viscoplastic properties such as octahedral shear strength, are strongly affected. Shear strength is decreased and ductility is increased.

It is unlikely that detailed slabbing and cracking at a cavern boundary can be predicted by modeling (Golder Associates 1979).

5.4.1 Cavern Depth (Y)

Cavern depth is important because it affects in situ stress conditions. A deeper cavern will experience greater closure than a shallow one with the same cavern air pressure. Here Y stands for cavern ceiling depth measured from the earth's surface to the top of the cavern.

5.4.2 Cavern Air Pressure (P_i)

Reduction of cavern air pressure could produce significant damage to the cavern wall if the reduction is large and prolonged, because deformation is proportional to the difference between earth lateral stress, P_L , and the cavern air pressure, P_i . The minimum acceptable P_i value for a CAES cavern operation should be determined for given geo-mechanical conditions of the cavern.

TABLE 2 Variables Considered in Analyzing CAES Cavern Design (Serata and McNamara 1980)

<u>I. Operational Variables</u>	<u>II. Geological Variables</u>	<u>III. Geometrical Variables</u>
A. Cavern air pressure	A. Material properties of rock salt	A. Cavern depth
1. Minimum cavern cyclic pressure	1. Viscoelastic behavior	B. Cavern diameter
2. Maximum cavern cyclic pressure	2. Viscoplastic behavior	C. Cavern length
3. Maximum cavern cyclic loading rate	3. Permeability to cavern air	D. Cavern shape
4. Maximum cavern cyclic pressure unloading rate	4. Thermal behavior	E. Cavern separation distance (multiple-cavern networks)
5. Cavern depressurization	5. Cyclic loading response	F. Cavern configuration (multiple-cavern networks)
B. Cavern air temperature cycle	6. Effect of impurities in salt	G. Salt thickness separating cavern wall and salt dome boundary
1. Minimum cavern air temperature	B. Material properties of rock formation surrounding salt formation	H. Salt thickness separating cavern roof or floor and salt layer vertical boundary
2. Maximum cavern air temperature	C. In situ stresses	
3. Maximum cavern air temperature rate	1. Overburden pressure	
C. Cavern humidity	2. Excess lateral stress	

TABLE 3. Values and Ranges of CAES Cavern Parameters
(Serata and McNamara 1980)

<u>Parameter</u>	<u>Typical Value</u>	<u>Range</u>
Cavern depth (Y)	610 m	305 to 1524 m
Cavern air pressure (P_i)	5.07 MPa	0 to 10.14 MPa
Excess lateral stress (ΔP_L)	50% max	-50% to 100% max
Octahedral shear strength (K_o)	4.14 MPa	3.8 to 5.18 MPa
Other salt properties (K_i)	Weak	Weak to strong
Height/Diameter Ratio (H/D)	5	5 to 20
Separation/Diameter Ratio (S/D)	4	2 to 10

5.4.3 Excess Lateral Stress (ΔP_L)

The excess lateral stress in any salt formation is usually unknown. The lateral stress can be greater than, equal to, or smaller than the overburden pressure. The maximum theoretical deviation of the lateral stress from the vertical stress, ΔP_L max, depends on the octahedral shear strength of rock salt, K_o , and is given by $3K_o/\sqrt{2}$ for viscoelastic conditions. A large excess lateral stress could induce cavern closure. The effect of excess lateral stress increases with depth.

5.4.4 Octahedral Shear Strength (K_o)

Other factors being equal, a salt cavern with low octahedral shear strength will experience greater closure and boundary strain than one in stronger salt. This effect increases exponentially with depth.

5.4.5 Other Properties of Salt (K_i)

Other elastic, viscoelastic, and viscoplastic properties of salt may affect cavern behavior significantly. Viscoplastic properties in particular may have the most important effect on long-term stability. For purposes of parametric analyses of salt cavern response to CAES conditions, the three strength categories of salt are compared with the numerical values of various material property coefficients in Table 4.

TABLE 4. Material Properties of Rock Salt at Room Temperature
(after Serata and McNamara 1980)

<u>Property</u>	<u>Unit</u>	<u>Weak</u>	<u>Medium</u>	<u>Strong</u>
G_1 : Shear modulus	6.9×10^2 MPa	1.00	1.50	2.30
G_2 : Retarded VE shear modulus	6.9×10^2 MPa	0.30	0.50	0.75
G_3 : Retarded VP shear modulus	6.9×10^2 MPa	0.50	0.70	1.00
V_2 : VE Viscoelastic viscosity	6.9×10^2 MPa/day	1.70	2.50	3.50
V_3 : VP Viscoplastic viscosity	6.9×10^2 MPa/day	1.00	1.50	2.10
V_4 : Viscoplastic viscosity	6.9×10^2 MPa/day	1.40	2.00	3.20
K_1 : Bulk modulus	6.9×10^2 MPa	2.00	4.00	6.00
K_2 : Retarded bulk modulus	6.9×10^2 MPa	2.00	3.00	4.00
D_2 : Bulk viscosity	6.9×10^2 MPa/day	6.25	9.00	12.50
K_B : Ultimate octahedral shear strength	MPa	3.45	4.83	5.18
p : Specific gravity	na	2.16	2.16	2.16

5.4.6 Cavern Height/Diameter Ratio (H/D)

A vertical cylindrical cavern shape was assumed in this study because that shape is used for most salt cavern designs. The cylindrical shape enables most effective use of the salt dome volume in multiple cavern arrays. Further, this shape is readily approached by solution mining.

5.4.7 Cavern Separation Distance (S/D)

The distance between caverns in a multiple-cavern system is important because the stress fields around the neighboring caverns might interfere destructively if the caverns are spaced too closely. On the other hand, unnecessarily large separation distances do not make maximum use of the available salt volume. The ratio of cavern center-to-center separation distance, S , to cavern diameter, D , is used.

5.5 PARAMETRIC STUDIES OF SINGLE CAVERNS

The finite element network of an axisymmetric cylindrical cavern was used for the parametric analysis of a CAES single cavern (Serata and McNamara 1980). The cavern modeled was assumed to have been created instantaneously. This cavern model experiences much greater closure than a similar cavern experiencing sequential excavation. The latter more closely resembles actual cavern excavation, which usually takes 1 to 2 years of solutioning. The instantaneous model was used because of a substantial saving in computation costs and because it represents a conservative approach to defining cavern stability. The sequential model exhibits radial closure less than half that of the instantaneous model. In both models, however, the stress conditions around the cavern 10^4 days after completion of the full excavation are found to be so similar that they are virtually indistinguishable.

Single cavern analyses focused on six critical parameters: cavern depth (Y); cavern air pressure (P_i); excess lateral stress (ΔP_L); octahedral shear strength of salt (K_0); other salt properties (K_i); and ratio of

cavern height to diameter (H/D). In evaluating individual parameters, only a single parameter was varied, while the rest were maintained constant at base values chosen to reflect moderate CAES operating conditions.

The maximum closure of about 9% occurred at about 61 m above the bottom of the cavern for $Y = 1372$ m. The viscoplastic radius does not reach 15 m above the roof but reaches more than 30 m below the floor. Both viscoplastic radius and strain in the wall increase with depth. Effects of the individual parameters were analyzed and are summarized below.

5.5.1 Cavern Depth (Y)

Varying the depth to the top of the cylindrical part of the cavern (Y) from 30 to 1372 m showed that radial boundary strain and radial closure increase sharply when Y exceeds 762 m. The stresses and strains in the roof, floor, and cavern walls prove that the viscoplastic zones are expanding and boundary strains are increasing as Y increases. Cavern depths of 1220 m are considered safe under moderate operating conditions (McNamara et al. 1981).

5.5.2 Cavern Air Pressure (P_i)

The results of five analyses in which cavern air pressure was varied from 0 to 10.14 MPa indicate that air pressure is not a critical parameter for the base conditions considered.

5.5.3 Excess Lateral Stress (ΔP_l)

Varying the excess lateral stress from -50% to +100% of the theoretical maximum value, $3K_o/\sqrt{2}$, demonstrated that radial closure and radial boundary strains increase sharply when the excess lateral stress exceeds 90% of the maximum. A significant amount of strain is produced in the salt far beyond the cavern boundary.

5.5.4 Octahedral Shear Strength of Salt (K)

Varying the octahedral shear strength of salt from 3.795 to 5.175 MPa did not produce significant differences in the cavern behaviors. Air

penetration resulting in deteriorating salt octahedral shear strength is expected to primarily affect local stability of CAES caverns and not significantly alter global stability (Serata and McNamara 1980).

5.5.5 Other Properties of Salt (K_i)

Results of varying other salt properties from weak to strong show that strong salt reduces the strains all around the cavern. Even with the weak salt, the maximum strain on the cavern boundary is found to be only about 1%, indicating a cavern in the weak salt should still be adequately free from boundary damage under the base conditions. The salt properties appear to have very little effect on the long-term behavior of the cavern, provided that no property deterioration of the salt by air penetration has taken place.

5.5.6 Cavern Height/Diameter Ratio (H/D)

Varying the H/D ratio from 5 to 20 produced negative results. Both strain and radial closure increase sharply at about 1220 m regardless of the H/D ratio.

5.6 TWO-CAVERN INTERFERENCE ANALYSIS

The two-cavern system was analyzed to determine cavern interference for various cavern separation distances assuming effects of the various parameters. For this study, both caverns were assumed to have the same air pressure, P_i .

As in the single cavern analysis, a base condition was established for each parameter, and then each parameter was varied independently with the others held at the base condition. The base values and ranges for each parameter are listed in Table 5.

Effects of the six variable parameters were analyzed in relation to radial boundary strain versus cavern age in logarithmic time. Similarly, effects of the six variable parameters on radial boundary strain were analyzed at the two different ages, $t = 10^2$ and $t = 10^4$ days.

TABLE 5. Base Values and Ranges of Principal Parameters Used in Two-Cavern Analysis (Serata and McNamara 1980)

<u>Parameter</u>	<u>Base Value</u>	<u>Range</u>
Horizontal section depth (Y)	610 m	152 - 1524 m
Cavern air pressure (P_i)	5.07 MPa	101.4 MPa
Excess in situ lateral stress (ΔP_L)	50% of max ΔP_L	0-100% of max ΔP_L
Octahedral shear strength (K_o)	4.14 MPa	4.14 - 5.175 MPa
Other salt properties (K_i)	Weak	Weak - Strong
Separation/diameter ratio (S/D)	4.0	2-10

5.6.1 Cavern Depth (Y)

Radial boundary strain increases sharply as depth increases below 915 m. Radial boundary strain exceeds 5% at the 1220-m depth. In the ground between the two caverns, no viscoplastic zone appears at depths less than 305 m. At 610 m a viscoplastic zone has developed to about 1.5 cavern radii. At depths of 915 m and more, the ground becomes totally viscoplastic. Away from the caverns, the viscoplastic zone expands from less than two cavern radii at a depth of 610 m to more than 8 cavern radii at $Y = 1524$ m. Significant strain occurs midway between the caverns at depths of 915 m and greater.

5.6.2 Cavern Air Pressure (P_i)

The radial boundary strain increases rather sharply with reduction of the air pressure. However, even with total depressurization, the maximum boundary strain is still less than 2% even after 10^4 days of depressurization. This means that cavern air pressure is not a critical parameter by itself under the base conditions.

5.6.3 Excess Lateral Stress (ΔP_l)

The excess in situ lateral stress was varied from 0 kPa, which corresponds to an hydrostatic initial stress state, to its maximum theoretical value of $3K_o/\sqrt{2}$. As in previous analyses, the radial boundary strain increases sharply when the excess lateral stress exceeds 90% of its theoretical maximum, but for the base condition, the maximum radial boundary strain is less than 4% even when the excess lateral stress is maximum. A small viscoplastic region surrounds each cavern when the excess lateral stress is 0% to 50% of maximum. This zone expands to include all salt between the two caverns when the excess lateral stress reaches 90% of maximum.

5.6.4 Octahedral Shear Strength (K_o)

With variation of the K_o value, very little difference is observed in the strain distribution around the cavern. Slightly more noticeable differences occur in the stress distributions, which show the expansion of the viscoplastic radius from about one cavern radius when $K_o = 5.18$ MPa to 1.5 cavern radii when $K_o = 4.14$ MPa. The maximum boundary strains are very small (less than 1%) in either case for the base conditions.

5.6.5 Other Properties of Salt (K_f)

The radial boundary strain for weak salt is more than twice that for strong salt. At any rate, all strains are less than 1% for the base conditions, regardless of the salt properties.

5.6.6 Cavern Separation Distance (S/D)

A sharp increase in radial boundary strain appears when the S/D ratio drops below 3. The ground becomes entirely viscoplastic when S/D equals 3 or less. Both stresses and strains between the caverns become noticeably larger when $S/D = 2$, but they are not very much affected by the S/D ratio when its value is greater than 3. A minimum cavern separation distance of 4.0 is recommended.

5.7 PRELIMINARY DESIGN CRITERIA

5.7.1 Basis of Criteria

Long-term boundary creep strain was used as the basic reference for evaluation of cavern stability (Serata and McNamara 1980). Then, based on field experience, a cavern boundary creep strain of 10% was considered as the acceptable limit of safety for CAES caverns. This value is considered to assure a very highly stable state of the caverns. In assessing the effects of the individual parameters, a "sensitivity factor" for the creep strain was utilized. It is defined as the ratio of the cavern boundary creep strain for the specified parameter value to the cavern boundary creep strain attained for the base condition value.

5.7.2 Cavern Depth

Cavern depth of approximately 1220 m is considered safe under most normal circumstances. In no case should cavern depth be extended below 1220 m unless the in situ stress state can be verified as nearly hydrostatic or less. A cavern depth of 915 m is more conservative and allows containment of air at 9.69 MPa for nonhomogeneous salt and 15.0 MPa for homogeneous salt. Caverns should not be placed deeper than 762 m when three critical parameters approach the following extremely unfavorable values:

- cavern air pressure, $P_i = 0$ (depressurization)
- excess lateral stress, $\Delta P_L = 100\%$ of maximum value
- cavern separation distance, $S/D < 4$.

5.7.3 Cavern Depressurization

Under normal conditions, even complete cavern depressurization will not push the boundary creep strain beyond the acceptable limit of 10%. The sensitivity factor for depressurization is about 2.5. The normal value for long-term radial closure is approximately 2%. Therefore, prolonged depressurization will produce creep closure only up to 5%. At 1220 m, however, the expected radial closure under the base condition is 5%. Therefore, depressurization at 1220 m is not acceptable because the boundary creep strain will exceed 12%. Caverns should be no deeper than 762 m if depressurization is likely to occur frequently (McNamara et al. 1981).

5.7.4 Excess Lateral Stress

In situ lateral stress, ΔP_L , should be determined prior to design of any CAES cavern, because excess in this parameter value has the most significant effect of any of those investigated. All analyses show very rapid increase in boundary strain when the excess stress, ΔP_L , exceeds 90% of its maximum calculated value. The sensitivity factor, ΔP_L , is about 2.5 at 90% and about 3.8 at 100%.

Cavern strain is to be limited to 10% over a period of 10,000 days (Serata and McNamara 1980).

5.7.5 Octahedral Shear Strength

The octahedral shear strength of salt has variable effects on cavern behavior in the range of the analyzed values of 3.795 to 5.175 MPa. The sensitivity factor can be considered to be 1 at depths less than 610 m. At greater depths, the factor will increase.

5.7.6 Other Properties of Salt

Salt properties other than octahedral shear strength have only a small effect on cavern stability. However, the difference between weak, medium, and strong salt has a greater effect under extreme conditions. The sensitivity factor is assumed to be 1 at the shallower depths of less than 610 m, by taking weak salt as the base condition. The value becomes larger at greater depths.

Increased cavern pressure is expected to increase long-term cavern stability unless it simultaneously causes increased air penetration along crystal boundaries, fracture surfaces, or discontinuities.

5.7.7 Cavern Height/Diameter Ratio

An increase in cavern height beyond $H = \mathfrak{D}$ was found to have little effect on cavern stability. The sensitivity factor for increase in length beyond $H = \mathfrak{D}$ is about 1. Serata and McNamara (1980) state that spherical shape minimizes strain.

5.7.8 Cavern Separation/Distance Ratio

A minimum S/D ratio of 4 is **recommended** for a two-cavern system, assuming that those caverns are operated at the same air pressure. Smaller S/D values would be acceptable only under conditions more favorable than the base conditions.

5.8 GENERAL CONCLUSIONS

5.8.1 Long-Term Stability

Design and operational requirements of CAES caverns were found to be fundamentally compatible with their long-term structural behavior (Serata and McNamara 1980). Within the scope of this study, such caverns were found to be structurally stable for any foreseeable period. No restrictions on design or operation were found to exist for the design parameters analyzed, which reflected the elastic, viscoelastic and viscoplastic behavior of salt caverns at room temperature.

5.8.2 Design Criteria

Design criteria for **long-term** stability of CAES caverns were developed according to the normally expected stresses, strains, and displacements in the cavern for 30 years of operation. A "sensitivity factor" was defined to identify the effects of extreme cavern conditions, so that **it** not only indexed the relative importance of individual parameters, but also served to estimate the coupled effects of two or more extreme parameters acting simultaneously.

5.8.3 Measure of Cavern Stability

Total cumulative creep strain was identified as the key indicator of cavern stability. Based on field experience, a total boundary creep strain of 10% in 30 years of continuous operation was set as a maximum limit, providing a sufficient safety margin against the uncertainties of cavern behavior not analyzed in this study.

5.8.4 Constitutive Equations

The constitutive equations of rock salt were updated by reviewing the latest laboratory and field data. Theoretical bases of the equations were shown to be capable of analyzing the complex effects of elevated temperature and brittle deterioration upon CAES caverns.

5.8.5 Cyclic Loading Tests

Laboratory tests indicated that cyclic loading of CAES caverns will increase, rather than decrease, the strength of rock salt, when salt is in the viscoplastic state. The tests simulated 45 years of continuous weekly cycles. No testing was conducted for brittle fracture of rock salt under cyclic loading.

5.8.6 Temperature Effects

Evaluation of laboratory test data showed that rock salt at high temperatures maintains a definite octahedral shear strength upon which CAES caverns can be stabilized. In the modeling discussed here, the viscoplastic viscosity coefficient decreases as temperature increases, causing the ultimate plasticity extension to be reached more quickly.

Although computer simulations of temperature were limited in scope, it was apparent that high temperatures will increase boundary strain. No other destructive effects of high temperatures were found. Further, because the high temperature also increases the ductility of salt at the cavern boundary, resulting in a reduction of brittle fracturing, the net result of operating at high temperatures should not necessarily be considered destructive.

For temperatures to 93°C, CAES caverns are expected to be highly stable, given that other critical parameters are maintained at moderate levels. Possibly temperatures to about 150°C could be withstood if the other critical parameters are favorable (Serata and McNamara 1980; McNamara et al. 1981).

Thoms (1978) points out that temperature and stress may be strongly coupled with respect to fatigue effects caused by CAES cycling. Thus, testing for explicit effects on rock salt due to pressure or temperature cycling alone may not be sufficient. Site specific studies for a particular situation are therefore strongly recommended.

6.0 CAVERN DESIGN AND OPERATION

Evaluation of strength of rock salt and site-specific geological inhomogeneities may heavily influence engineering design concerning salt thickness above cavities necessary to contain pressurized air. Rock mechanics of the Huntorf CAES facility indicated 100 m of salt thickness would ensure a maximum cavity integrity to 10 MPa and an upper-level operating pressure of 7 MPa (Quast and Lorenzen 1979).

Feasible depths for CAES caverns in salt domes will be influenced by site-specific material properties of the salt and also by the operating cycle of the surface plant. However, a general range of feasible depths can be estimated, with more confidence in limits on minimum depth than on maximum depth (Thoms and Martinez 1978b).

6.1 DESIGN GUIDELINES

Most design features are subject to quantitative specification within fairly narrow limits. These include physical air storage conditions, mechanical behavior of the salt, and dimensional factors.

A minimum depth to cavern roof (and well casing "seat" into the salt) of 610 m would be consistent with an allowable maximum operating pressure of approximately 12.4 MPa for static storage of hydrocarbons in Louisiana salt dome caverns (State of Louisiana 1977). Thus, a maximum operating peak pressure of approximately 10 MPa appears reasonable for a CAES cavern with roof and well casing seat at 610 m depth. Alternately, for CAES pressure cycles with maximum pressure of 10 MPa, cavern roof depth should not be less than approximately 610 m (Thoms and Martinez 1979). In other words 1 MPa is allowable per 61 m of depth.

Golder Associates (1979) states that the most critical dimensions are 1) distance from top of salt to top of cavern (d), 2) maximum cavern span (s), and 3) thickness of the wall shared with an adjacent cavern.

The d/s ratio should not be less than 2.2 and the wall between caverns should be 76 to 92 m thick, according to German guidelines.

6.2 GEOLOGIC FACTORS

Rock strength, faulting, anomalous zones (in salt domes), presence of gas, rate of dissolution by ground water, and seismic susceptibility (Aamodt et al. 1975) are a few of the factors that have a bearing on the predicted stability of a salt deposit.

The in situ strength of salt is generally more uniform and consistent than that of most other rock types. Under load, redistribution and dispersal of strain occur because of the time-dependent behavior of salt. This structural characteristic is important for maintenance of excavation stability (Aamodt et al. 1975).

Controlled solution mining, guided by a detailed analysis of the structural properties of the salt, can generally ensure an adequate cavern lifetime (Weinstein et al. 1978).

6.2.1 Effect of Impurities on Mining

Large amounts of potash and other impurities in rock salt may limit use of some salt domes as cavern sites for CAES operations. Insoluble stringers of anhydrite as well as potash may contribute to marked anisotropic effects upon solution cavern development. Engineering design must take into consideration the formation of shelves and ledges of insoluble material during solution mining, which may break down and endanger cavern development and production tubing (Asiala 1974).

Currently an analytical modeling technique does exist for predicting the megascopic response of rock salt to the effects of solution mining. This analytical program, developed for KBB GmbH, utilizes core testing techniques, and can model solution mining in nonhomogeneous salt. Rock mechanics analysis for Huntorf was conducted by Professor W. Dyer of the Institute for Petromechanics and Rock Physics of the Clausthal Technical University (Quast and Lorenzen 1979).

6.2.2 Caprock Instability

Certain domes are active "solution" domes, that is; a highly permeable zone exists between the salt surface and caprock. Such zones are so extensive as to accommodate large amounts of drilling mud by direct loss during drilling operations. The Winnfield Dome, for example, has a layer or seam of highly permeable anhydrite sand varying from 15 cm to more than 1 meter thick between the salt and caprock. If a high rate of circulation exists in this sand, it will tend to corrode any unprotected well casings and other pipe connecting the CAES caverns to surface facilities. Construction problems also could be incurred because of this porous zone.

The caprock also can be cavernous and vuggy. If lost circulation occurs during drilling the hole can collapse; but, specifically from the long-term stability viewpoint, a cavernous caprock will tend to increase well casing corrosion problems. Unprotected well casings can corrode and leak within a decade under such conditions. A leak in the casing can directly affect stability by permitting a rapid pressure drop within a cavern (Thorns 1978). Rapid pressure drops in rock salt storage caverns have apparently precipitated roof falls, and thus are highly undesirable.

6.2.3 Creep Deformation

The volume, internal pressure, and temperature requirements of CAES cavities represent a departure from hydrocarbon storage applications of proven structural stability.

Although cavities seldom collapse under direct earth pressure, they will experience a reduction in volume under certain conditions of loading and temperature because of the time-dependent nature of salt deformation (Corcoran et al., 1970 and 1974b). As soon as the salt cavity is dissolved, salt creep may take place, depending on the initial unbalanced wall stresses and back pressure within the chamber. Compressed air stored within the cavern will tend to offset overburden and lateral stresses. Depressurization

will tend to accelerate creep. The rate of depressurization is arbitrarily limited to 1 MPa per hour to prevent dynamic instability.

A possible consequence of creep deformation in salt that is subjected to stresses, strains, or temperature is structural failure, which can result in caving and rupture (Katz and Lady 1976; Lewis 1970; Lewis 1974). Of great importance in the practical design of storage cavities is an estimate of the time to creep rupture under stress. Of course, any closure of the storage cavity that occurs reduces the usable volume.

Prior to cavity construction, the prospective site should undergo a complete geologic investigation, which includes drillholes, logs, and cores, to estimate creep and other salt properties, as well as the size and other properties of the deposit. In situ stress measurements are required for a full analysis of cavity behavior. Some measure of in situ stress can be obtained from stress meters and deformation gauges (Katz and Lady 1976; Serata 1970). Hydraulic fracture propagation also offers a possible method for determining states of stress in salt.

6.2.4 Surface Subsidence

The construction of an underground chamber causes movements and induces stress changes in the surrounding rock mass. These stress changes may cause subsidence of ground surface above the opening (Chang and Nair 1974; Panek 1970).

Failure may occur in compression or tension. Rock failures in the vicinity of an opening do not have a significant effect on surface subsidence unless they propagate to the surface. Then the massive subsidence associated with sinkholes and ground breakage can occur (Lewis 1974; Chang and Nair 1974). Generally, failure does not propagate to the surface unless the salt over a cavern has been breached by dissolution; otherwise it is only necessary to predict the subsidence that can occur from the creation of solution cavities.

Information must be acquired on the amount of volume reduction and the extent of the subsidence rate to be expected. The complexity of the

caprock structure, the lack of accuracy of information obtained on the salt deposit from a limited number of drillholes, and the unknown mechanical properties of discontinuities can make it difficult to predict the subsidence rate (Weinstein et al. 1978). Computational techniques have been developed to predict fracture propagation around solution caverns. Similar analyses can also be made for slippage along bedding planes and other geologic discontinuities (Corcoran et al. 1974b; Panek 1970).

6.3 CAVERN CHARACTERISTICS

Cavern parameters include octahedral shear strength, excess lateral stress, depth to cavern top, lateral salt thickness, vertical salt thickness and span, and height to diameter ratio.

6.3.1 Octahedral Shear Strength

Various octahedral shear strengths have been reported. These values include: 3.8 to 5.2 MPa (Serata and Cundey 1979); ca. 3.45 MPa (King 1971); and 1.04 MPa (Baar 1970, 1971). According to Baar (1977), values of octahedral shear strength measured in the laboratory may not apply under field conditions. At this writing a tested octahedral shear strength of between 3.8 and 5.2 MPa is a recommended value.

Recommended specification: Minimum octahedral shear strength is to be 3.8 MPa.

6.3.2 Excess Lateral Stress

Serata and McNamara (1980) define excess lateral stress in terms of a maximum theoretical value, $3K_o/\sqrt{2}$, where K_o denotes the octahedral shear strength. For an assumed value of $K_o = 4.5$ MPa the maximum excess lateral stress would be 9.55 MPa. The authors state that the radial boundary strain increases sharply when the excess lateral stress exceeds 90% of its theoretical maximum. This 90% value would be 8.6 MPa greater than the vertical overburden pressure.

Within the depth range of interest a more conservative specification would restrict the horizontal stress to 120% of the overburden pressure. For example, at a depth of 800 m the overburden pressure would be 16.96 MPa (assuming 100% dense rock salt overburden) and the allowable horizontal stress would be 20.35 MPa. The differential stress would be 3.39 MPa, which is only 36% of the calculated maximum. At 1600 m, however, the differential stress would rise to 6.78 MPa, but this is only 71% of the theoretical maximum. However, if viscoplastic behavior dominates at 800 m and below, it is likely that vertical and horizontal stresses will be approximately equal because the rock salt will lack sufficient rigidity to maintain an anisotropic stress field.

Recommended specification: Horizontal stress is not to exceed 120% of overburden pressure.

6.3.3 Depth to Cavern Top

Serata and McNamara (1980) consider a depth of 1220 m safe under "most normal circumstances". They state that the cavern depth should not be greater unless the in situ stress behavior is hydrostatic. These authors would limit cavern depth to 760 m when three critical parameters occur:

- complete depressurization of cavern
- excess lateral stress = 100% of theoretical value.
- cavern separation distance is less than 4 diameters.

Thoms and Martinez (1978a) proposed a maximum depth to the cavern floor of 1524 m unless new research proves feasibility of greater depths. They recommend a minimum depth to cavern roof of 610 m.

Recommended specification: Maximum depth to cavern top is to be 1220 m. This will allow storage of air at 12.93 MPa in nonhomogeneous salt and at 20 MPa in homogeneous salt.

6.3.4 Lateral Salt Thickness

For multiple caverns Serata and McNamara (1980) recommended a minimum separation/diameter (S/D) ratio of 4, provided that the caverns

are operated at the same air pressure. "S" is the center-to-center separation distance. If the caverns have equal radii the salt wall thickness is $(S-2R)$, which is equal to three cavern diameters. The S/D ratio at Huntorf is 3.67 (Quast and Lorenzen 1979). The salt wall thickness between the two caverns is 160 m, which is equal to 2.67 cavern diameters because maximum cavern diameter is 60 m.

Wall thicknesses as low as 30.5 m separate hydrocarbon storage caverns within Louisiana salt domes (Thoms and Martinez 1978a). However, this specification may not be adequate to accommodate the pressure and thermal cycling of CAES.

Recommended specifications: The cavern wall thickness between two CAES caverns is to be at least three times the sum of the adjacent cavern maximum radii. The lateral salt thickness between an "outside" cavern and the lateral boundary of the salt dome or anticline should be 100 to 150 m or at least three times the cavern diameter, whichever is larger, because the geologic conditions of stress unbalance beyond the dome might be comparable to those within an adjacent cavern.

6.3.5 Vertical Salt Thickness and Span

At Huntorf the salt thickness above the cavities is approximately 150 m (Quast and Lorenzen 1979). Golder Associates (1979) states that the ratio of vertical salt thickness to maximum cavern span should not be less than 2.2. For Huntorf, with maximum cavity diameter of 60 m, this ratio is thus 2.5.

Recommended specifications: The vertical salt thickness should be at least 150 m. The cavern span should not exceed more than 60 m. The ratio of vertical salt thickness to maximum cavern span should be at least 2.5.

6.3.6 Height-to-Diameter Ratio

A vertical cylindrical cavern shape was assumed by Serata and McNamara (1980). This shape is considered as a model for most dissolution

salt cavern designs. The cylindrical shape also enables most effective use of the salt dome volume in multiple cavern arrays. The height-to-diameter ratio was varied from 5 to 20 in modeling studies. Regardless of the ratio, the strain and radial closure increased sharply at about 1220 m. Possibly the biggest drawback of caverns with a large ratio is that their deep lower portions may be subject to viscoplastic creep.

The ratio adopted in the Huntorf design is 3.0 (height 180 m, maximum diameter 60 m).

Recommended specification: Height-to-diameter ratio is not to exceed 5.0.

6.4 INJECTION AND DECOMPRESSION PARAMETERS

In CAES salt cavities, daily cycling of temperature and pressure can affect the cavity walls. Air is injected at as high a temperature as possible into the storage chamber, and the single air-phase compression of air will elevate the temperature of air already present (Katz and Lady 1976).

Investigations carried out for the Huntorf facility showed that a maximum rate of depressurization of 1.014 MPa/hour and cycling between 20° and 50°C was within safe limits (General Electric Co. 1976).

Information on the effects of temperature and pressure cycling on cavities in salt deposits is from experiments concerned with hydrocarbon storage. Storage periods for this purpose are seasonal rather than daily. Also, excessive internal cavity pressure can induce tensile stresses that reinforce those produced by the structural features created during mining. Penetration of the air into the salt may affect the material properties of the salt, as well as the state of stress of the salt cavity walls.

Further studies are needed on the effects of temperature and pressure cycling in CAES salt cavities. Before any cycling over wide temperature and pressure changes takes place, the rock mechanics of the selected salt deposit should be thoroughly investigated (Weinstein et al. 1978).

Recommended specifications: Temperature cycling is to be bounded between cavern ambient temperature and 80°C. Maximum rate of depressurization is to be 1 MPa/hour.

6.4.1 Cavern Temperature

The response of rock salt to stress is strongly temperature dependent. Lomenick (1968) studied the creep behavior of rock salt model mine pillars as a function of temperature and load. He concluded that elevated temperature is the most important cause of cavity closure in salt mines. Lomenick developed an empirical relationship in which creep rate of pillar models is proportional to absolute temperature raised to the 9.5 power. He stated that at 200°C severe structural stability problems will occur. Deformation at 100°C is significantly higher than it is at 60°C. However, naturally occurring temperatures range around 80°C in some Gulf Coast salt domes at depths of 1524 m (Thoms 1979). For CAES reservoir walls an upper temperature limit of 80°C is recommended by Thoms and Martinez (1978a) and Serata and Cundey (1979). This temperature takes into account the design life requirement of 35 years.

Thoms and Martinez (1978a) also note that maximum air temperatures could be higher during injection periods. Rock salt has relatively high values of heat capacity and thermal conductivity (Clark 1966) which would tend to restrict temperature rise within the salt cavern wall. Also, air has a relatively low heat capacity and it will be injected into the cavern away from the walls. Salt temperatures will probably be close to mean values of operating CAES cycles, even relatively close to the cavern wall surfaces; temperature will decline rapidly away from the cavern wall, probably approaching ambient within several meters.

Recommended specification: Cavern temperature is not to exceed 80°C.

6.2 Cavern Air Pressure

Cavern air pressure will be limited by depth below ground surface. Maximum pressure is to be 16.39 kPa per meter of depth (1.639 MPa per

100 meters). This quantity is based upon a relationship defined by Thoms and Martinez (1978b). This pressure is 77% of the overburden pressure computed for 100% dense halite. The 23% safety factor will be enhanced to the degree that non-halite minerals are incorporated within the overburden. However, porosity would tend to offset the extra weight per unit depth due to these more dense minerals. (Rock-forming minerals with higher specific gravities than halite include quartz, feldspars, carbonates, ferro-magnesian minerals, and clay minerals.)

For nonhomogeneous salt stocks, such as the salt anticlines of the Paradox Basin, it may be desirable to reduce cavern air pressure to 10.6 kPa per meter of depth. This is 50% of the overburden pressure for 100% dense halite.

Recommended specifications: For homogeneous salt maximum pressure is to be 16.39 kPa per meter of depth. For nonhomogeneous salt maximum pressure is to be 10.6 kPa per meter of depth.

6.4.3 Depressurization Rate

The most extreme cavern air pressure condition is complete depressurization. This condition may result in large closure and boundary strain (Serata and Cundey 1979). Because there is always a possibility of loss of cavern pressure by accident or other unforeseen causes, cavern depressurization should be considered a reality. A cavern at a 1220-m depth should not have a prolonged depressurization, because the expected 5% radial closure under the normal condition would become more than 12% under a prolonged depressurization. At the present level of understanding of cavern stability, depressurization should not be allowed other than in a period of emergency (Serata and Cundey 1979).

Recommended specification: When depressurization is necessary it should be limited to one MPa per hour. This is slightly less than 10 atm/hour, the maximum depressurization rate specified at Huntorf (General Electric Co. 1976).

6.4.4 Injection Parameters at Huntorf

Compressed air injection at Huntorf was described by Herbst et al. (1979) and by Quast and Lorenzen (1979). The design conditions for operation include pressure of 8 MPa, and temperature of 80°C. In actual operation the upper storage pressure is 7 MPa and the lower storage pressure is 5 MPa. This pressure drop of 2 MPa would be permissible in a minimum period of 2 hours. The exhaust temperature from the high pressure compressor is 50°C. The mass flow rate is 108 kg/sec. The compressed air in the cavities is saturated with water vapor. The amount of water that precipitates can total several thousand kilograms per cycle.

6.5 COMPARISON OF NONCOMPENSATED AND COMPENSATED CAVERNS

6.5.1 General

Two types of cavern appear feasible for CAES air reservoirs in salt domes: 1) the noncompensated, or constant volume cavern, and 2) the compensated, or constant pressure cavern (Thoms and Martinez 1978a).

Noncompensated caverns consist of dry cavities in salt. A sufficient volume of compressed air must be maintained to furnish an adequate flow within required limits of pressure over the time interval of power-peaking generation. The required air flow and pressure magnitudes are based on a combination of the anticipated power demand load, the characteristics of the surface facilities of the CAES plant, and the limits set by the site-specific stability criteria for the air reservoir caverns.

Compensated caverns are maintained at nearly constant pressure by a brine column extending to a ground surface lake. The pressure within the cavern does not attain the amplitudes exhibited by noncompensated caverns; however, this system is complicated by an additional reservoir and conduit to handle the compensating liquid. Smaller volume CAES reservoirs can be used because a "cushion" of air is not required to maintain the pressure within limits over the interval of power generation.

6.5.2 Relative Effects on Cavern Stability

Table 6 summarizes relative effects on cavern stability for compensated versus noncompensated CAES caverns (Thoms and Martinez 1978a).

Erosion-dissolution due to the cyclic flow of the compensating brine in a compensated cavern and associated conduits and/or reservoir could possibly be a negative effect (Thoms 1978). If the brine is not always completely saturated the long-term effects on highly soluble rock salt surrounding openings could be destructive. Degree of brine saturation is not very sensitive to pressure and temperature variations; but the frequent and long-term cycling associated with CAES could cause cumulative effects of significance.

The champagne effect for compensated caverns refers to the rapid exsolution of air from the compensating brine column. It is caused by decrease in hydrostatic pressure when the column is raised during air injection. The onset of exsolution tends to exacerbate the effect. The final stage, in principle, could cause a rapid depressurization of the CAES cavern. This, in turn, could cause a severe roof fall or other brittle-fracture effect within the walls of the salt cavern.

TABLE 6. Relative Effects for Compensated Versus Noncompensated CAES Caverns in Salt Domes

<u>Topic</u>	<u>Noncompensated</u>	<u>Compensated</u>
• Erosion-Dissolution	Not Applicable	Possibly Negative
• Champagne Effect	Not Applicable	Possibly Negative
• Pressure Magnitude	More Flexibility	Limited
• Cyclic Loadings	Possibly Negative	Decreased Effect
• Volume of Caverns	Larger Volume Required	Smaller Volume
• Complications of Construction	Few	Possibly More

The pressure magnitude within noncompensated caverns can be controlled; however, compensated caverns are restricted to pressures consistent with the brine "head" to the ground surface. Pressures within noncompensated caverns therefore could be increased to correspond more nearly with geostatic pressure levels, provided a maximum value was not exceeded. Decreasing the pressure difference between geostatic and cavern pressure should increase cavern stability.

Compensated caverns will be limited to about 10 kPa per meter of depth. This corresponds to a depth from ground surface to cavern floor of 900 m for a pressure of 9.0 MPa. The maximum feasible depth for a compensated salt cavern may be less than the 1200-m depth proposed for uncompensated caverns.

Cyclic loading effects constitute a major unknown factor in long-term stability of CAES caverns in salt domes. The amplitudes of cyclic pressure and temperature loadings obviously will be larger for noncompensated than for compensated caverns. Thus the associated long-term stability effects could be more severe for noncompensated caverns.

Volume of caverns will be larger for noncompensated caverns. Thus, the volume of salt affected by the state of stress will be more extensive. Alternately, a number of caverns can be constructed to avoid possible negative effects associated with very large openings in rock salt. If an adequate volume of salt is present, no difficulty should prevent constructing multiple caverns for a CAES air reservoir system.

Complications of construction will be of much greater magnitude for compensated caverns. This may not directly affect long-term stability; however, the probability of stability related concerns could increase. For example, well casings, valves, and reservoir connections would increase in number; thereby, possibilities would also increase for events affecting long-term cavern stability, e.g., brine induced corrosion of metal components.

In conclusion, two factors will determine the choice between compensated and uncompensated caverns, reliability and cost. Given reasonable design

in terms of rock mechanics, the simplicity of the uncompensated system would strongly support its choice in terms of reliability. Cost considerations would be based on comparing incremental solutioning costs for additional cushion volume against the cost of a large compensation shaft designed for high flow rates and surface compensating brine reservoir. An engineering study for the specific situation may be required to assess this cost impact, but the low incremental cost of volume by solutioning would probably be less than the compensation system in the average case. **It** is **recommended** that the noncompensated system be considered **first** in investigation of CAES feasibility.

6.6 CAVERN MONITORING

Cavern monitoring includes sensor detection of the following: three-dimensional shape, stress levels, elastic waves originating in or near the cavern, acoustic waves, tilting and subsidence, air leakage, temperature, pressure, humidity and presence of liquid water, and presence of cavern wall minerals within withdrawn air.

Three-dimensional mapping can be performed by laser ranging through pressurized gas, photogrammetry, television, and extensometers. The laser ranging device can monitor distances within a gas-pressurized salt cavern to ± 10 cm (Thoms 1978). Sonar can be employed to survey the cavity configuration during and immediately after dissolution, but **it** is not applicable to a gas-filled cavern. Changes in stress levels can be followed with stress meters and microseismic monitors. Microseismic disturbances may divulge and locate roof falls or slabbing from walls. Five sensors at different locations are **recommended** to locate the source. **Tiltmeters** and precise level-recording instruments will reveal minute degrees of subsidence (Thoms 1978). Significant air leakage **will** be detectable by loss of performance. Lesser leakage may be detected by monitoring observation wells for gaseous tracers added to the compressed air. Thermistors, pressure sensors, microphones, and humidity measuring devices will monitor physical characteristics of the cavern atmosphere. A simple bypass or screen can be used to collect fine mineral grains in the withdrawn air.

Surveys at Huntorf showed that caverns have withstood 1000 load changes without significant change (Quast 1981). Exact long-term behavior has been followed with a new laser survey procedure. Temperature measurements within the caverns indicated stable air cushions existed during all phases of operation.

Golder Associates (1979) has conducted detailed studies of oil storage caverns in salt domes. After a cavern has been completed they recommend a shut-in pressure test to a maximum of 20.37 kPa per meter of overburden. The shut-in cavern pressure is monitored continuously for 24 hours. A pressure drop of less than 69 kPa was judged satisfactory for oil storage. During any depressurization microseismic monitoring can be used to detect fracturing, slabbing, spalling, buckling, or heaving of cavern surfaces.

Throughout cavern use a surface survey network can detect vertical and horizontal movements. Surveys of strain in well casings should also be conducted. The caprock overlying the salt dome is often highly fractured and cavernous, which may induce or modify surface displacements.

Borehole logs of cavern access holes should include: 1) caliper, 2) three-dimensional velocity, 3) cement bond, 4) neutron, 5) compensated density, 6) temperature, and 7) velocity. One reason for logging is to characterize the roof rock before and after cavern pressurization.

The two most important devices used to monitor deformations above a roof are extensometers, which measure deformations parallel to the axis of the borehole, and inclinometers which sense deformations normal to the direction of the borehole (Golder Associates 1979).

Techniques are available to obtain a measure of absolute stresses and stress changes adjacent to cavern walls. Most methods would require separate holes drilled to the top and sides of the cavern. More than one technique should be used.

7.0 DESIGN AND STABILITY CRITERIA

The design and stability criteria currently available to the CAES salt cavity designer, are presented in Table 7. Categories include general geologic environment, hydrology, petrography, structure, design dimensions, operating characteristics, and rock mechanical characteristics. In evaluating a particular site, the minimum acceptable design should be compared with the known geology and environmental requirements before recommending preliminary exploration. Such factors as salt dome history, caprock and halite quality, brine disposal, and dimensional compatibility with the planned cavern array should be considered.

TABLE 7. Design and Stability Criteria

<u>Category</u>	<u>Requirement</u>	<u>Qualification</u>
<u>General Geologic Environment</u>	Salt dome or anticline with adequate depth, geometry, lithology and absence of high lateral stress field	Analysis of existing geological information. Seismic surveying, exploratory drilling, salt and caprock core analysis, geophysical logging, in situ stress measurement
<u>Hydrology</u>		
a. Water availability	Solution mining will require up to 10 million m ³ of fresh water. The volume of water needed is about 8 times the volume of the cavern to be dissolved.	Analysis of existing hydrological data pertaining to river volumes, lakes, ground water and aquifers. In arid regions sufficient water may not be available.
b. Saline water disposal	An environmentally and economically acceptable means of brine disposal must be identified. Up to 10 million m ³ of salt-saturated water may require disposal.	Possible disposal modes include pumping to deep saline aquifers, surface saline or dry lakes, and ocean waters. Industrial use of brine is also possible.
c. Ground water encroachment	Salt caverns must be protected from ground water encroachment other than an artificial compensating brine column in chemical equilibrium with the salt.	A detailed exploration program to define hydrologic conditions within the near and intermediate geologic regions must be carried out. Uncontrolled drilling and excavation not related to CAES are to be prohibited within the salt body.

<u>Category</u>	<u>Requirement</u>	<u>Qualification</u>
<u>Petrography</u>		
a. General	Rock salt shall consist of at least 95% halite. Accessory minerals must not be distributed in preferential zones which could cause severe solution anisotropy, cause air leakage, or inhibit halite's potential to recrystallize under stress.	Locations of accessory mineral zones are most readily identified by drilling. Other potential exploration methods include shallow seismic surveying, gravimetry, magnetometry, acoustic holography, and sampling of the insoluble fraction during solution mining.
b. Grain size	Grain size influence must be characterized with respect to air and water penetrations along grain boundaries and their influences on rock mechanical behavior.	Rock salt behavior under CAES conditions must be simulated by laboratory experiment.
c. Caprock	Caprock mineralogy, geochemistry, physical characteristics and degree of adherence to salt must not compromise borehole casings or salt integrity.	The drilling program will reveal such undesirable characteristics as cavernous zones, presence of hydrogen sulfide, and structural separation between caprock and dome. Well completion through the caprock zone should be carefully engineered to the specific situation.
<u>Structure</u>		
a. Internal	Spatial inhomogeneities (trends) either linear or tabular, which may contain other saline minerals, silicate inclusions, hydrocarbons, high porosity/permeability zones and exhibit relatively low strength are to be avoided within the cavern walls.	These trends must be located and mapped by core drilling and geophysical methods. Trend intersections are especially treacherous.

<u>Category</u>	<u>Requirement</u>	<u>Qualification</u>
b. Surface subsidence	Subsidence must not be permitted as a design allowance.	Numerical modeling, laboratory experiments on rock salt, and in situ field measurements of stress and deformation are needed. Surface instrumentation will monitor the topography above and near caverns for horizontal and vertical deformation.
c. Creep closure	Loss of cavern volume due to creep closure must not impact CAES performance significantly over the life of the project. This parameter is strongly tied to cavern depth and temperature.	Cavern should be sufficiently oversized to allow for predicted decrease in volume. Cavern volume can be monitored by measuring pressure versus injection time and withdrawal time.
<u>Design Dimensions</u>		
a. Depth to cavern roof	760 to 1200 m depending upon salt quality, design parameters and operating pressure. Most likely depth is near 800 m.	Required cavern depth is determined by operating pressure. For homogeneous salt stocks maximum operating pressure is 16.39 kPa per meter of depth. In nonhomogeneous salt the maximum operating pressure is 10.6 kPa per meter of depth.
b. Cavern height-to-diameter ratio, H/D	Preferred ratio between 1 and 5.	Increase in the ratio to 10 is not likely to cause serious instability. A spherical cavern would have maximum stability.
c. Cavern separation to diameter ratio, S/D (separation is defined as the center-to-center horizontal distance)	Minimum S/D ratio is to be 4. The cavern wall thickness is to be at least three times the sum of the adjacent cavern maximum radii.	The Huntorf S/D ratio is 3.67.

<u>Category</u>	<u>Requirement</u>	<u>Qualification</u>
d. Thickness of salt above cavern ceiling	Minimum thickness is to be 150 m. Ratio of overburden salt thickness to cavity span is to be at least 2.5. Local or state regulations may establish minima here.	The Huntorf thickness and ratio are 150 m and 2.5 respectively. Evaluation of strength and geological inhomogeneities may revise these quantities upward at some sites.
e. Distance of cavern wall from nearest salt dome or salt anticline geologic contact	Minimum distance is to be 100 to 150 m or at least 3 times the cavern diameter, whichever is larger.	Establishing the contact geometry and location may be difficult due to overhanging salt, other intrusive irregularities, fault gauge zones, etc. The salt contact should be mapped with an appropriate margin for error, e.g., 25 to 50 m.

Operating Characteristics

32	a. Cavern temperature	Wall temperature should not exceed 80°C. Injected air temperature may be somewhat higher.	Wall temperature is to be monitored continuously at the roof with redundant thermistors.
	b. Cavern air pressure	Not to exceed 16.39 kPa per meter of depth for homogeneous salt. Not to exceed 10.6 kPa per meter for nonhomogeneous salt. Most likely maximum pressure is near 9.0 MPa.	Cavern pressure is to be monitored continuously at the roof with redundant pressure transducers or other sensors. The specified maximum is 77% of overburden pressure computed for 100% dense halite.
	c. Temperature cycling	Between cavern ambient temperature and 80°C maximum.	Temperature is to be continuously monitored.
	d. Pressure cycling rate	Depressurization limited to 1 MPa per hour.	This is slightly less than 10 atm/hour, the maximum rate specified at Huntorf. Pressure is to be monitored continuously.

<u>Category</u>	<u>Requirement</u>	<u>Qualification</u>
<u>Rock Mechanical Characteristics</u>		
a. Horizontal stress	Not to exceed 25.42 kPa per meter of depth. At 800 m the maximum horizontal stress would be 20.34 MPa.	To be measured during geological qualification procedures by instrumentation of boreholes. These numbers correspond to 120% of the overburden pressure of halite at a specific gravity of 2.16 (2,160 kg per m ³)
b. Octahedral shear strength	Not less than 3.8 MPa	To be measured by laboratory procedure and corroborated by field data. This is equivalent to 551 psi.

REFERENCES

- Aamodt, P. L., M. R. Engler, P. Madden, and R. B. Stone. 1975. Evaluation of Hazardous Wastes Emplacement. EPA-600/2-75-040, Fenix and Scisson, Inc., Tulsa, Oklahoma.
- Allen, K. 1972. "Eminence Dome - Natural Gas Storage In Salt Comes of Age." J. of Petroleum Technology. November, pp. 1299-1301.
- Asiala, R. A. 1974. "Cavern Storage of Feedstock for Synthetic Natural Gas Plant." In Proceedings of the Fourth Symposium on Salt, Vol. 2, pp. 301-303. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Baar, C. A. 1970. "Correct Interpretation of Data for Better Understanding of-salt Pillar Behavior in Mines." In Proceedings Second Symposium on Salt, eds. J. L. Rau and L. F. Dellwig, Vol 2, pp. 280-289. Northern Ohio Geol. Soc., Cleveland, Ohio.
- Baar, C. A. 1971. Applied Rock Mechanics in Deep Potash Mines. Internal Report No. E71/2, Saskatchewan Research Council, Canada.
- Baar, C. A. 1977. Applied Salt Rock Mechanics I, the In-Situ Behavior of Salt Rocks. Elsevier Scientific Publishing Company, New York, New York.
- Billings, M. P. 1972. Structural Geology. Prentice-Hall, Inc., New York, New York.
- Boresi, A. P., and D. U. Deere. 1963. Creep Closure of a Spherical Cavity in an Infinite Medium (with Special Application to Project Dribble, Tatum Salt Dome, Mississippi). Holmes and Narver, Inc., Orange, California.
- Chang, C-Y and K. Nair. 1974. "Analytical Methods for Predicting Subsidence Above Solution Mined Cavities." In Proceedings of the Fourth Symposium on Salt, Vol 2, pp. 101-117. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Chang, G. C., P. A. Thompson, R. D. Allen, and W. V. Loscutoff. 1980. "Underground Compressed Air Energy Storage for Electric Utilities." In Rockstore 80, subsurface Space, Proceedings of the International Symposium, ed. S. M. Bergman, Vol 2, pp. 579-585. Pergamon Press, Oxford, England.
- Clark, S. P., Jr. 1966. Handbook of Physical Constants. Memoir 97, The Geological Society of America, New York, New York.
- Corcoran, A. E., F. W. Jessen, and H. Von Schonfeldt. 1974a. "Feasibility of Storing Large Quantities of Crude Oil in Salt Dome Solution Cavities." In Proceedings of the Fourth Symposium on Salt, Vol 2, pp. 277-283. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.

- Corcoran, A. E., C-Y Chang, R. D. Singh, and A. M. Abdullah. 1974b. "Time-Dependent Analysis to Predict Closure in Salt Cavities." In proceedings of the Fourth Symposium on Salt, Vol 2, pp. 129-139. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Corcoran, A. E., R. L. Thoms and V. K. Jindal. 1970. "Model Studies of Effects of Closure of Solution Caverns in Salt Domes." In Proceedings of the Third Symposium on Salt, Vol 2 pp. 308-320. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Cruden, D. M. 1971. "The Form of the Creep Law for Rock Under Uniaxial Compression." Int. J. Rock Mechs Min Sci. 8(2):105-126, Pergamon Press.
- Cundey, Thomas E. and Shosei Serata. 1978. "Numerical Modeling of Behavior of caverns in Salt for Compressed Air Energy Storage." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 394-401, CONF-781046, National Technical Information Service, Springfield, Virginia.
- Desai, C. S. 1971. "Nonlinear Analysis Using Spline Functions," In Proceedings ASCE, Jour. Soil Mechanics and Foundation Design. 97(10).
- Dreyer, W. E. 1974. "Results of Recent Studies on the Stability of Crude Oil and Gas Storage in Salt Caverns." In Proceedings of the Fourth Symposium on Salt, Vol 2, pp. 65-92. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Dwyer, M. G. and R. L. Thoms. 1974. "Finite Element Analysis of Salt Domes with Stored Hot Wastes." Fourth Symposium on Salt, ed. A. H. Coogan, V. II, pp. 343. Northern Ohio Geol. Soc., Cleveland, Ohio.
- Fenix and Scisson. 1978. "Conceptual Design for Compressed Air Energy Storage (CAES)." prepared for Middle South Services, Inc. by Fenix and Scisson, Tulsa, Oklahoma.
- Gay, F. W. "Means of Storing Fluid for Power Generation," U.S. Patent 2433896, January, 1948.
- General Electric Company. 1976. Economic and Technical Feasibility Study of Compressed Air Storage. ERDA-76-76, Schenectady, New York.
- Golder Associates. 1979. "Report to Gulf Interstate Engineering Company on Discussions held in New Orleans concerning Potential Problems with Underground Oil Storage Caverns in Salt Domes." Vols I and II, Vancouver, British Columbia, Canada.
- Heard, H. C. 1972. "Steady State Flow in Polycrystalline Halite at Pressure of 2 Kilobars." Flow and Fracture of Rocks, In Geophysical Monograph Series Vol 16, pp. 191-209. American Geophysical Union, Washington, D.C.

Herbst, C. H., H. Hoffeins, and Z. S. Stys. 1979. "Huntorf 290 MW Air Storage System Energy Transfer (Asset) Plant Design, Construction, and Commissioning." In 1978 Compressed Air Energy Storage Symposium Proceedings, Vol. 1, pp. 1-17, CONF-780599, National Technical Information Service. Springfield, Virginia.

Howells, D. A. 1977. "Effects of Pressure and Temperature Change in a Compressed Air Storage Cavern." In Rockstore 77, Proceedings of the First International Symposium, ed. M. Bergman, Vol 3, p. 789. Pergamon Press Oxford, England.

Hurlbut, C. S. 1941. Dana's Manual of Mineralogy. 15th ed. John Wiley & Sons, Inc., New York, New York.

Katz, D. L. and E. R. Lady. 1976. Compressed Air Storage. pp. 139-169. Ulrich's Books, Inc., Ann Arbor, Michigan.

King, M. 1971. "A Method for Determining the Long-Term Strength of Evaporites." Can. Inst. Min. and Met. Bull. 64(711), July.

Kupfer, D. H. 1976. "Shear Zones Inside Gulf Coast Salt Stocks Help to Delineate Spines of Movement." Amer Assoc Pet. Geols Bull. 60:1434-1447.

Kupfer, D. H. 1978. "Problems Associated with Anomalous Zones in Louisiana Salt Stocks, U.S.A." Paper presented at 5th International Symposium on Salt, May 1978, Hamburg, West Germany.

LeCompte, P. 1965. "Creep in Rock Salt." Journal of Geology 73. p. 469-484, May.

Lewis, G. J. 1970. "The Problem of Subsidence in Salt-Producing Areas." In Proceedings of the Third Symposium on Salt, Vol 2, pp. 293-297. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.

Lewis, G. J. 1974. "Utilization of Stress Envelopes in Design of Solution Cavities." In Proceedings of the Fourth symposium on Salt, Vol 2, pp. 51-64. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.

Lomenick, T. F. 1968. Accelerated Deformation of Rock Salt at Elevated Temperatures and Pressure and its Implications for High Level Radioactive Waste Disposal. Ph.D Dissertation, University of Tennessee.

Martinez, J. and R. Thoms. 1977. "A Systems Concept of Space Utilization in Gulf Coast Salt Domes." In Proceedings of the First International Symposium on Storage in Excavated Rock Caverns. Rock Store 77, pp. 105-109. Pergamon Press, Oxford, England.

- McNamara, J. F., F. Tsa'i and S. Serata. 1981. "Field Calibration of the REM Computer Method Used for CAES Cavern Design," In Proceedings of International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, pp. 545-552, CONF-811066, Vol 2, National Technical Information Service, Springfield, Virginia.
- Medley, A. 1978. "Crude Oil Storage in Salt Domes." Paper presented at API 1978 Pipeline Conference, April 17-18, 1978, Houston, Texas.
- Morgan, H. S., R. D. Krieg and R. V. Matalucci. 1981. "Comparative Analysis of Nine Structural Codes Used in the Second WIPP Benchmark Program," Sandia Report SAND 81-1389, November.
- Nair, K. and D. U. Deere. 1970. "Creep Behavior of Salt in Triaxial Extension Tests." In Third Symposium on Salt, Vol 2, pp. 208-215. Northern Ohio Geol. Soc., Cleveland, Ohio.
- Obert, L. 1962. "In Situ Determination of Stress in Rock." Mining Engineer, p. 51-58, August.
- Panek, L. A. 1970. "Methods and Equipment for Measuring Subsidence." In Proceedings of the Third Symposium on Salt, Vol 2, pp. 321-338. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Quast, P. and H. Lorenzen. 1979. "The Huntorf 290-MW CAES Power Plant: Design, Construction and Commissioning of Underground Facilities." In 1978 Compressed Air Energy Storage Symposium Proceedings, Vol. 1, pp. 19-49, CONF-780599, National Technical Information Service, Springfield Virginia.
- Quast, P. 1981. "The Huntorf Plant: Over Three Years Operating Experience with Compressed Air Caverns," In Proceedings of International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, pp. 562-573, CONF-811066, Vol 2, National Technical Information Service, Springfield, Virginia.
- Querio, C. W. 1980. "Design and Construction of Solution Mined Caverns for LPG Storage." Paper presented at the Solution Mining Research Institute, October 13, 1980, Minneapolis, Minnesota.
- Rohr, H. U. 1974. "Mechanical Behavior of a Gas Storage Cavern in Evaporitic Rock." In Proceedings 4th International symposium on Salt, Vol II, pp. 93-100. Northern Ohio Geol. Soc., Cleveland, Ohio.
- Russell, J. E. 1978. "A Creep Model for Salt." Paper presented at Vth International Symposium on Salt, May 1978, Hamburg, West Germany; also, Report Y/OWI/TM-32, Office of Waste Isolation, Oak Ridge, Tennessee.

- Serata, S. 1970. "Prerequisites for Application of Finite Element Method to Solution Cavities and conventional Mines." In Proceedings of the Third Symposium on Salt, Vol 2, pp. 249-279. Northern Ohio Geol. Soc., Inc., Cleveland, Ohio.
- Serata, S. and T. E. Cundey. 1979. Numerical Modeling Behavior of Caverns in Salt for Compressed Air Energy Storage (CAES). Serata Geomechanics, Inc. Berkeley, California.
- Serata, S. and J. F. McNamara. 1980. Numerical Modeling of Behavior of Caverns in Salt for Compressed Air Energy Storage with Elevated Temperatures. Serata Geomechanics, Inc., Berkeley, California.
- State of Louisiana. July 1977. Rules and Regulations Pertaining to the Use of Salt Dome Cavities for Storage of Liquid and/or Gaseous Hydrocarbons, etc. Statewide Order No. 29-M, Department of Conservation, Baton Rouge, Louisiana.
- Stickney, R. G. 1977. "Case History Rock Mechanical Examination of the Jefferson Island Salt Mine: III. Evaluation of Effects of Laboratory Specimen Dimensions on the Uniaxial Strength and Deformational Characteristics of ~~Dome~~ Salt." Tech. Mem RSI-0059, RE/SPEC, Inc., Rapid City, South Dakota.
- Thoms, R. L. 1978. "Preliminary Long-Term Stability Criteria for Compressed Air Energy Storage Caverns in Salt Domes." In Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting, pp. 376-383, CONF-781046, National Technical Information Service, Springfield, Virginia.
- Thoms, R. L. 1979. "Long Term Stability of Compressed Air Energy Storage Cavities in Salt Domes." Paper presented at Soc. of Mining Engineers of AIME Annual Meeting, February 1979, New Orleans, Louisiana.
- Thoms, R. L. 1980. "Laboratory Tests of Rock Salt." In Proceedings of Mechanical, Magnetic, and Underground Energy Storage 1980 Annual Contractors' Review, pp. 199-205, CONF-801128, National Technical Information Service, Springfield, Virginia.
- Thoms, R. L. and J. D. Martinez. 1978a. Preliminary Long-Term Stability Criteria for Compressed Air Energy Storage Caverns in Salt Domes. Louisiana State University, Institute for Environmental Studies, Baton Rouge, Louisiana.
- Thoms, R. L. and J. D. Martinez. 1978b. "Blowouts in Domal Salt." Paper presented at 5th Inter. Symposium on Salt, May-June, 1978, Hamburg, West Germany.

Thorns, R. L. and R. M. Gehle. 1981. "In Situ CAES Tests for Salt Reservoirs," In Proceedings of International Conference on Seasonal Thermal Energy Storage and Compressed Air Energy Storage, pp. 553-561, CONF-811066, Vol 2, National Technical Information Service, Springfield, Virginia.

United States Department of Interior, Bureau of Reclamation. October 1962. Triaxial Compression Tests of Salt Rock Cores for the United States Atomic Energy Commission - Project Dribble, Laboratory Report No. C-1043, Clearinghouse TID-21592.

Wawersik, Hannum. 1978. "Mechanical Behavior of ~~New~~ Mexico Rock Salt in Triaxial Compression Up to 200°C." Paper presented at Vth International Symposium on Salt, May 29-June 1, 1978, Hamburg, West Germany.

Weinstein, K. D., et al. 1978. Geologic Issues Related to Compressed Air Energy Storage Systems. Booz, Allen & Hamilton, Inc., Bethesda, Maryland.

DISTRIBUTION

Nb of
Copies

Nb of
Copies

OFFSITE

	Acres American, Inc. Attn: M. J. Hobson The Clark Building Suite 329 Columbia, MD 21044	US Department of Energy Attn: J. Mathur Division of Environmental Safety and Engineering MS-E201, Germantown Washington, DC 20545
	Acres American, Inc. Attn: D. Willett Liberty Bank Building Main at Court Buffalo, NY 14202	US Department of Energy Attn: R. A. Dunlop Division of Electric Energy Sys. 12 & Pennsylvania Washington, DC 20585
27	DOE Technical Information Center	Illinois Power Company Attn: Mr. G. E. Huck Manager of Planning 500 South 27th St. Decatur, IL 62525
5	US Department of Energy Attn: R. Shivers Office of Energy Systems Res. Forrestal Building, CE-142 1000 Independence Ave., S.W. Washington, DC 20585	2 Lawrence Livermore Laboratory Attn: Tech. Info. Dept., L-3 University of California PO Box 808 Livermore, CA 94550
	US Department of Energy Attn: J. H. Swisher Office of Energy Systems Res. Forrestal Building, CE-142 1000 Independence Ave., S.W. Washington, DC 20585	5 Louisiana State University Attn: R. L. Thoms Institute for Environmental Studies Room 42, Atkinson Hall Baton Rouge, LA 70803
	US Department of Energy Attn: A. A. Churm Chicago Patent Group Chicago Operations Office 9800 South Cass Avenue Argonne, IL 60439	Marchwood Engineering Labs. Attn: I. Glendenning Head of Long-Term Studies Southampton, England
5	US Department of Energy Attn: I. Gyuk Office of Energy Systems Res. Forrestal Building, CE-142 1000 Independence Ave., S.W. Washington, DC 20585	Middle South Services Attn: L. A. Wilson Advanced Energy Program Section Box 6100 New Orleans, LA 70161

No of
Copies

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

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

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

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

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

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

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

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

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

No of
Copies

Tennessee Valley Authority
Attn: Arnold Betbeze
1150 Chestnut, Tower 2
Chattanooga, TN 37401

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

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

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

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

ONSITE

DOE Richland Operations Office

H.E. Ransom/D. R. Segna

Pacific Northwest Laboratory

R.D. Allen (5)
T.J. Doherty (5)
L.D. Kannberg (25)
Technical Information (5)
Publishing Coordination (2)