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CAVITY DEGRADATION RISK—INSURANCE ASSESSMENT

Final Report for September 1, 1978—February 28, 1980

By
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Work Performed Under Contract No. AC02-78ET29245

International Research and Technology Corporation
McLean, Virginia

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Cavity Degradation Risk Insurance Assessment

FINAL REPORT

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FOREWORD

The following report describes the principal findings and conclusions of a study of risk exposures and risk management problems involved with underground energy storage by Compressed Air Energy Storage (CAES) and Underground Pumped Hydro (UPH) systems. The study is sponsored by the Chicago Operations Office of the U.S. Department of Energy (DOE) and executed by the International Research and Technology Corporation (IR&T), its subcontractor, Dames and Moore, and by its consultant, John S. McGuinness Associates, during the period September 1, 1978 to February 28, 1980, under DOE Contract No. DE-AC02-78ET29245.

The purpose of this study is to examine the risks and risk management issues involved with implementation by electric power utilities of CAES and UPH energy storage systems. The study is divided into six tasks, covering:

1) Collection of Background and Relevant Information;
2) Obtain Data;
3) Risk Analysis;
4) Preliminary Definition of Insurance Alternatives;
5) Survey Insurers and Estimate Costs; and
6) Finalization of Assessment.

Generally, IR&T played the leading role in Tasks 1, 4 and 6. Dames and Moore played a similar role on Tasks 2 and 3. John S. McGuinness Associates, of Scotch Plains, New Jersey, played the lead role in Task 5, and provided invaluable assistance throughout the study. IR&T has benefited from guidance provided by Dr. Eric M. de Saventhem of Geneva, Switzerland, Director for Europe for the Clarkson Insurance Group.

The project director of the study was Christopher Hampson. Other key IR&T personnel were Polly Neill, Robin Rodensky Severn, Lawrence H. deBivort, Charles C. Humpstone, and Kerry Chrisman.

The Dames and Moore principals in charge of this project were Andrew Woloshin and Grant Hocking. The following individuals provided key contributions to the various technical areas: John R. Williams, Neill Rudd, R. Winar, T. Maini, and L. Eriksson.

Robert Pikul, General Manager of International Research and Technology Corporation, and Robert Burt, head of IR&T's Regulatory Analysis group, provided valuable guidance and review of initial drafts of this report. The highest caliber of support in document preparation was supplied by Kerry Chrisman.

During the course of the study, numerous interviews took place with representatives of the insurance, electric utility, gas utility, and construction industries, State and Federal insurance program spokespersons, coal mining firms, engineering design specialists, industrial developers, utility research organizations, etc. We wish to thank the many persons who shared their knowledge with us, sometimes in confidence.

Comments, suggestions, or criticisms are most welcome, and may be addressed to:

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Underground energy storage has been offered as a favorable option for producing intermediate and peak-period electric power, exploiting the energy obtained by recycling fluids such as air and water. As a result, the U.S. Department of Energy is conducting a comprehensive program of research and analysis of the underground storage technology, addressing any identified barriers to commercialization of Underground Pumped Hydro (UPH) and Compressed Air Energy Storage (CAES) techniques. An implementation barrier of concern to the DOE involves the risks of utilization of, and the utility risk management problems posed by, the CAES and UPH systems. On September 1, 1978, the DOE commissioned International Research and Technology Corporation to perform a risk-related insurance analysis of the two proposed energy storage systems. The five basic tasks of the IR&T project are: (1) to determine the risks involved by designating the potential Failure Modes for both storage schemes in hard rock excavations, and for CAES risks involved in salt cavities and in aquifers; (2) to specify the insurance rates implied for each category of failure identified; (3) to determine the conditions for insurability that will be applied by prospective insurers of CAES and UPH systems; (4) to outline the components of possible insurance programs; and (5) to assess the needs for a more detailed risk assessment, including identifying the insurance market structures and brokering requirements that are likely to emerge. Chapter 1.0, Preface, describes the IR&T role in greater detail.

UPH and CAES systems are projected to offer considerable savings in peak-period electrical production fuel costs. They are also expected to provide a means by which electric utilities can level production loads, thus mitigating the portion of operating costs that is due to fluctuating system load factors.

The problems of insurability and of risk exposure with respect to CAES/UPH technology may assume national importance. Projections by the Regional Reliability Councils (as filed with the Federal Power Commission in 1976) indicate that CAES/UPH use could comprise 24 to 40 percent, or 36 million kW, of new peaking capacity by the year 1995. The feasibility of insurance for these systems may be a deciding factor in the use of CAES/UPH technology for electrical generation. The role of CAES/UPH in domestic production is discussed in Chapter 2.0.

The UPH system is essentially a version of the pumped water storage systems used widely in the U.S. and abroad. Modification of pumped hydro storage techniques, to use underground chambers excavated in rock mass as the lower reservoir, permits wider placement of UPH facilities. CAES systems utilize air compressed in underground cavities to alleviate much of the parasitic power demands in the compression stage of electricity production.

The three types of geologic structures that may be employed for CAES/UPH technology include hard rock, salt domes, and porous media reservoirs (aquifers). In all, four configurations are contemplated: UPH is designed for installation in only hard rock mass; CAES systems will utilize all three structures, that is, hard rock excavations, solution-mined salt domes, and aquifers. (See Table Summary-1.) Chapter 3.0 provides a technical background on the three geologic structures, including illustration of the proposed configurations, technical unknowns pursuant to the risk assessment, and current research in the area.

TABLE SUMMARY-1

CAES/UPH CONFIGURATIONS

	CAES	UPH
Salt	x	
Hard Rock	x	x
Aquifer	x	

The construction methods for CAES and UPH in all three geologic structures are virtually the same methods presently used for other purposes. Salt cavity construction utilizes a solution-mining process that is involved both in sulfur mining and in construction of salt storage facilities for oil and gas. Conventional excavation techniques in hard rock will be used for UPH and CAES development. Aquifer development for natural gas and storage involves drilling wells for testing, injection, production, and monitoring using established methods. Utilization of these geologic structures for technical processes, including cycling of pressurized gases, is a risk exposure accepted by the domestic and foreign insurance industries today. In addition to storage in salt formations, oil and gases have been stored in hard rock excavations as well as in aquifers. Section 3.2 describes both construction features and some present operating modes in these structures.

Loss history information of the CAES and UPH systems is effectively lacking, with the exception of 11 months' use of the CAES plant in West Germany. (The plant began operation after the start of the study, so little meaningful experience was available for this analysis.) The assessment of insurability of these risks was conducted, therefore, by a comparative analysis of the CAES/UPH risk exposure through comparison with evidently similar technical risks.

The risk assessment of CAES and UPH systems proceeded through four distinct phases:

1) Geotechnical and engineering analysis of the modes of failure affecting each of the four configurations, described in Chapter 4.0;

2) Interviews with insurance and utility executives, to determine similarities in the risks between CAES and UPH systems and other technical risks. Other risks include conventional electric utility activities and some non-utility operations;

3) Actuarial analysis of the CAES/UPH risk exposure, using existing industry rate structures, loss statistics from similar risks, Failure Modes analysis, and actuarial judgment to estimate generic annual insurance loss rates, per $1,000 of utility

investment. (A hazard index algorithm is suggested as a mechanism for adjusting these generic loss rates to the conditions of a particular site.) Chapter 5.0 contains the summary of these steps; and

4) An evaluation of the likely insurance programs for electric utilities is reported in Chapter 6.0. The evaluation utilized the considered advice and opinions of utility risk managers and of insurance underwriting executives to check the conclusions from actuarial and geotechnical analyses.

The study findings with respect to the inherent insurability of the CAES and UPH technologies (see Section 1.2) leaves open the prospects of insurance for a particular utility proposing to install one or the other of these storage schemes at a given site. The insurance programs chosen by individual utilities involves matters of corporate risk management policies, of the historical results from previous technology development programs, and perhaps most importantly, the vagaries of negotiations with prospective insurers.

1.2 SUMMARY OF MAJOR FINDINGS

- The insurance risks of implementing CAES and UPH systems differ both for the construction and operations phases, and for the above-ground and underground components of each system (Chapter 6.0).

- Underground CAES system components feature the greatest novelty in terms of risk exposure. Figure Summary-1 displays the relative degrees of familiarity of components of the proposed configurations.

FIGURE SUMMARY-1

RELATIVE FAMILIARY OF CAES/UPH

	ABOVE-GROUND		UNDERGROUND	
	CONSTRUCTION	OPERATIONS	CONSTRUCTION	OPERATIONS
CAES	familiar	familiar	familiar	?
UPH	familiar	familiar	familiar	familiar

The insurance risks involved in construction of both above-ground and underground CAES and UPH system components, in operation of both above-ground and underground UPH system components, and in operation of the above-ground component of the CAES system are not significantly different from the present risk exposures to utilities or insurers from these processes. The most operating experience is associated with UPH, both in operation and construction, and with construction of CAES underground. The only loss history for operation of CAES systems is currently being accrued by the operation of the CAES system in salt by Nordwestedeutsche Kraftwerke AG, in Huntorf, West Germany (Chapter 3.0).

o Ranking the insurability of CAES systems in salt, hard rock, or aquifer is not feasible. The three geologic structures contemplated for use have distinct characteristics and offer varying degrees of familiarity of use, which require site-specific consideration in a risk analysis (Chapter 3.0).

Salt. Salt offers significant technical advantages, primarily because of a visco-plastic nature which mitigates much of the uncertainty in its use. Expected losses in salt, however, may be relatively large. A number of oil and gas storage plants have been built in salt. The CAES-salt unit in West Germany has had no loss incidents related to the use of underground storage in its first year of operation.

Hard Rock. Considerable experience with the construction problem in hard rock has been accumulated from excavations and operations including hydroelectric schemes, mining, oil storage, defense structures, and transportation tunneling for water, rail, and highway uses. There is little to no experience with the effects of daily pressure, temperature, and humidity variations on hard rock structures.

Aquifers. The threat of loss of aquifer integrity is greatly reduced by the use of judicious standards for selection of aquifers for CAES use. Storage of energy in aquifers involves compression of air in the pores of the rock mass. Aquifers present the most familiar medium for storage, due to their extensive use for storage of natural gas at high pressures. Detailed hydrological and likely operating characteristics of a site remain largely unknown until the advanced stages of aquifer development.

o The risk exposure in operation of the underground component of CAES systems requires special consideration. These risks may be divided into three basic coverage concerns:

- Coverage for pressurized storage of gas.

- Coverage for cycling a stored product on daily or hourly schedules.

- Coverage for the physical integrity of an underground cavity over time.

Ultimate insurability of the underground component of CAES systems will depend on the willingness of underwriters to write policies that cover the perils from all three concerns. Insurance is currently written for one, or for the combination of any two of these three basic coverage concerns, most often for facilities used for storage of oil and natural gas (Chapter 6.0).

- o Four technologies were examined for comparative risk analysis. Each demonstrates at least one of the three coverage concerns which are assessed relative to CAES underground. These technologies include:

  - Pressurized storage of natural gas in geologic formations.
  - Conventional hydroelectric facilities.
  - Pumped hydro storage.
  - Coal mining and tunneling (Chapter 3.0).

- o The insurance loss rates calculated in Phase (3) are included in Tables Summary-2 through Summary-6 (Chapter 5.0).

- o Appropriate loss-preventive measures will increase the likelihood of insurability of a given CAES or UPH installation. These measures can be specified for each of the following five phases of system development:

  - Siting
  - Design and construction
  - Equipment specifications
  - Operational procedures
  - Monitoring and maintenance provisions (Chapter 5.0.)

- o A relatively uncommon type of coverage may be sought by utilities. Insurance written for the physical integrity of an underground cavity might be desirable for some electric utilities. This type of insurance is presently written for facilities storing other gas products, and is expected to be available in the case of stored air. This policy covers any loss due to a cavity's inability to perform the function for which it was designed, indemnifying for any cost of repair or

TABLE SUMMARY-2

Risk Assessment of Perils to Property--Hard Rock Cavities
(Dollars)

Perils	Yearly Loss Rate per $1,000 Value: Compressed Air, Earthquake*, Zone 1	Compressed Air, Earthquake*, Zone 4	Pumped Water, Earthquake*, Zone 1	Pumped Water, Earthquake*, Zone 4
1. Earthquake	.70	.20	-	-
2. Seismicity induced from operations				
a. No induced pressuer	-		.01	
b. Compressed air in dry cavity, or balanced by water column	.05		-	
c. Compressed air in closed cavity partly filled with liquid	.10		-	
3. Flooding				
a. Rising surface waters	10.00		10.00	
b. Leakage through floor, walls, or roof	1.00		1.00	
4. Loss of volume from wall or roof failure				
a. Roof collapse	.50		.40	
b. Pillar or wall collapse	.10		.20	
c. Gradual roof or wall subsidence	.10		.10	
d. Lateral shift or creep of parts	.05		.05	
5. Uncontrolled increase in volume				
a. Opening of pores or creation of other openings	.20		.10	
b. Changes in groundwater flow patterns	.10		.10	
6. Failure of pressure containers, joints, or seals				
a. Cavity blowout	.10		.01	
b. Leakage through existing openings	.20		.01	
c. Water blowout	.20		.01	
d. Joint failure	1.00		.50	
e. Seal failure	1.00		.50	
7. Mechanical failure of equipment				
a. Abrasion or breakage	Use Boiler Manual Rates		Use Boiler Manual Rates	
b. Chemical corrosion				
c. Breakdown				

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuinness Associates.

TABLE SUMMARY-3

Risk Assessment of Perils to Property--Salt Domes or Cavities
(Dollars)

Perils	Yearly Loss Rate per $1,000 value Compressed Air Earthquake* Zone 1	Zone 4
1. Earthquake		
a. No water or other liquid present	.70	.20
b. Partly filled with liquid	.80	.30
2. Seismicity induced from operations		
a. Compressed air in dry cavity	.01	
b. Compressed air in closed cavity partly filled with liquid	.10	

Perils	Natural Void	Dry Mined & Pillared	Solution Mined
3. Flooding			
a Rising surface waters	10.00	10.00	10.00
b. Leakage through floor, walls, or roof	2.00	3.00	6.00
4. Loss of volume from wall or roof failure			
a. Roof collapse	3.00	4.00	20.00
b. Wall or peripheral collapse or major rock fall	1.00	2.00	5.00
c. Gradual roof or wall subsidence	1.50	7.00	10.00
d. Lateral shift or creep of parts	1.00	2.00	5.00
5. Uncontrolled increase in volume			
a. Opening of pores or creation of other openings	2.00	4.00	10.00
b. Changes in groundwater flow patterns	1.00	1.00	2.00
6. Failure of pressure containers, joints, or seals			
a. Cavity blowout	.10	.10	.20
b. Leakage through existing openings	.20	.20	.50
c. Joint failure	1.00	1.00	1.00
d. Seal failure	1.00	1.00	1.00
7. Mechanical failure of equipment a. Abrasion or breakage b. Chemical corrosion c. Breakdown	Use Boiler Manual Rates	Use Boiler Manual Rates	Use Boiler Manual Rates

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuiness Associates

TABLE SUMMARY-4

Risk Assessment of Perils to Property--Aquifers
(Dollars)

Perils	Yearly Loss Rate per $1,000 Value Compressed Air Earthquake* Zone 1	Zone 4
1. Earthquake		
a. Porous rock	.70	.20
b. Porous sand or other small particles semi-suspendible in water, partly filled with liquid (resonance or plastic effect)	1.25	.40
2. Seismicity induced from operations		
a. Air pressure confined to porous rock or particulate material	.05	
b. Air pressure zone overlying materially fractured or faulted hard rock	.15	
3. Flooding (damage to surface installations)		
a. Rising surface waters	10.00	
b. Leakage into aquifer	-	
4. Loss of storage volume from wall, roof, or aquifer failure		
a. Roof caprock failure	.75	
b. Plugging of pores	2.00	
5. Uncontrolled increase in volume		
a. Opening of new pores or creation of other openings	5.00	
b. Changes in groundwater flow patterns	2.00	
6. Failure of pressure containers, joints, or seals		
a. Caprock blowout	1.50	
b. Lateral blowout (umbrella effect)	1.50	
c. Joint failure	1.00	
d. Seal failure	1.00	
7. Mechanical failure of equipment		
a. Abrasion or breakage	Use Boiler Manual Rates	
b. Chemical corrosion		
c. Breakdown		

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuinness Associates.

TABLE SUMMARY-5

LOSS RATE ADJUSTMENT FACTORS FOR INTERRUPTION OF OPERATIONS COVERAGE

	Percent of Physical Damage Rate*
Business Interruption, during the period required to restore the damaged installation to operating condition:	
Gross earnings:	
Including ordinary payroll	70
Excluding ordinary payroll	80
Extra Expense:	
Of securing power from alternate sources	200
Debris removal	200
Other	200
Outage or loss of use of specific items of equipment, for a specified number of days or weeks, at a specified rate per unit time	varies

* The assumed physical damage and machinery insurance rates are those which are based on an amount of insurance equal to at least 80 percent of the full value of the insured property.

Source: Adapted from data provided by John S. McGuinness Associates.

TABLE SUMMARY-6

Risk Assessment of Liability Hazards for Underground Energy Storage Installations
(Dollars)

	Type of System		OPERATIONS: Basic Rates				OPERATIONS: Surcharges: All Areas			PRODUCTS -OR- COMPLETED OPERATIONS		Basis of Premium[1]	
			Bodily Injury Liability		Property Damage Liability		x	c	u	Most States			
	Compressed Air	Pumped Water	Urban	Other	Urban	Other	Explosion	Collapse	Underground Damage	B.I.L.	P.D.L.	Operations	Products
Construction of Installation													
Excavation	x	x	2.40	1.60	.99	.94	2.25	incl.	.50	.39	.26	Payroll	Receipts
Mining, not surface	x	x	.16	.12	.10	.043	.05	-	-	-	-	Payroll	-
Liquid spoil (brine), sale or disposal	x		-	-	-	-	-	-	-	.07	.10	-	Mft[3]
Solid spoil, sale or disposal	x	x	-	-	-	-	-	-	-	.09	.05	-	Sales
Irrigation or Drainage System Construction	x		.81	.53	.45	.43	.55	-	.10	.15	.14	Payroll	Receipts
Tunneling	x	x	.81	.53	.45	.43	2.25	incl.	.50	.40	.28	Payroll	Receipts
Core Drilling	x	x	.87	.51	.63	.54	-	-	-	.09	.05	Payroll	Receipts
Drilling	x		.87	.51	.63	.54	-	-	-	.25	.11	Payroll	Receipts
Concrete Construction--including foundations, making, setting up, or taking down falsework, forms, scaffolds, or concrete distributing apparatus	x	x	1.70	1.10	.28	.28	-	-	-	.25	.10	Payroll	Receipts
Dam or Reservoir Construction		x	2.00	1.70	.80	.75	1.70	incl.	.25	.25	.10	Payroll	Receipts
Levee Construction	x	x	1.60	.66	.76	.73	-	-	-	.15	.14	Payroll	Receipts
Millwright Work--erection or repair of equipment or machinery	x	x	.96	.72	.35	.34	-	-	-	1.00	.27	Payroll	Receipts
Operation of Completed Installation													
Electric Light or Power Firms:													
Companies	x	x	2.10	1.90	.45	.27	.25	incl.	.25	-	-	Payroll	-
Rural Electrification Administration Cooperatives	x	x	4.80	3.70	.99	.72	.25	incl.	.25	-	-	Payroll	-
Blowout or cratering from pressure cavities	x		-	-	-	-	-	-	-	.05	.10	-	Mft[3]
Chemical, dust, or noxious gas pollution of air	x		-	-	-	-	-	-	-	.05	.03	-	Mft[3]
Chemical pollution of surface water		x	-	-	-	-	-	-	-	.02	.01	-	Mft[3]
Chemical pollution of underground water	x	x	-	-	-	-	-	-	-	.02	.01	-	Mft[3]
Collapse or subsidence of land surface on others' property:												-	Mft[3]
Salt dome: natural void	x		-	-	-	-	-	-	-	.07	.40		
dry mined & pillared	x		-	-	-	-	-	-	-	.06	.12		
solution mined	x		-	-	-	-	-	-	-	.20	2.00		
Other	x	x	-	-	-	-	-	-	-	.05	.10		
Operation and existence of reservoirs		x	-	-	-	-	-	-	-	incl.	incl.	-	Mft[3]

[1]Bases of premium are $1,000 of payroll, $1,000 of receipts and thousand cubic feet of volume or capacity

Source: Adapted from data provided by John S. McGuinness Associates.

replacement up to the original cavity investment cost. The size of the market for this coverage is undetermined at this point (Chapter 6.0).

- The insurance policies written may be expected to respond in direct proportion to the level of familiarity; construction of all components and operation of both UPH components and above-ground CAES components will be very similar to conventional coverages now written. Availability of conventional insurance for utility operations will be minimally affected by use of CAES or UPH systems. The risk exposure from CAES/UPH technology is such that utilities will find conventional terms of insurance can be written for these operations. The coverage that will be requested of insurers by electric utilities is a good gauge of the coverage that the insurance industry should be prepared to write. Such coverage may be expected to include "All Risks Builders Risk" and casualty policies (either in wrap-up form or as separate policies) for construction; Named Peril, Difference in Conditions, and Boiler and Machinery policies for property perils during plant operations, with Comprehensive General Liability and Workers' Compensation on the casualty side. Due to the flexibility of utility risk management programs, the insurance sought by utilities for CAES/UPH investments will in many cases not present unusual exposures to insurers. Flood and earthquake coverage for both above- and underground properties is available; judging from the calculated loss rates, these premiums will be relatively expensive (Chapter 6.0).

- Final determination of the risk levels of a CAES or UPH site will require analysis of the site-specific conditions. This study has assessed the question of inherent insurability of a CAES/UPH energy storage configuration, as currently proposed. Additional data needs are specified, which will refine the reliability of subsequent site-specific risk analyses. In addition to the details regarding geologic and design characteristics at an individual site, additional geologic research of a more general nature might result in findings that will be useful in actuarial processes:

- Quantitative data on the behavior of geologic structures when exposed to the stresses of pressure, temperature, and humidity cycling.

- Modeling of salt, hard rock, and porous media structures to quantitatively derive the primary and secondary consequences of various failure modes.

- Complete and in-depth profiles of loss histories for "similar technologies" (Chapters 4.0 and 6.0).

This baseline risk assessment is most valuable in defining the similarities of CAES and UPH systems to current insurable risks. Conclusions regarding insurability are considered to be relatively obvious. These findings should not be interpreted to imply greater specificity of application than is intended (see Section 1.1). It must be emphasized that the Failure Modes and Hazard Index analyses are of a generic nature. In terms of their reference to a specific CAES/UPH case, they should be considered as preliminary findings.

1.3 LIMITATIONS OF THE ANALYSIS

A major weakness in this risk insurance assessment is the nature and thoroughness of the input data. Each step of the analysis required utilization and reliance on the data available at that time; updating previous steps to include more recent research findings is not a viable approach in this type of analysis. In each input area of the assessment, more extensive data would lead to greater reliability in the numerical results of the actuarial analysis. Analysis of the risks and insurability of a CAES/UPH project must depend on the characteristics of individual prospective projects and sites. Such specificity is beyond the scope of this assessment.

2.0 INTRODUCTION

2.1 BACKGROUND

When oil prices rose sharply following the 1973-74 oil crisis and nation-wide energy conservation was urged, forms of energy storage designed to reduce oil consumption and the fuel costs of electricity production became more attractive than in previous years. Electric power generating utilities grapple with a problem of fuel supply that is compounded by the operating requirements of meeting demand schedules for electricity which fluctuate daily, weekly, and seasonally. To supply fluctuating demand loads, many large utilities currently use peaking plants powered by petroleum-fired turbines to meet short-term increases in demand with minimum plant investment. Peaking systems have an annual capacity factor of 5 to 15 percent. They are operated intermittently, as system requirements vary; sometimes they may operate as much as 8 to 12 hours per day, and as many as 5 days per week, while on other occasions they sit idle for a number of days.[1] Intermediate- and peak-period fuel costs are higher and plant efficiencies are lower in relation to base-load units.

Energy storage has the potential for contributing significantly toward both alleviating U.S. dependence on imported petroleum and in easing electric utility economics by mitigating a large portion of a utility's costs which are due to sharply varying system load factors. It is a mechanism by which more plentiful resources may be used in ways that can reduce the reliance on uncertain energy sources: much of the present premium fuel requirements of electrical production will be eliminated by storing energy generated during relatively low-cost periods in the utility production cycle. Moreover, the concept of storing energy may not only provide a means for utilities to expedite the cost-efficiencies of base-load power generation periods, but at the same time to also reduce the expense and technical hazards involved with sharp increases in utilities' generating capacities to supply the short-term periods

---

[1]To illustrate, an average use of 4 hours per day for 6 months represents 520 hours per year, or 6 percent capacity factor.

of high demand for electricity. Figure 2-1 illustrates a typical U.S. electric utility demand cycle.

Underground energy storage has been offered as a favorable option for use in production of intermediate and peak-period electrical power. This form of energy storage utilizes the potential energy obtained by recycling fluids such as air and water; compressing air into an underground cavity (Compressed Air Energy Storage - CAES) during off-peak hours of production and tapping the storage reserve during periods of high demand is one alternative. Another scheme is Underground Pumped Hydro storage, a version of conventional pumped hydro energy storage that utilizes lower fluid reservoirs underground.

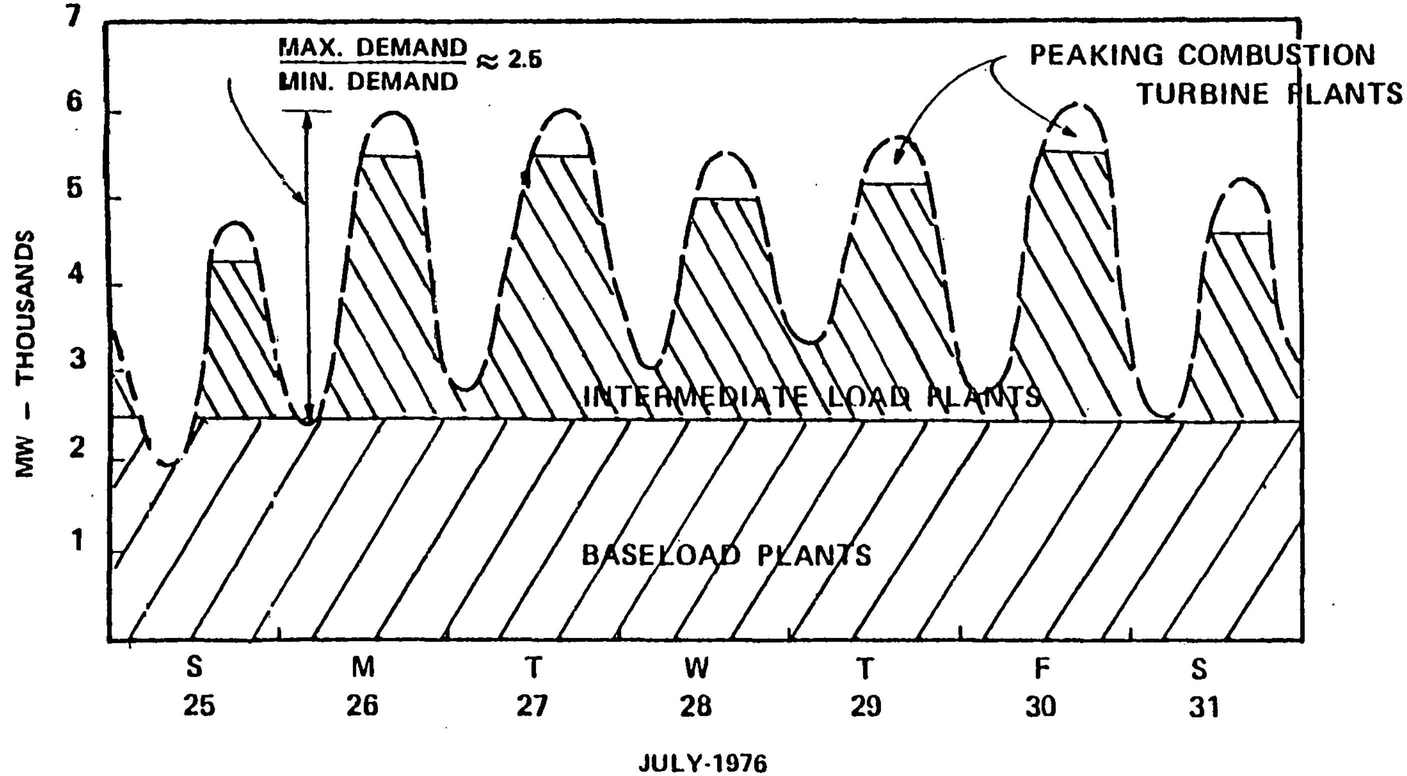
Approximately two-thirds of the power output of a combustion turbine is required to drive the compressor which provides cycle air for the turbine, leaving about one-third of the power available to drive an electrical generator. Energy storage using compressed air is expected to increase combustion turbine system efficiencies and reduce premium fuel requirements by eliminating the parasitic compressor load on turbines. An approximate comparison of costs of different forms of energy production can be made (Figure 2-2). CAES compares favorably with all other systems, and until the load requirements on the systems exceed some 3,000 hours per year, CAES utilization exhibits lower fixed and operating costs than all other systems. Pumped storage (including UPH) is also relatively economical, exceeded in the load range of 1,000 to 2,300 hours' annual use only by CAES.

The scale of implementation of energy storage projects will be related to growth rates in both the total electric power demand and in peak- and intermediate-period load factors. According to demand projections filed with the Federal Power Commission in 1976 by the Regional Reliability Councils, 90 million to 150 million kW of additional peak generating capacity will need to be installed during the 10-year period beginning in 1985. Of this, 36 million kW, or up to 40 percent of new peaking capacity, may be carried by CAES or UPH capacity by the year 1995. By the year 2005, 90 million kW of CAES or UPH

FIGURE 2-1

WEEKLY POWER DEMAND OSCILLATION

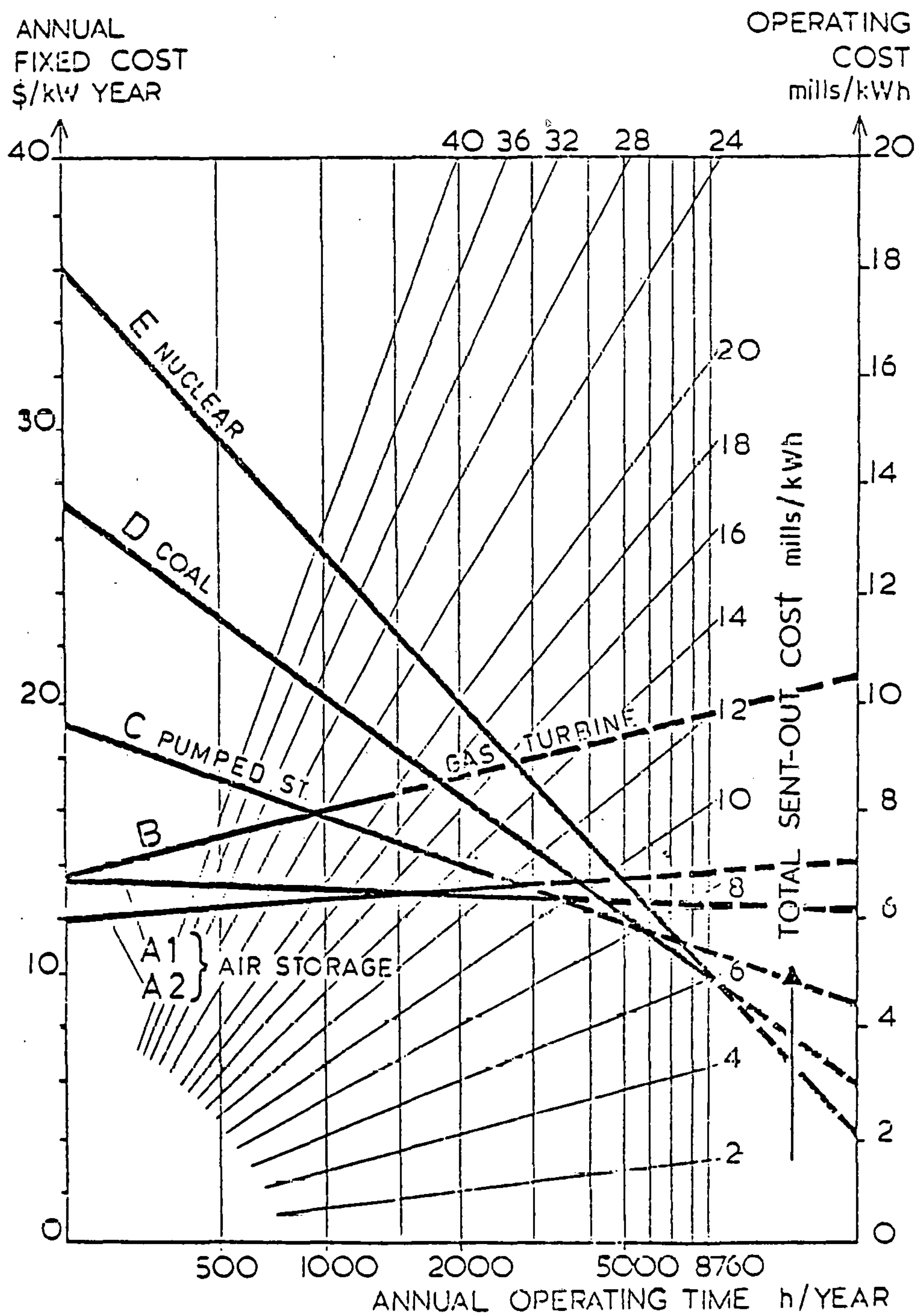
AND POSSIBLE PLANT LOAD DISTRIBUTION



Source: "Geologic Assessment of Compressed Air Storage Sites in Kansas." Prepared for Electric Power Research Institute by Black & Veatch, Kansas City. August 1978.

FIGURE 2-2

COMPARISON OF VARIOUS FORMS OF ENERGY PRODUCTION



Source: Adapted from material provided by Dames & Moore capacity is forecast, representing some 4.1 percent of total domestic generating capacity.[2] Recycled fluid energy storage systems provide opportunities for supplying intermediate load demand and for carrying part of peak load requirements, but will require capital commitments both for additional research and for deployment.

2.2 STUDY OBJECTIVES

The U.S. Department of Energy is conducting a comprehensive program of research and analysis of underground energy storage systems aimed at developing the information that will encourage the necessary capital expenditures by the private sector, and addressing any identified barriers to commercialization of energy storage techniques. One of the implementation barriers perceived by DOE involves the risks of utilization which may be apparent to utilities considering Compressed Air Energy Storage (CAES) and Underground Pumped Hydro (UPH) systems, along with the risk management problems that are posed. These are the issues which define the scope of this study. Five basic tasks are specified: (1) to determine the risks involved by designating the potential Failure Modes for both storage schemes in hard rock excavations, and for CAES risks involved in salt cavities and in aquifers; (2) to specify the insurance rates implied for each category of failure identified; (3) to determine the conditions for insurability that will be applied by prospective insurers of CAES and UPH systems; (4) to outline the components of possible insurance programs; and (5) to assess the needs for a more detailed risk assessment, including identifying necessary courses of action for obtaining insurance.

2.3 STUDY METHODOLOGY

The analysis performed proceeded through the following five steps:

1) Technical description and generation of Failure Modes and Scenarios for the feasible technology configurations;

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[2] "Underground Pumped Hydro Storage and Compressed Air Energy Storage," Harza Engineering, Chicago. March 1977.

2) Performance of risk analysis, describing loss preventive measures, risk reduction methods, and estimates of insurance rates;

3) Description of appropriate forms of coverage and policy terms;

4) Development of a Hazard Index as a means of applying general risk concerns to individual CAES and UPH facilities; and

5) Definition of the actions necessary for utilities pursuing commercial insurance for risk management of CAES and UPH systems.

A study of the risk potential of an untried technical process necessarily begins with an analysis of the failure modes that are pertinent to the new technology. Such an assessment for this study was based on the review by geotechnical engineering specialists of current data and research findings of the geologic configurations proposed for use with CAES and UPH schemes. Chapter 1.0 summarizes the study findings. Chapter 3.0 includes a description of the technology components.

A Hazard Index methodology and the Failure Modes Analysis of CAES and UPH configurations are described in Chapter 4.0. The Failure Modes Analysis, owing to the absence of extensive and site-specific data, is of a generic nature. Using the Hazard Index algorithm, the risk specifications of a chosen site may be combined to determine the aggregate hazard level for the site which can be used for insurance-related analysis or for relative ranking of alternative sites.

Chapter 5.0 outlines the concept and procedure used for conducting the Risk Assessment of CAES and UPH. The depth of the geologic findings outlined in Chapter 4.0 are reduced to a technical basis in terms that will be useful for actuarial analysis. The results of the Risk Assessment are tabulated as insurance loss rates that describe the risk exposure in terms of expected annual loss per $1,000 of utility investment. The result of a first-level assessment may suffice to reject a site. If it does not, a structural analysis and other analytic methods for reducing uncertainty about the risks are set forth in later sections of the chapter.

In Chapter 6.0, the conclusions drawn from discussions with executive and underwriting decision-makers of both domestic and London-based insurance brokerage, primary, and reinsurance organizations, as well as with risk management consultants and managers of an electric utility captive insurance underwriter, are presented. Table 2-1 lists the 27 members of the insurance industry that were contacted during the study.

Additional interviews were conducted with electric and gas utilities, whose experience might be drawn upon for useful commentary in different phases of the study. The exploration of claims histories and insurance experience of companies operating technologies similar to CAES led to conversations with many sources, including utilities using depleted wells and human-made geologic formations pressurized for storage of natural gas. Such companies were involved in some or all of the industry aspects of gas transmission, distribution, or retail sales. For the purpose of obtaining information on operations similar to UPH, contacts were established with engineers and insurance managers at companies owning or operating conventional hydroelectric and pumped storage facilities. These contacts are summarized in Table 2-2.

To determine the risks perceived by utilities -- which ultimately will define the types of insurance that are sought -- IR&T conducted interviews with several electric utilities in order to define insurance risks associated with CAES/UPH from a user perspective. These firms are either conducting research under the auspices of DOE, or have experience with CAES/UPH research of a technical or economic feasibility nature. Insurance presently in effect for the research utilities interviewed is summarized in Table 2-3. In this table, "All Risks Builders Risk" in the Construction Phase section refers to a property policy of the sort maintained by a general contractor, which covers against loss to buildings, machinery, and equipment in the course of construction and to materials incidental to construction. "Wrap-up," in the same section, is an umbrella liability policy for construction that combines

TABLE 2-1

INSURANCE INDUSTRY CONTACTS

Company	Primary Insurers	Reinsurers	Brokers	Captive Managers	Risk Management Consultants	Surety Bonding Companies
Aetna Life and Casualty Company	x					x
Alexander and Alexander, Inc.			x			
Allendale Mutual Insurance Company	x					
American Home Insurance Company	x					
American Reserve Insurance Brokers			x			
Arkwright-Boston Insurance Company	x					
Crump-Davis, Inc.			x			
Ebasco Risk Management, Inc.				x	x	
Factory Mutual Engineering and Research	x				x	
Fidelity and Deposit Company of Maryland						x
Hartford Insurance Company	x					
Hartford Steam Boiler	x					
Home Insurance Company	x					
Insurance Company of North America	x					
Johnson and Higgins			x			
Kemper Insurance Company	x					
Marsh and McLennan, Inc.			x			
Marine Office of America Corporation	x					
Munich-American Reinsurance Corporation		x				
Protection Mutual Insurance Company	x					
Ralph D. Hill Agency			x			
Shand, Morahan & Company, Inc.	x					
Starr Technical Risks, Inc.	x					
The Surety Association of America, Inc.						x
Travelers Insurance Company	x					x
U.S. Fidelity and Guaranty Company	x					x
Victor O. Shinnerer and Company	x					

TABLE 2-2

UTILITY INDUSTRY CONTACTS

Company	CAES/UPH Research Utilities	Gas Storage Utilities	Hydro-electric Facilities	Pumped Storage Facilities
American Electric Power	x		x	x
Central Illinois Light		x		
Cincinnati Gas and Electric		x		
Citizens Gas & Coke Utility		x		
Colorado Public Service		x		
Commonwealth Edison				x
Consolidated Gas Supply Corporation		x		
Consumers' Power			x	x
Detroit Edison				x
Electric Power Research Institute	x			
General Public Utilities	x		x	x
Green Mountain Power Company			x	
Illinois Power Company		x		
Kansas Power and Light Company	x			
Laclede Gas Company		x		
Los Angeles, Dept. of Water and Power			x	
Louisville Gas and Electric Company		x		
Michigan Consolidated Gas Co.		x		
Middle South Services	x			
Minnesota Gas Company		x		
Mississippi River Fuel Corporation		x		
Natural Gas Pipeline Company of America		x		
New England Power Company			x	x
Northeast Utilities Service Company			x	x
Northern Illinois Gas Company		x		
Northern Indiana Public Service Company		x		
Northern Natural Gas Company		x		
Ontario Hydro			x	x
Pacific Gas and Electric Company			x	

TABLE 2-2

UTILITY INDUSTRY CONTACTS
(Page 2 of 2)

Company	Research Utilities	Gas Storage Utilities	Hydro-electric Facilities	Pumped Storage Facilities
People's Gas Company		x		
Potomac Electric Power Company	x			
Power Authority of the State of New York			x	x
Public Service Company of Indiana	x			
Salt River Project			x	
Sacramento Municipal Utility District			x	x
Seattle, Dept. of Lighting			x	
Southern California Gas Company		x		
Southern Company Services			x	x
Tennessee Valley Authority	x		x	x
Union Electric Power Company			x	x
Vermont, Dept. of Water Resources			x	
Virginia Electric Power Company			x	x
Washington Water Power Company			x	

TABLE 2-3

CURRENT TERMS OF INSURANCE FOR
ELECTRIC UTILITIES SURVEYED

CONSTRUCTION PHASE 1/

	ALL-RISK, BUILDER'S RISK	WRAP-UP
LIMITS	$40-$300 MM, average at $100 MM	$500,000 - $1 MM
DEDUCTIBLES	NA	NA
PREMIUMS	Total premiums for All Risk Builders Risk, CGL and Workers' Compensation will range between 1-1/2 and 5 percent of construction costs. Twenty percent of premiums is for Builder's Risk, 20 percent for CGL, and 60 percent is for Workers' Compensation. 2/	

OPERATIONS PHASE

	NAMED PERIL	DIFFERENCE IN CONDITIONS	BOILER AND MACHINERY	CASUALTY 3/
LIMITS	Replacement value approximately $50 MM	Same as Named Peril	Vary by size and value of equipment	$50 MM
DEDUCTIBLES	$250,000-$500,000		"	Up to $1 MM 4/
PREMIUMS	.03-.25*	.02-.025* 5/	"	.10-.20*

NA = Not Available

*Per $100 insurable value

1/ Boiler and Machinery coverage during this phase is unnecessary if the manufacturer's warranty is in effect.

2/ Errors and Omissions in Design premiums range from 5-8 percent of the designer's fee.

3/ Includes CGL and Workers' Compensation.

4/ First dollar coverage is available.

5/ This rate includes coverage for flood and earthquake; without it the rate would decline to .01-.15.

Comprehensive General Liability (CGL) and Workers' Compensation or comprehensive personal liability insurance. For the Operations Phase, "Named Peril," as the title implies, is a policy which specifies the specific perils or hazards that are insured against. "Difference in Conditions" coverage may be found either as a rider to a current named perils policy or as a separate policy altogether. As a rider, D.I.C. expands insurance written whereby all risks subject to exclusion are incorporated into the coverage. In the latter case, a D.I.C. policy covers loss from all causes other than those specified in the policy. "Boiler and Machinery" coverage extends protection against stated damage to property and legal liability for damages caused by accident of boilers, pressure vessels, or related machinery. "Casualty" refers to liability insurance.

Representatives from firms engaged in underground design, construction, and mining operations were also consulted. The firms contacted are listed in Table 2-4. Courses of action that will lead to appropriate insurance programs for utilities planning to utilize geologic cavities for energy storage are found in Chapter 7.0.

In the course of actual underwriting analyses, certain technical and engineering factors will be deferred to specialists in the geotechnical and mechanical fields. Chapters 3.0 and 4.0 will be of primary use to these individuals, although the first few sections of Chapter 3.0 will be of general interest. Chapters 5.0 and 6.0 will be of relative use for actuarial and underwriting analyses, respectively.

3.0 TECHNICAL BACKGROUND

3.1 DESCRIPTION OF CAES AND UPH SCHEMES

This section of the technical overview entails a structural description of the proposed Underground Pumped Hydro (UPH) in hard rock cavities, and Compressed Air Energy Storage (CAES) in salt, porous media (aquifers), or hard rock geologic structures.

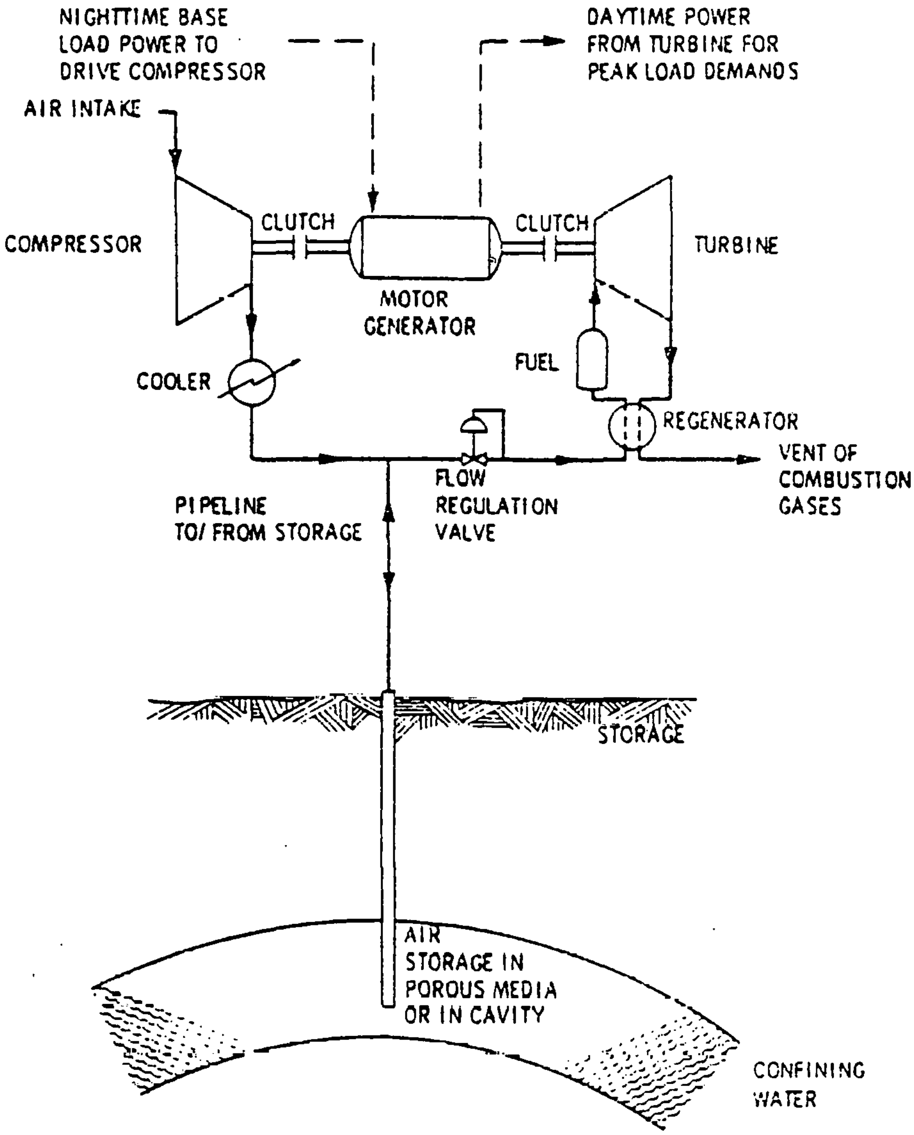
3.1.1 Compressed Air Energy Storage

The term Compressed Air Energy Storage refers to a process of storing base-load capacity energy by compressing air in underground cavities. Caverns in salt, hard rock, and in aquifers presently appear most favorable. The schematic flow sheet in Figure 3-1 shows the components of an undergound storage system serving an electric utility plant, and Figures 3-2 and 3-3, the equipment detail for the generating station. Off-peak electricity is used to drive compressors in the storing mode and the compressed air is delivered to store caverns after being cooled to near-geothermal temperatures to minimize both cavern volume and the risk of thermal damage to cavern walls. In the generating mode, the compressed air is drawn from the store, raised in temperature by the combustion of a high-grade fuel and expanded through the power turbines to supply intermediate and peak electricity. In the CAES mode, the output rating of the turbo-machinery is increased by gas turbine peak electricity systems.

The two present concepts of underground CAES in hard rock formations are the balanced and unbalanced systems, illustrated in Figure 3-4a and 4b respectively. The balanced system consists of a small upper reservoir on the surface, connected to underground chambers by a shaft with separate air lines to each chamber. The chambers are filled with partially compressed air at constant pressure. Cyclic movement of the air/water interface occurs, due to the volume of air pumped into and withdrawn from the chambers on a daily basis. The unbalanced system is comprised of underground chambers which are connected to the surface via an air line. Since the volume of air in the chambers is consistent, the pressure of the air varies with the daily cycle. Both of these modes of operation may be considered for use with excavated hard

FIGURE 3-1

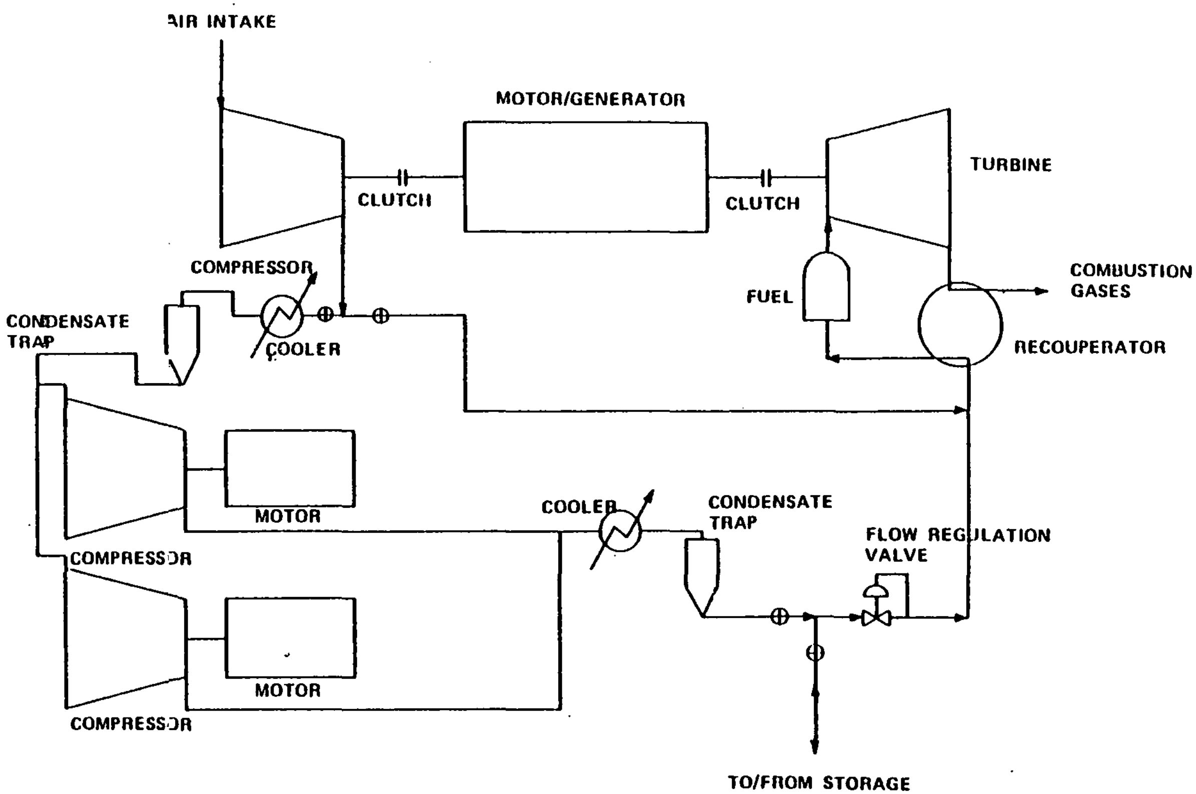
IDEALIZED COMPRESSED AIR ENERGY STORAGE SCHEMES



Source: Dames & Moore

FIGURE 3-2

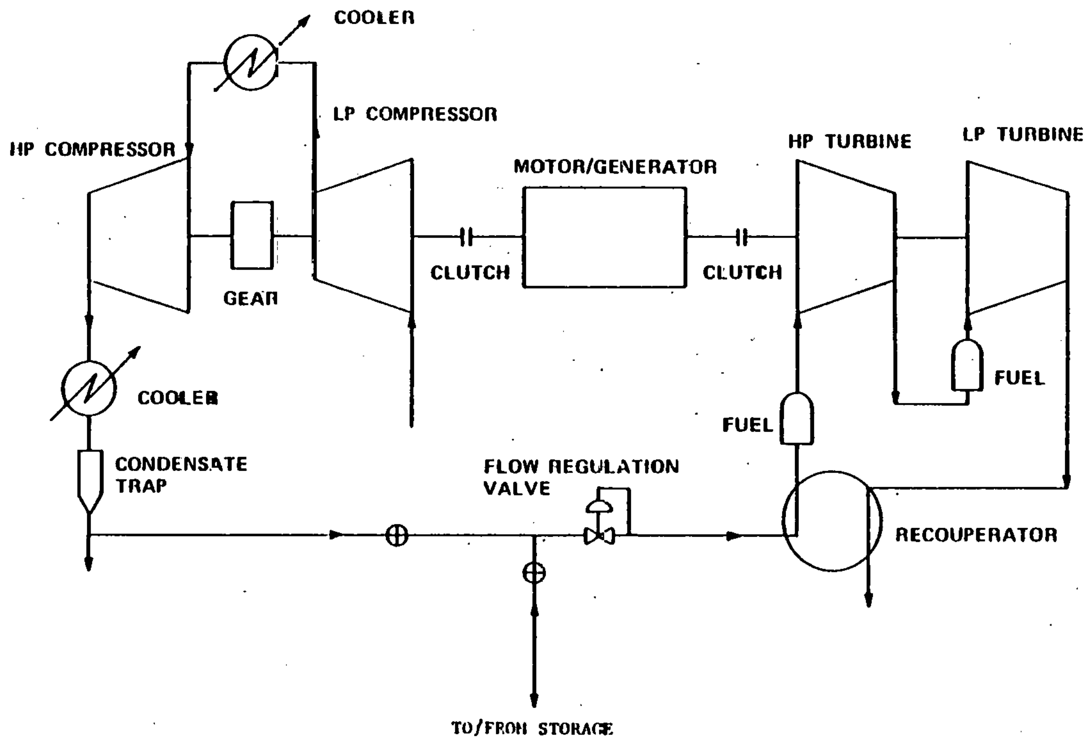
LOW PRESSURE CAES PLANT ARRANGEMENT



Source: "Geologic Assessment of Compressed Air Storage Sites in Kansas." Prepared for Electric Power Research Institute by Black & Veatch, Kansas City. August 1978.

FIGURE 3-3

HIGH PRESSURE CAES PLANT ARRANGEMENT



Source: "Geologic Assessment of Compressed Air Storage Sites in Kansas." Prepared for Electric Power Research Institute by Black & Veatch, Kansas City. August 1978.

FIGURE 3-4a

THE BALANCED SYSTEM OF CAES

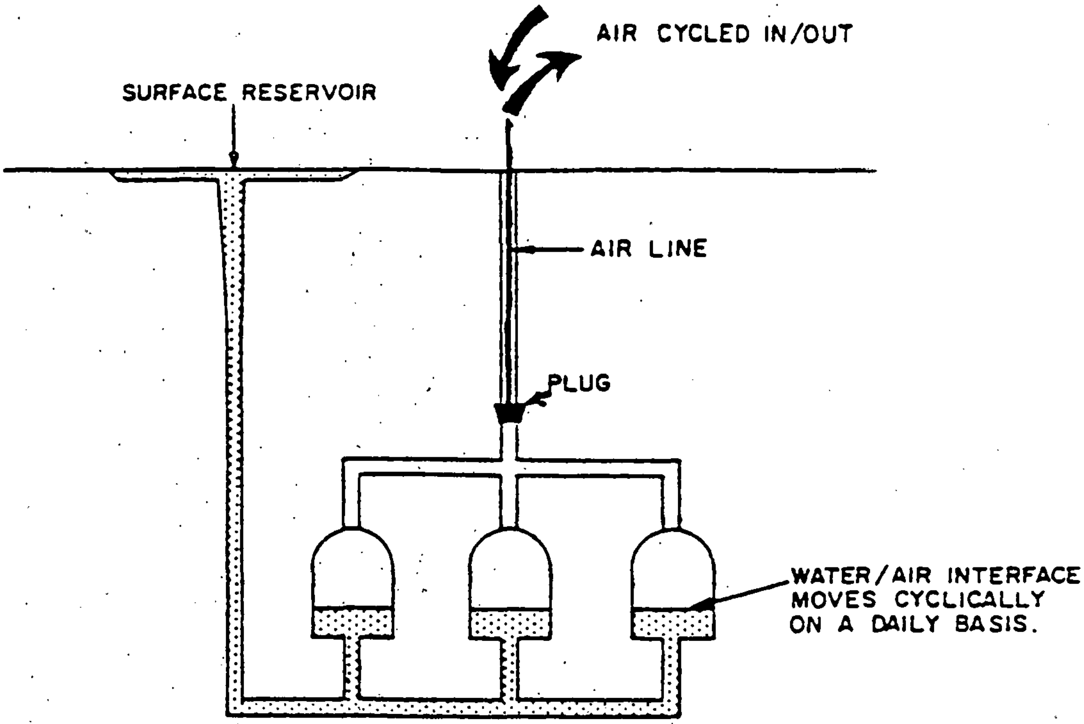
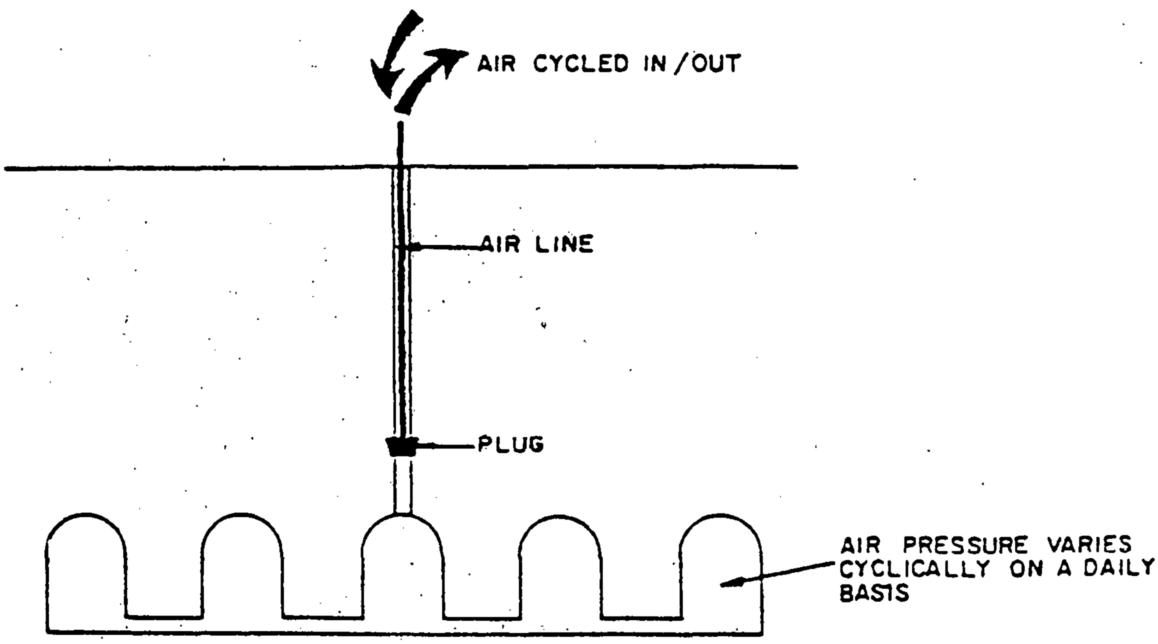


FIGURE 3-4b

THE UNBALANCED SYSTEM OF CAES



Source: Dames & Moore

rock caverns. The projected cost of constructing unbalanced systems gives this configuration a significant advantage over the balanced version, with the predictable results in terms of probable relative scales of implementation. Inasmuch as both systems are technically feasible, this and subsequent discussion entails both in the interests of completeness.

A possible weekly schedule of air storage and withdrawal is shown in Figure 3-5. For porous media reservoirs or caverns without water displacement, sufficient base pressure remains to serve the combustion turbine by free flow at the end of the weekly withdrawal period. Some advantage will be taken of the low system demand over weekends so that the compression rate during the four week nights, Monday through Thursday, can be only 70 percent of the withdrawal rate on those days. Such a schedule requires a maximum storage capacity in a cavern of 220 percent of that which would be necessary if the system used equal daily storage and withdrawal volumes. The size of a storage reservior sets the pressure swing during the week under these operating conditions. Figure 3-5 also shows the fractional hourly change in pressure, as related to the range above the base pressure necessary to accommodate the 220 percent of the daily withdrawal quantity.

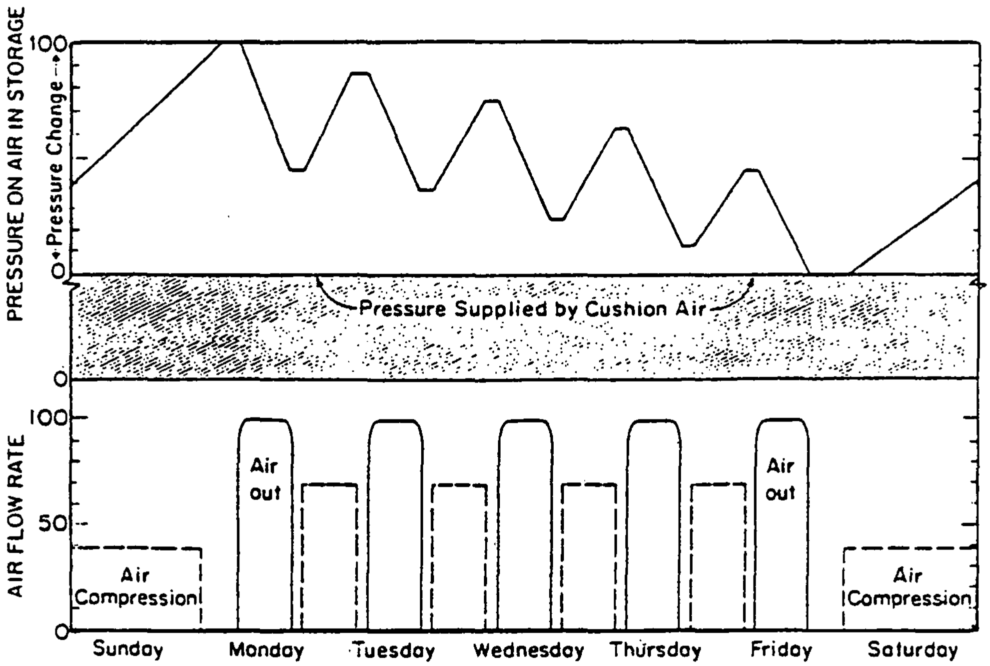
3.1.2 Underground Pumped Hydro

A form of energy storage which is employed at present is the system conventionally described as pumped hydro storage, in which base-load energy is used at night to pump water to a higher elevation; during peak electrical loads the water is allowed to flow through power turbines to return the potential energy stored by the elevated water. About 70 percent of the base-load energy is thus returned in the form of peaking energy. Few suitable sites exist where two surface reservoirs may be constructed with adequate head between them for a conventional pumped hydro scheme. In many regions of the world the prime sites have already been exploited.

Underground Pumped Hydro (UPH) refers to a system similar to the conventional pumped hydro scheme, except for the location of the lower reservoir in excavated rock mass underground. The possibility of constructing the lower reservoir below ground level augments the range of suitable geographic

FIGURE 3-5

WEEKLY SCHEDULE OF AIR STORAGE AND WITHDRAWAL



Source: Dames & Moore

locales. The added cost of cavern excavation is offset in large measure by the added flexibility for plant design, e.g., specification of the drop between the upper and lower reservoirs which can be made in accordance with utility operating requirements, cost factors, etc. Another advantage of underground siting of a generating facility and reservoir is the possible lesser environmental impact caused by that reservoir.

These systems are illustrated in Figures 3-6 and 3-7, in which the design similarities between them are apparent. The difference in head between the upper and lower reservoirs varies from 500 meters to approximately 1000 meters for proposed UPH schemes. The essence of both versions of pumped by hydro storage is that off-peak energy is stored by pumping water from the lower reservoir to the upper one so that during peak electricity demand periods, the potential energy stored in the water is released and converted into electricity by returning the water to the lower reservoir through turbines.

3.2 GEOLOGIC CONFIGURATIONS

Three types of geologic structures are most promising for commercialization of CAES or UPH energy storage schemes:

1) Cavities in salt domes. Salt is a very promising medium for CAES; salt cavities are used presently to store pressurized natural gas, and can be mined by dissolution techniques.

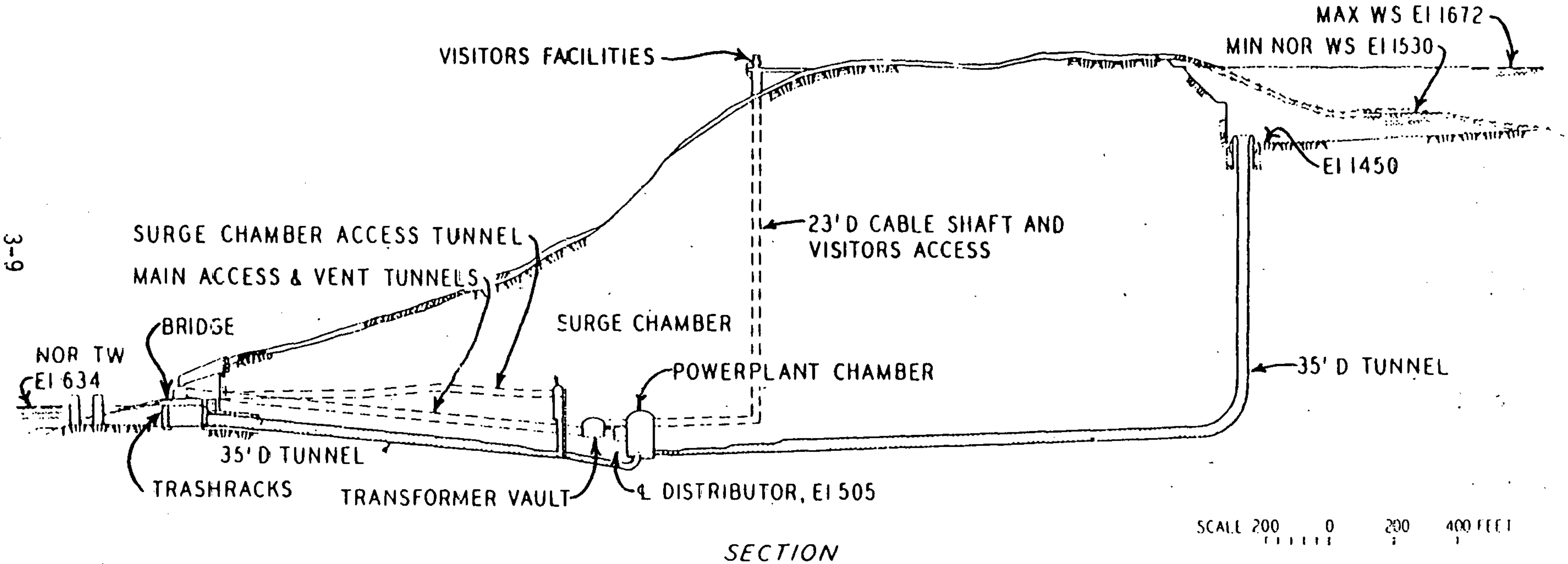
2) Aquifers in sand, gravel, or porous rock are being considered for CAES use. Aquifers covered by impermeable soil strata are in current use for storage of methane.

3) Hard rock formation. Excavations within or overlain by tight strata also promise suitable conditions for both CAES and UPH schemes.

Technical backgrounds on these geologic structures, the appropriate mining techniques, and hazard areas involved with using each are described in this section.

FIGURE 3-6

SECTION: RACCOON MOUNTAIN PLANT

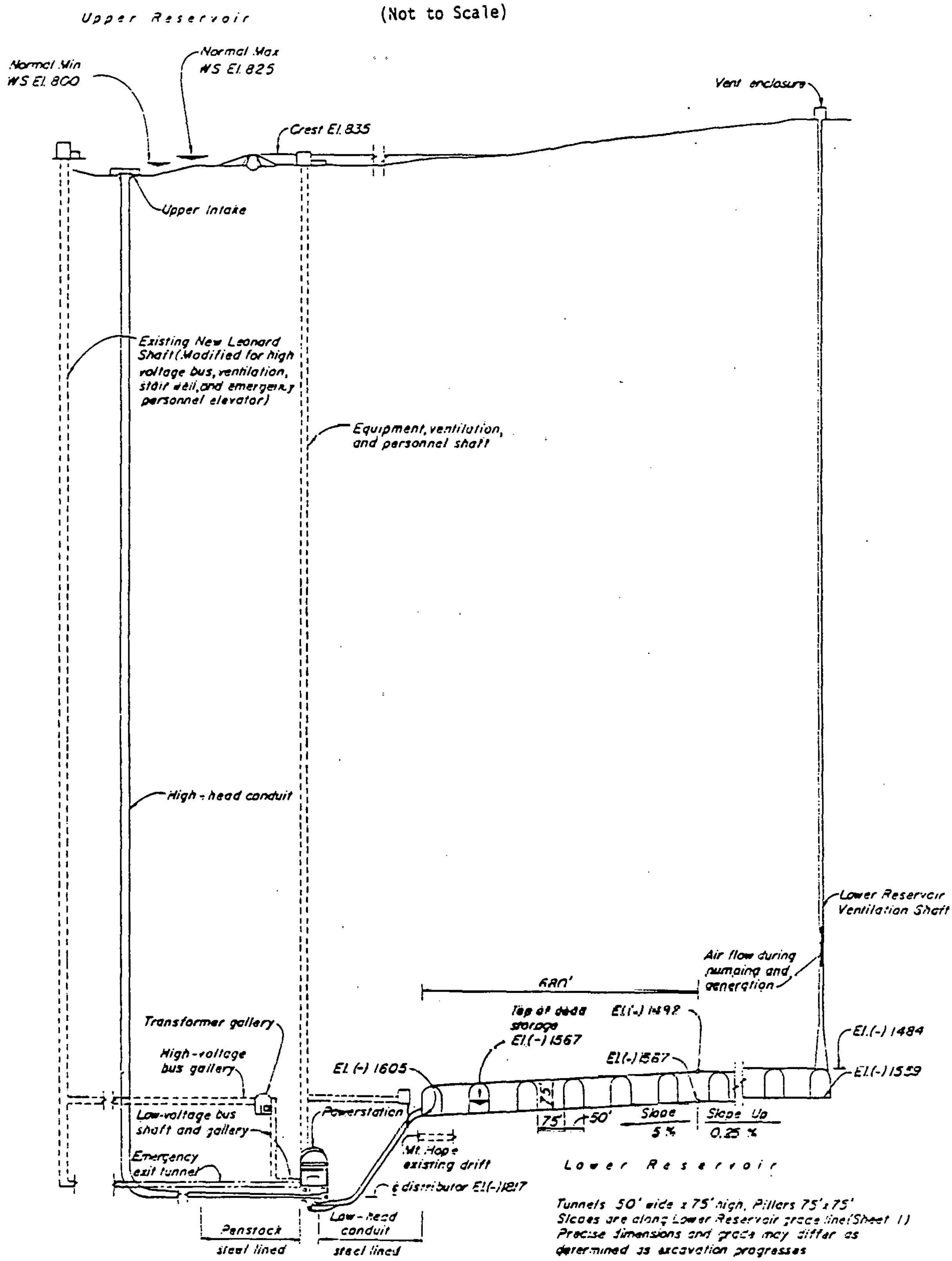


Source: "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities." Prepared for Electric Power Research Institute by Public Service Electric and Gas Company, Palo Alto. July 1976.

FIGURE 3-7

SECTION: UNDERGROUND POWER PLANT

(Not to Scale)



Source: "An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities." Prepared for Electric Power Research Institute by Public Service Electric and Gas Company, Palo Alto. July 1976.

3.2.1 Salt

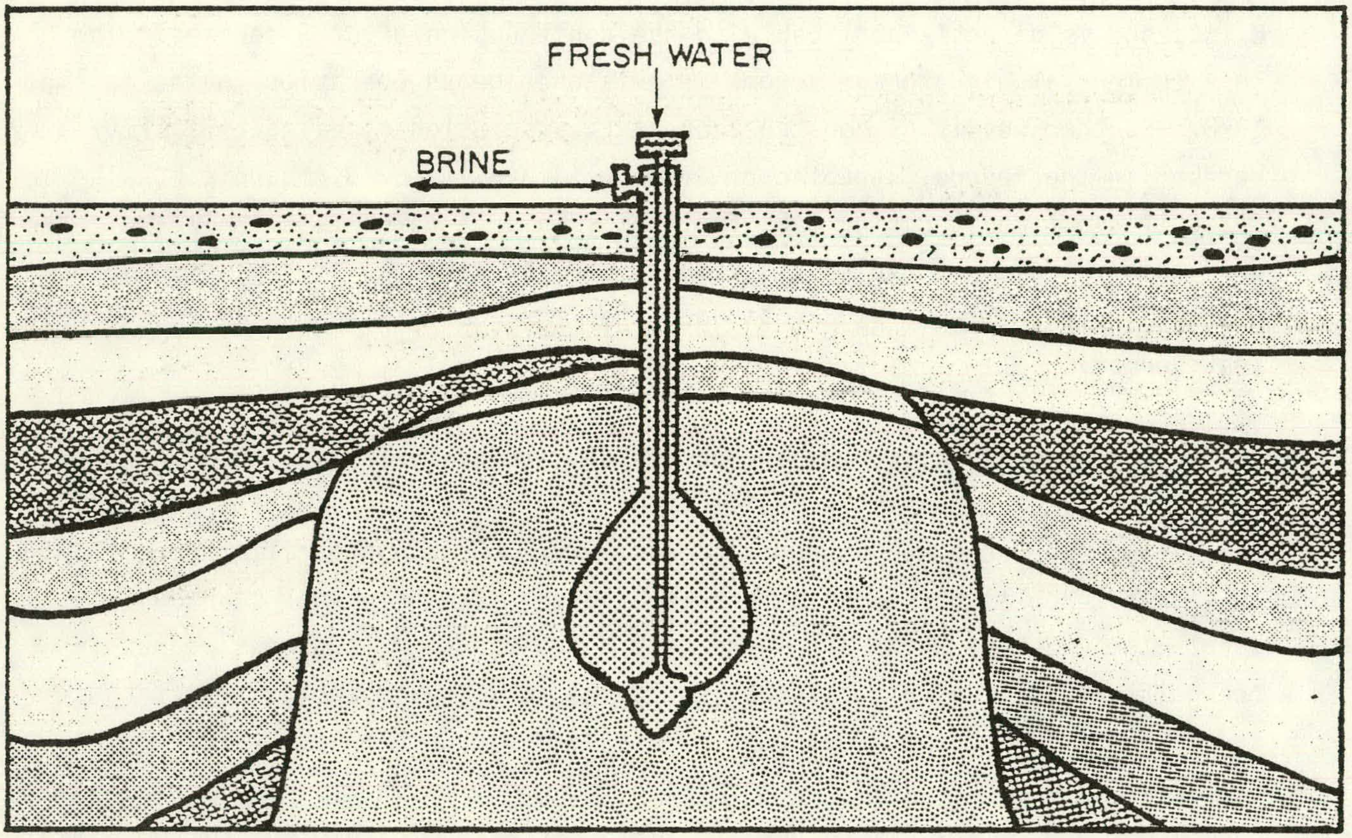
Salt deposits may be made economically viable for use in CAES systems by solution-mining them to create large, stable salt caverns. Appendix D describes in detail the characteristics for selection and solution-mining of salt domes. A complete history of salt dome storage is found in Appendix E. A wealth of experience in storing oil and gas in solution-mined salt cavities exists and is directly applicable to the construction of CAES schemes. The only commercial air storage scheme in existence began operation in the fall of 1978. Further detail of construction of this solution-mined salt facility at Huntorf in the Federal Republic of Germany is available in Appendix F. The feasibility of constructing CAES facilities in salt domes is clearly indicated from this example. A typical salt dome, showing attitude of a mined cavern, appears in Figure 3-8. Figure 3-9 outlines the geologic formation at Huntorf, West Germany.

Background in Salt. Large deposits of salt exist in many areas of the world. Salt is an evaporite sediment, an accumulation of crystals precipitated from impounded sea water in an arid environment. A familiar example of this phenomenon is the Great Salt Lake of Utah. The principal salt deposits within the U.S. are shown in Figure 3-10. The Louann Salt, shown bedded in the gulf coastal regions of Texas, Louisiana, and Mississippi, is very thick and is about 30 thousand feet deep. This is the bed that spawns salt domes.

Domes are relatively narrow stems of salt extending upward and sometimes rising to the surface. The number of domes in existence is not known, for undoubtedly many terminate at such great depth that their presence is undetectable. However, over 520 have been discovered, and many are shallow enough to have commercial significance. Each salt dome has its own unique size, shape, and characteristics, but a typical dome might be described as being reasonably cylindrical and symmetrical about a mile in diameter, and as terminating about 1,500 feet below the surface. It might be overlain by a 500 foot thick caprock. Small pockets of gas might be entrapped within the salt, but these have no commercial significance and would be judged a nuisance to drilling and leaching if encountered.

FIGURE 3-8

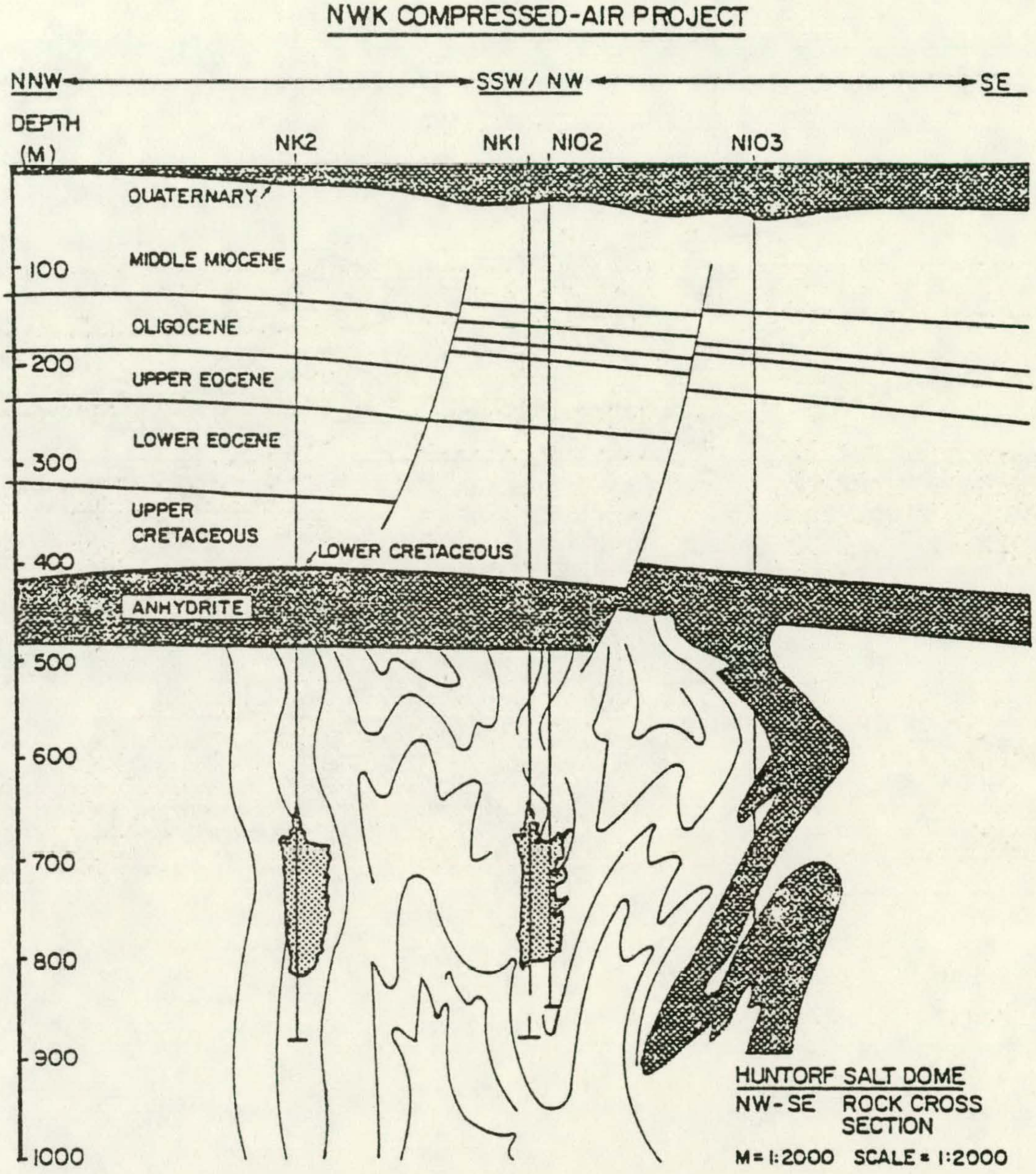
TYPICAL SALT DOME CAVERN



Source: Dames & Moore

FIGURE 3-9

CAVERN SECTIONS AT HUNTORF



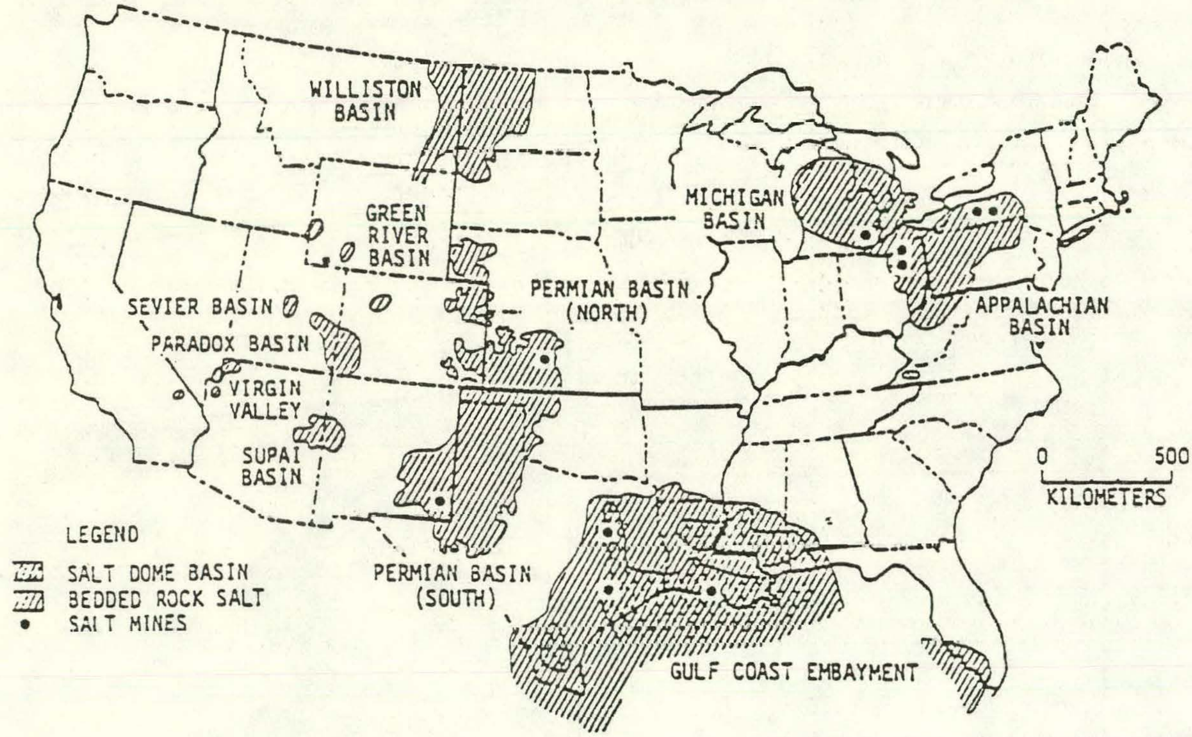
HUNTORF SALT DOME WITH AIR STORAGE CAVERNS

Source: Dames & Moore

FIGURE 3-10

DISTRIBUTION OF PRINCIPAL SALT DEPOSITS

IN NORTH AMERICA



Source: Dames & Moore

Several geologic theories on the origin of salt domes exist. There is general agreement, however, that the stems of most domes extend downward to the Louann Salt. Subjected to high temperature and tremendous pressure, the deep salt flows like a soft plastic. At shallower depths where the pressure, and temperature are lower, it displays more of the characteristics of a hard plastic. When relieved of restraining pressure, as when a core is brought to surface, it becomes brittle and often shows a coarse crystalline structure.

It is the hard plastic characteristic of salt that enables it to become an excellent storage medium when it is made parent to a cavern at the proper depth. Its ability to yield and divert stress from the cavern wall nullifies the stress concentrations that cause other parent rocks to spall or collapse. Salt's plasticity allows it to close and seal fractures.

A great deal of geologic effort, time, and money have been expended in the search for salt domes. The earliest efforts were directed toward locating domes that nearly reached surface levels, permitting the removal of the salt as a commodity. In later years, salt has been recovered from deeper domes by solution mining, primarily to provide saturated brine as feedstock to the chemical industry. The petroleum industry has conducted the most extensive salt dome exploration effort. The object has been the location of distortions in sedimentary rock that could serve as entrapment zones for oil and/or gas. It soon learned that oil traps might exist above the cap-rock, in the cap-rock, or along the flanks of a dome.

Salt dome cap-rocks also have been the object of considerable commercial interest. In fact, much of the drilling performed over domes has been conducted to evaluate possibilities for sulfur recovery from the cap-rock using the Frasch solution-mining process.

Most geologic investigators now agree that cap-rocks represent accumulations of insoluble material, originally transported within the salt. Presumably, as the salt moved upward relative to the surface of the earth, its upper face was continually leached by unsaturated brines lying above. As the salt dissolved, gypsum, sulfur, and other minerals may have evolved as the products of altered anhydrite. As the cap-rock gained in thickness and maturity, it, too, suffered from the leaching action of shallow, saline waters. Abundant vugs often are found joined to form extensive labyrinths. Perhaps as a result of weaknesses caused by natural leaching, most cap-rocks are highly fractured.

As the result of the search for oil, holes have been drilled around the flanks of many domes and a generous amount of information is available on the surrounding geology. Far less is known about the salt. The explorers for oil, gas, and sulfur were not interested in salt and usually abandoned their holes when it was encountered. Significant quantities of salt have been extracted from only 41 domes; from a statistical standpoint, only eight percent of the over 520 known domes have been adequately sampled.

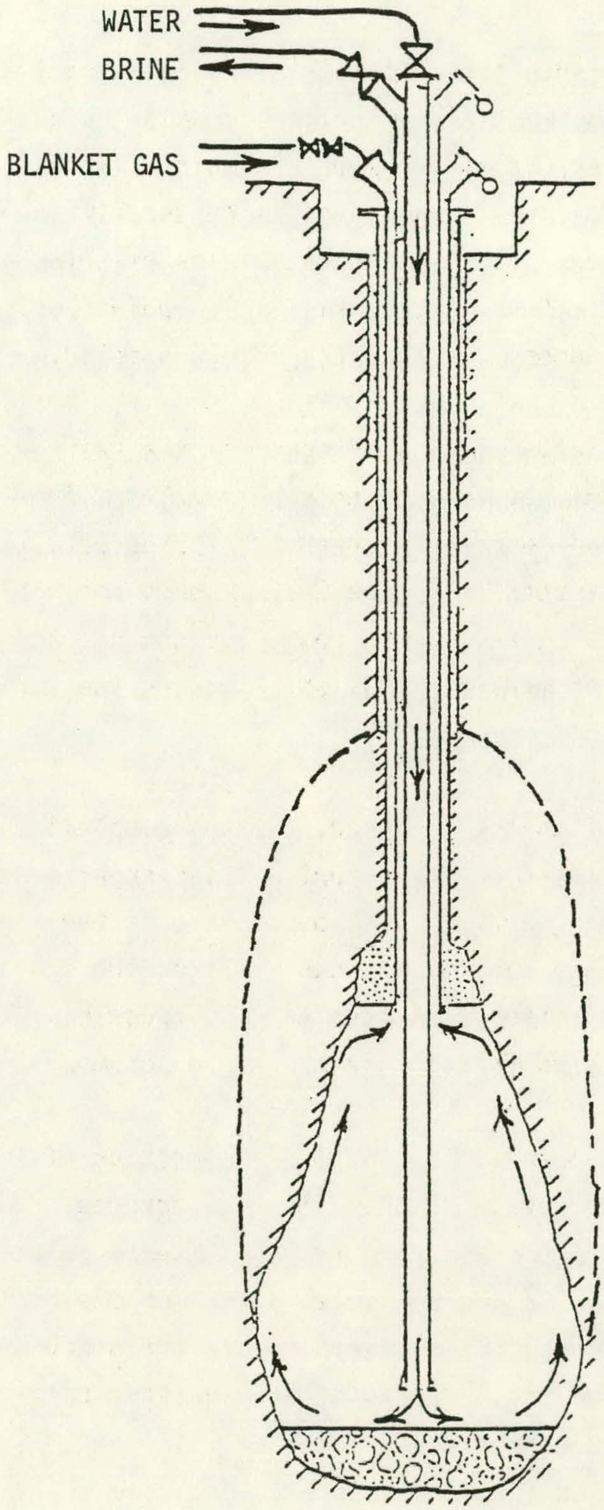
Solution-Mining. The basic process of developing a salt dome cavern is straightforward. A single oil field-type hole is completed into a salt dome, and fresh water is pumped in, forcing the resultant brine out. This process of solution-mining is illustrated in Figure 3-11. While the wells are generally shallow affairs using technology common to the oil fields for the past 30 years, many design options are available, making the work somewhat specialized.

Large diameter wells often are required, and the complexity of completing high quality wells through cap-rock has surprised many experienced oil field drillers. The proper leaching options must be chosen, as the relative elevations of water entry and brine departure greatly affect the shape of the developing cavern and the efficiency of the leaching process. In addition, the insoluble material released from the salt must be accommodated.

The support facilities are also critical: acquisition of leaching water and/or the disposal of brine may be the key items of expense. Many areas underlain by high quality bedded salt, having good water supplies and excellent development potential, have been rejected solely on the basis of the high cost of brine disposal. The Gulf Coastal salt domes are surrounded by superb saline aquifers, the sands of which can absorb large amounts of brine without significant effect.

FIGURE 3-11

SOLUTION MINING



Source: Nordwestdeutsche Kraftwerke, AG

The key to low-cost brine disposal is proper completion of injection wells. Each dome is unique, but almost all have adequate sands for the completion of 1,000 gpm injection wells. When the best technology is not applied, wells may only be capable of a few hundred gpm.

Hazards from Gas Storage in Salt. A list of the problem areas of oil and gas storage in salt describes the hazards of CAES usage. While experience in salt use is considerable, and the major problem areas are of smaller numbers than for hard rock or aquifers, the hazards of faulty design or construction technique are at least as great. Relatively high potential losses, compared to hard rock and aquifer storage media, is indicated by analysis of the construction design for salt air storage cavities. This is due in part to the visco-plastic nature of the material which, though offering advantages to the actual construction process over the aquifer and hard rock alternatives, introduces a geophysical phenomenon known as salt creep; the unknowns associated with the unpredictability and the possible effects of salt creep are discussed further in Section 4.5. The potential problem areas include:

- volume reduction of the cavity due to creep;
- corrosion of turbo-machinery;
- failure of well casing;
- progessive collapse of roof;
- accelerated creep and possible cavity collapse due to poor mining design.

No geology-related problems have developed from the use of the mined salt cavern in Huntorf (see Appendix G).

3.2.2 Aquifers

The proposed method of using aquifers for air storage begins with drilling wells through the solid overburden into the porous bed. When air at some pressure above the hydrostatic aquifer pressure is injected into the wells, it displaces the water in the pores of the aquifer, forming a stable bubble. The displaced water either moves internally, itself displacing peripheral water, or is compressed into previously voided spaces. When air is removed from storage, the displaced water tends to move slightly backward towards the well bore. A schematic cross-section of a hypothetical CAES project using aquifer storage is illustrated in Figure 3-12. Notes on the desirable characteristics of a storage aquifer are found in Appendix H, with a description of the history of aquifer use in Appendix I.

Low-temperature storage. Current designs are based on low-temperature (200°F/93°C) air injection. One of the primary conclusions of a preliminary DOE study is that the technology now exists to handle the pertinent engineering and/or operational impediments so that a full-scale demonstration plant may be designed and constructed in the near future. Few significant technical questions remain concerning aquifer storage at low temperatures.

High-temperature storage. Storage of the thermal energy of compression by injecting the air into the storage horizon at elevated temperatures (200 to 650°F/93 to 343°C) is also being investigated. Some additional uncertainty resides with the high-temperature concept, specifically in the areas of:

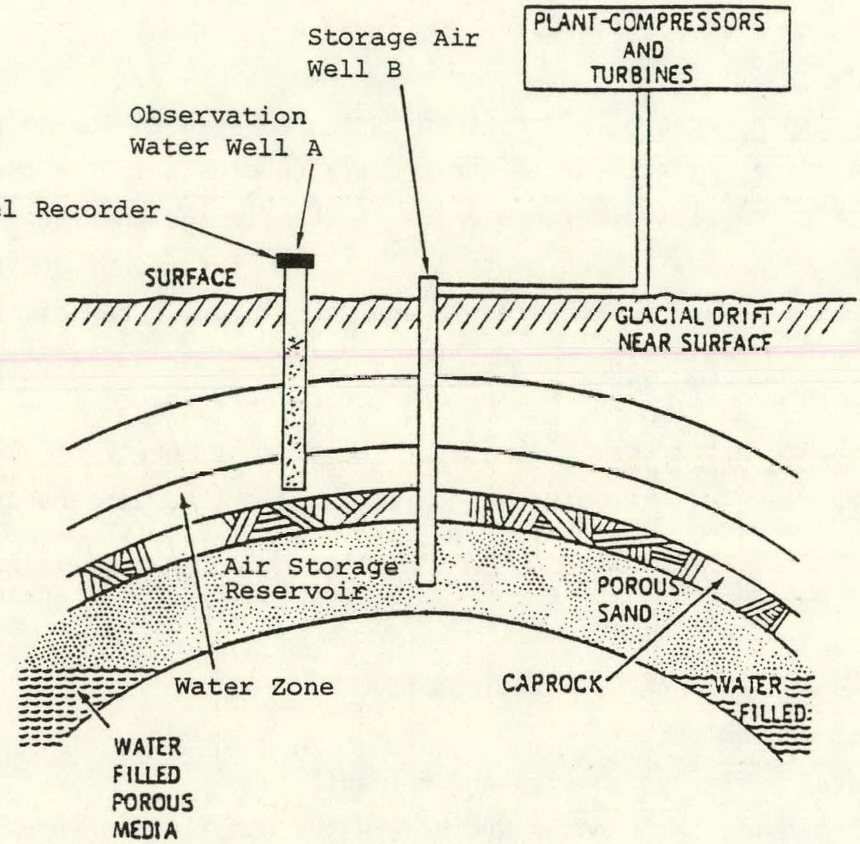
- well-bore and reservoir engineering;
- system economics;
- surface facilities' design and reliability;
- thermodynamic cycle efficiencies and the usability of low-quality energy.

To develop an air storage bubble within an aquifer, air is injected at pressures exceeding local hydrostatic pore pressure (0.43 to 0.52 psi/ft). Development of this cushion or base air bubble will typically require a period of 2 months to more than 4 years. Further enlargements may be accomplished over the first 10 years of operation. In general, the total quantity of cushion air required to support a 600 MW facility will be on the order of 1.5 X 10^9 lb_m. After the cushion air bubble is of sufficient size to support weekly plant operation, the working air mass will be injected and withdrawn in the cyclical nature depicted in Figure 3-13.

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

FIGURE 3-12

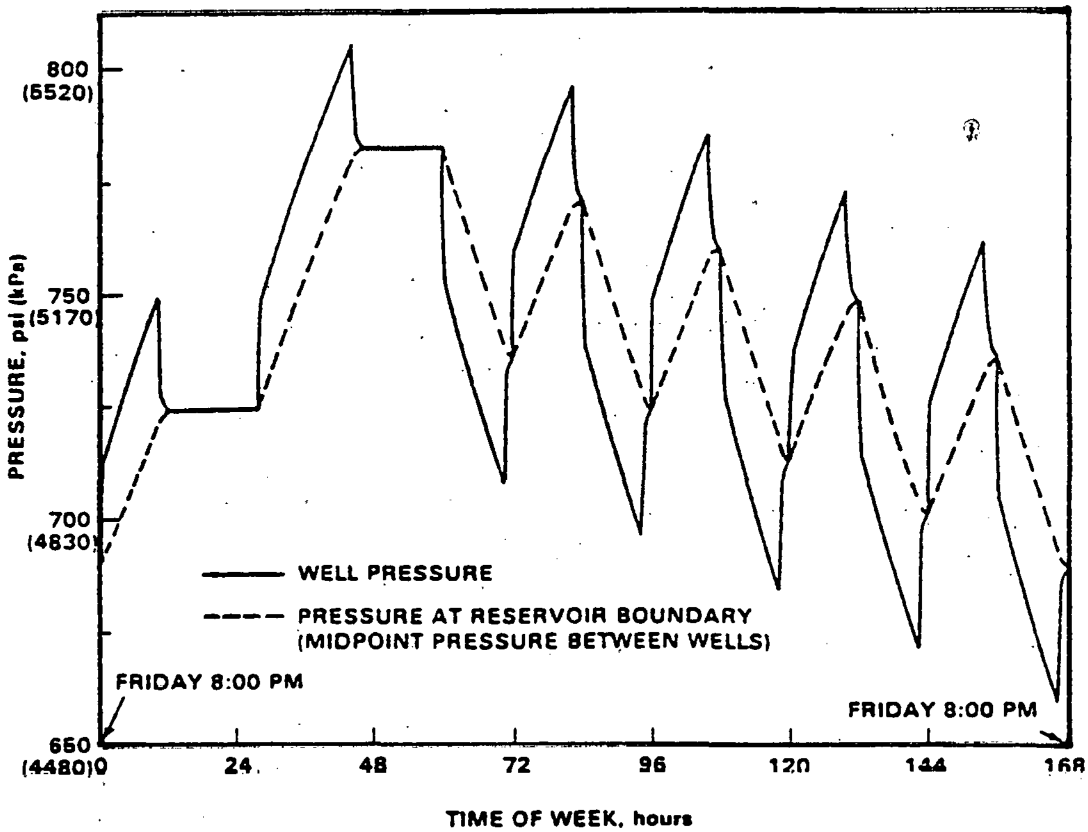
SCHEMATIC VIEW OF C.A.E.S. IN AN AQUIFER



Source: Dames & Moore

FIGURE 3-13

AIR INJECTION CYCLE IN AQUIFER STORAGE



Source: Dames & Moore

1) integrity of well casing and completion cement
2) liquid and vapor phase water
3) cap-rock integrity
4) geochemical reactions
5) physical response of the storage matrix

1. Well Casing and Completion Integrity

One of the most important problems to be addressed is the thermo-mechanical response of the metal well casing and the cement grouting sheath when exposed to elevated temperatures and thermal cycling. Casing failures in the steam-drive oil recovery industry are extensively documented. Thirty such failures have been verified in California alone.

2. Humidity and Fluids

The humidity within the storage zone has been previously identified as an important parameter for both low- and high-temperature injection. The presence of interstitial liquids, especially near the well-bore, can result in a reduction of air deliverability at certain use pressures. For example, water saturations of 50 percent can reduce the specific permeability of gas by some 30 percent of the dry value.

3. Cap-Rock Integrity

Two different mechanisms may be used for exposing a shale cap-rock to elevated temperatures. First, there can be thermal losses as the high-temperature air flows downwards. Conduction of this thermal energy will result in elevated temperatures of the cement sheath and part of the shale cap-rock. Evaluation of temperatures so attained will permit assessments of impending physical and chemical degradation, leading to loss of containment capacity.

The second mechanism for assessing potential cap-rock degradation involves considering vertical heat losses from the storage zone into the overlying cap-rock. Elevated temperatures, liquid phase water and free oxygen and carbon dioxide may all be present to some degree at this interface, indicating a potential for migration of the water/air interface zone, adverse chemical reactions, and some physical degradation.

4. Geochemical reactions

The possible interactions of elevated temperatures, oxygen, and carbon dioxide with liquid phase water and sandstone or shale deem it necessary to address geochemical reactions and potential consequences for a CAES facility. This is an ideal environment for classical chemical-weathering reactions. Elimination of the liquid phase water and/or reduction of the temperature to a level below 70 to 90° C would result in a stable, non-reacting system. In other words, the temperature and saturation conditions are key parameters.

5. Physical Response of the Porous Rock

Some attention has been given to the potential for microscopic-level spalling, and subsequent production of mobile fine particles. These particulates could potentially block constrictions in the available pore-space, leading to decreased porosity and permeability. Adverse thermal effects may occur to the granular structure. Conversely, the high flow rates and cyclic nature of a CAES facility might clean out the matrix and improve porosity and permeability.

3.2.3 Hard Rock: CAES

Hard rock excavation techniques have been applied around the world for over a century, including several underground operations for mining of various commodities, for storage cavern excavation, and for drilling and tunneling for highway and subway developments. The concept of Compressed Air Energy Storage was first introduced in Sweden in 1949, but was preceded by a number of different applications of underground compressed air chambers.

The first compressed air storage scheme was constructed in the Striberg Mine in Sweden, in 1910. The volume of the chamber is approximately 26,000 cubic feet, storing air at 100 psia. (Withstanding leakage problems early-on, this storage facility is still in operation.) The use of rock chambers for storage of air as feedstock to drill equipment in mines has been introduced in other countries, beginning with Finland in 1936.

Despite this considerable experience in constructing underground caverns and tunnels in hard rock, no CAES facility has yet been constructed in a hard rock cavern mined for the purpose. Major existing and planned CAES systems, and other uses of underground geologic compressed air storage, are listed in Table 3-1. The caverns in CAES systems will be subject to large temperature and pressure variations on a daily basis. There is little quantitative data available on the response of rocks to the frequent and prolonged cycling of actual CAES use. Appendix B describes in detail the characteristics desirable in a hard rock formation for CAES use. Design features, variables, and procedures for underground chambers in hard rock are defined in Appendix C.

Hazards to CAES in Hard Rock. Present knowledge of large-scale behavior of rock masses and groundwater flows in hard rock formations experiencing cyclic air pressure differentials is from existing air-cushion surge chambers. The thermo-mechanical stresses generated by the pressure and temperature fluctuations and by elevated storage temperatures could conceivably cause chemical and mechanical changes to the cavern walls. Certain conditions might lead to material deterioration which could contribute to permeability reductions or particle carryover to the turbines. In mined caverns, spalling of the walls could lead to the generation of particulate matter and even cavity closure.

The possibility of these and other potential problems is often alluded to in the literature; however, empirical geologic data such as will provide for complete risk analysis are only recently being developed. This data will enable prediction of conditions for which problems might be expected, actions required to probibit their occurrence, or the full associated consequences of untoward events.

TABLE 3-1

COMPRESSED AIR STORAGE SCHEMES IN HARD ROCK

COUNTRY	LOCATION	TYPE	VOLUME (m^3)	ABSOLUTE PRESSURE (MPa)	ROCK TYPE	OPEN YEAR
FINLAND	Outokumpu	Balanced	6,200	0.8	leptite biotite cordierite amphibolite	1955
	Vihanti	"	2,400	0.8		1958
	Kotalahti	"	3,000	0.8		1963
	Pyhasalmi	"	2,000	0.8		1973
	Otanmaki	"	5,000	0.8		1958
LUXEMBOURG	Vianden (300MW)	"	100,000	5	clay slate	planned
NORWAY	Driva	"	5,000	4.3	biotite gneiss	1973
	Jukla	Unbalanced	6,200	2.5	gneiss	1974
	Sima	Balanced	6,500	5.1	gneiss quartzite	Under Const
	Kvilldal	"	100,000	4.3	quartz dioritic gneiss	""
	Oksla	"	18,000	4.5	granitic gneiss	""
	Fosdalen mine	"	4,000	1.3	schistose greenstone	1939
	Rausand mine	"	2,500	0.8	gabbro	1948
SWEDEN	Striberg mine	"	800	0.7	granulite	1910
	Elygtekniska	Unbalanced	11,000	0.02-0.06	granite	1955
	Volvo Trollattan	Balanced	11,000	0.8	gneiss	1930
	Glan (230MW)	"	400,000	2.6	sed gneiss	planned
FED. REP. GERMANY	Bremen Test Cavern		6,500		clay slate	

The major problem areas associated with CAES in hard rock are:

1) failure of well plug
2) cavern degradation of temperature and pressure cycling
3) air leakage through rock mass
4) loss of volume due to water inflow
5) geochemical reactions

1. Plug Failure

Repeated temperature and pressure changes may cause loss of the integrity of the well plug. This occurred at the Striberg mine.

2. Cavern Degradation

Temperature and pressure cycling in the presence of air and water are the necessary conditions for weathering. Excessive pressure in the cavern can lead to excessive tensile stresses.

3. Air Leakage Through Rock Mass

The permeability of the rock mass must be sufficiently low to prevent pressure loss. The presence of cracks, joints, or a major fault can lead to air loss.

4. Water Inflow

The water pressure in rock pores should be sufficiently high to minimize air leakage. Any net influx of water will lead to loss of cavern volume.

5. Geochemical Reactions

The presence of oxygen, water, and relatively high temperatures can lead to chemical reactions that affect the properties of the rock mass.

A particular hazard to balanced hard rock CAES systems is a phenomenon called the "Champagne Effect." This phenomenon is described in Section 4.2.9.

3.2.4 Hard Rock: UPH

There are many pumped water storage plants in Europe, America, and in Australia, in which both upper and lower reservoirs are a surface feature (Figure 3-6). Some are listed with relevant details in Table 3-2. Present engineering design has posited 5,000-foot depths for a UPH facility, considerably greater than in previous pumped hydro installations. On the basis of the experience of both design engineers and the major construction firms in the world, the construction of an underground cavern for UPH is considered as falling within the limits of present technical knowledge. Appendix C describes the design features, variables, and functional guidelines for underground chambers in hard rock. Certain features of the proposed UPH configuration, due in part both to the dimensions and novelty involved, will require special development. The potential problem-areas are listed below:

1) water inflow
2) stability of caverns at depth
3) penstocks and shafts
4) powerhouse siting below ground

1. Water Inflow

Excessive water influx will cause decreased system efficiency, possible contamination of the circulant water, and greater operating costs.

2. Cavern Stability

The melting and drying environment may give rise to block loosening, accelerated weathering, and other forms of physical cavern deterioration.

TABLE 3-2

PUMPED STORAGE PROJECTS 1/

COMPANY/PROJECT NAME	CAPACITY (MW)	PUMPING ENERGY 2/ (millions Kwh)	DESIGN HEAD (ft)	1975 NET GENERATION (million Kwh)
Arizona Power Authority/Montezuma (AZ)*	505.0	-	1,660	-
City of L.A., Dept. of Water & Power/Castaic (CA)	481.0	-	1,018	319.8
CA Dept. of Water Resources & City of L.A./Castaic Addition (CA)*	1,275.0	-	1,063	-
Public Service Co. of Colorado/Cabin Creek (CO)	300.0	457.8	1,226	250.3
CO River Water Conservation Dist./Azure Project (CO)*	240.0	-	1,180	-
Oak Creek Power Co./Oak Creek Water & Power (CO)*	3,600.0	-	2,150	-
Power Authority of NY/Blenheim-Gilboa (NY)	1,000.0	-	1,100	1,009.0
Consolidated Edison of NY/Cornwall (NY)	2,000.0	-	1,050	-
Carolina Power & Light Co./Madison County (NC)*	1,500.0	-	1,175	NR
Tennessee Valley Authority/Raccoon Mountain (TN)*	1,530.0	-	1,040	-
VA Electric & Power Co./Bath County (VA)	1,500.0	-	1,050	-

NR - Not Recorded

* Under construction or proposed as of 1 January 1977

1/ Installations listed have design heads of over 1,000 ft.

2/ Pumping energy indicates how much energy was actually used for the pumped storage. Where it is not listed, it was not used.

Source: "Hydroelectric Plant Construction Cost and Annual Production Expenses." Prepared by the Federal Power Commission, Washington, D.C. 1975.

3. Penstocks and Shafts

Penstocks and shafts will traverse several thousand feet underground. The length and surge pressures make them more vulnerable to seismic factors than are conventional pumped storage installations.

4. Powerhouse Siting Below Ground

If powerhouses are sited at the lowest points of plants, the consequences of flooding may be more serious than at previously constructed facilities.[1] In addition, the problems of water removal are accentuated by the extreme heads contemplated for UPH facilities.

3.3 TECHNICAL UNKNOWNS

In order to permit enhanced confidence in the breadth and accuracy of risk analyses for prospective CAES and UPH sites, research must derive certain data for each of the three geologic structures. The following are potential phenomena whose likelihood, magnitude, and impacts are unknown at present:

1. Salt

   Safe limits for variations in thermal, mechanical, and humidity cycling have yet to be defined; much work remains to be completed on the effects of temperature, pressure cycling, and air penetration into salt.

2. Aquifer

   o In relation to a possible decrease in permeability, laboratory efforts should address the following potential problems:

   a) Differential thermal expansion,

   b) Grain microfracturing and disintegration, and

   c) Dehydration of intergranular cements with subsequent disintegration and matrix compaction.

[1]Private correspondence from Commonwealth Edison Corp.

- o The possibility that temperature-effects may lead to a loss of permeability greater than that predicted by thermal expansion and confinement.
- o There is the likelihood of pore space clogging within the aquifer storage volume.
- o The present aquifer gas storage schemes involve storing products such as natural gas and propane. The storage of air could lead to chemical or biological reactions different from those experienced in gas storage. This effect could be determined by analytical and field studies, and remedial action taken, such as changing the operating capacity specifications.

3. Hard Rock--CAES and UPH

- o Present techniques for measuring in-situ rock permeabilities for water are not capable of defining equivalent porous permeabilities less than 10^{-6} cm/sec for shorter packer lengths, except to indicate that the rock is impermeable rather than permeable. When the rock is excavated for CAES, the permeability could prove to be higher than anticipated by geological and geotechnical investigations, since the exposed rock mass is significantly larger than that exposed for in-situ tests.
- o The effect of cyclic loading on cavern performance is impossible to assess quantitatively until laboratory testing of hard rocks under conditions similar to those to be experienced by a CAES scheme has been performed.
- o There is the likelihood of induced seismicity from either initial pressurization or from cyclic loading. The experience with induced seismicity from reservoir filling and well injection could be used as a basis for predicting possible CAES-induced seismic events. This is described in Appendix J.
- o The effect of cyclic thermal, mechanical, and humidity variations on the thermo-mechanical and hydrological properties of hard rock formations is unknown presently.

3.4 CURRENT RESEARCH

At present, the U.S. Department of Energy is funding research for development of design and stability criteria for underground air and water reservoirs used in CAES plants. The purpose is to assess the long-term stability of these cavities for the benefit of the utilities which may contemplate investment. The CAES Reservoir Stability Program is divided into three sub-programs according to the type of reservoir (porous media, hard rock, salt), and each sub-program is subdivided into four phases. These phases are:

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

An outline of the program is given in Figure 3-14. Among the unknowns affecting the technical and economic feasibility of Compressed Air Energy Storage are those related to the response of an underground reservoir to pressure and temperature fluctuations that will be encountered in the daily charge and discharge operations.

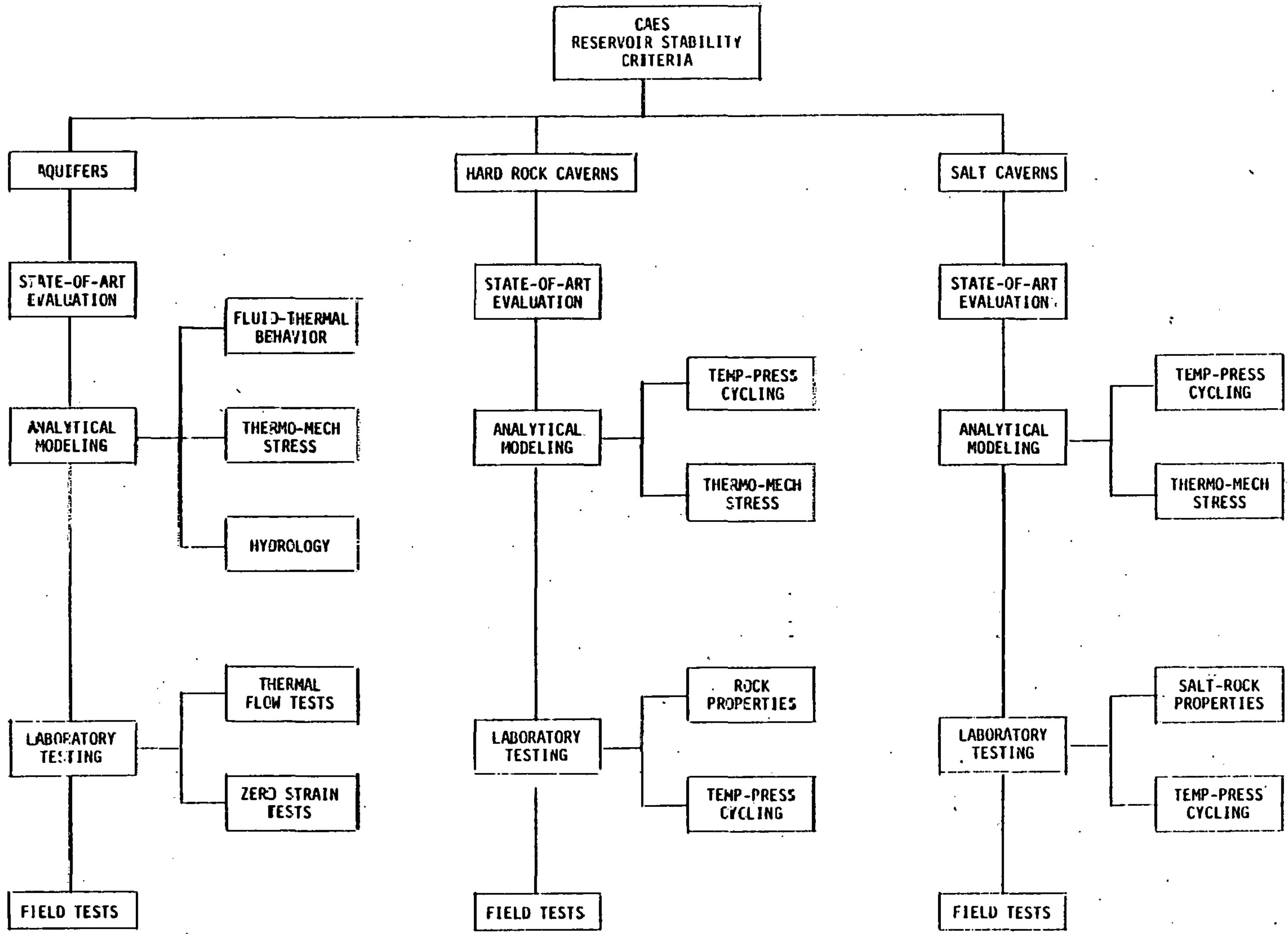
Hard Rock and Salt

Through the Pacific Northwest Laboratories (PNL), the DOE has a program underway to investigate the behavior and develop criteria for CAES reservoirs in aquifer, salt, and hard rock formations (Figure 3-14). The CAES reservoir stability criteria programs in hard rock and salt are in early stages, with contracts recently let for numerical modeling in hard rock and for salt. Laboratory testing for hard rock and for salt are being commissioned under separate contracts. If the DOE programs in hard rock and salt proceed rapidly, it will be possible for analysts to update this study as data become available, using the Hazard Index algorithm. The DOE has a program underway for developing a Strategic Oil Reserve, of which a portion will be stored in salt. The data available from this study are presently being reviewed. Technical information on development and operating results at the Huntorf facility have been compiled and are included in Appendices F and G, respectively.

FIGURE 3-14

C.A.E.S. RESERVOIR STABILITY PROGRAM

U.S. DEPARTMENT OF ENERGY



Aquifers

The potential failure modes of aquifer CAES schemes are being investigated by the DOE, and are being coordinated by Pacific Northwest Laboratories. The results of preliminary work were reported in the FY/1977 Progress Report where two classes of storage schemes are investigated; the high-temperature scheme (T200° F), and the low-temperature scheme (T200° F) (Section 3.2.2). The high-temperature scheme involves greater risks and will only be attempted if the low-temperature version is successful. Research into low-temperature air injection has dealt with the following areas:

- o Cavity structure and cap-rock dimensions
- o Geotechnical characteristics (e.g., porosity, temperature, pressure and permeability)
- o Impacts on surrounding property
- o Operating design limits

A sample of aquifer research results is shown in Table 3-3.

TABLE 3-3

PRELIMINARY DESIGN AND STABILITY CRITERIA
FOR LOW TEMPERATURE INJECTION

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

(a) NA = Not Applicable
(b) Site specific, based on 0.43-0.52 psi/ft of depth
(c) Site specific, based on 0.8 psi/ft of depth
(d) Delta pressure = Maximum Charging Pressure less the discovery hydrostatic pore pressure

4.0 FAILURE MODES ANALYSIS

The Failure Modes Analysis will describe scenarios of the geotechnical, design, and siting constraints on utilization of hard rock, salt, and porous media formations for CAES use, and on UPH in hard rock, using existing technical information. The hazards apparent from natural, excavation-related and operations-mode sources are described, with possible effects and remedial actions reported.

The failure modes and scenarios included below are representative of the state of knowledge at the time the study was conducted of geophysical response to intrusion of the presently schematized CAES and UPH systems. In acknowledgment of the current research in the areas of both CAES/UPH geo-behavioral effects and CAES and UPH system design, it is to be expected that modification to current technical presumptions and addenda to existing data may be forthcoming based on the findings of this research. For the sake of continuity and coherence in the analysis, however, it has been necessary to characterize the existing knowledge as fully descriptive of the technology in the course of preparing the required products for subsequent study phases. The implications of further geotechnical and structural engineering research with regard to the major insurance-related conclusions of this study are discussed in Chapter 7.0.

4.1 THEORETICAL BACKGROUND AND DEFINITION

The definition of terms used in this section are:

1) Failure Mode: A failure mode is the last of a series of events which causes the system to malfunction.

2) Scenario of a Failure Mode: The scenario of a failure mode is the linked series of events preceding the ultimate failure mode.

EXAMPLE: Failure Mode: Cavern collapse

Scenario: Earthquake leading to failures on existing faults.

The general hazards associated with all types of CAES and UPH schemes are listed below. The failure modes and scenarios of these modes applicable to each type of scheme in hard rock, salt and aquifers will be addressed separately. The hazards have been separated into three categories, depending on the source of the hazard.

- NATURAL HAZARDS: These are hazards which exist at the site due to its geographic location. The exposure to these hazards is modified during site selection and design phases of development.
  - Seismicity
  - Flooding from surface
  - Geologic faults, etc.
  - Tectonic stresses

- EXCAVATION-RELATED HAZARDS: These are hazards which occur due to the process of excavation of the cavity. Construction methods and techniques must be sufficient to minimize these risks.
  - Shaft Closure
  - Pillar Collapse
  - Roof Falls
  - Groundwater Flooding
  - Subsidence
  - Groundwater Contamination During Leaching

- STORAGE-RELATED HAZARDS: These are hazards which are induced by the air or water storage cycles. Monitoring, maintenance and operating design specifications are variables affecting the levels of storage-related perils.
  - Cyclic loading fatigue
  - Thermally induced stresses
  - Humidity degradation of rock
  - Internal pressure-generated tensile stresses

- Loss of well grout integrity
- Physical/chemical change of rock due to temperature and humidity variations
- Induced-seismicity
- Excess cavity leakage
- Groundwater contamination
- Airborne particulates
- Champagne phenomenon
- Umbrella effect
- Clogging of pores

The listing of these phenomena is not intended to imply that failure will occur solely as a result of one failure mode. On the contrary, the failure modes are interrelated to the extent that a combination of phenomena may be required to create a cavern failure, while each phenomenon acting alone may not be sufficient to cause failure of the cavern.

The concept of failure is somewhat broad in definition. A failure of individual segments of the cavern may or may not induce total failure of the cavern itself, although it may influence the CAES scheme in some other aspect. Further, a failure may result in loss of system efficiency instead of total loss of use of a cavern.

As was noted above, some hazards would be more likely to occur as the duration of the CAES operation increases. Storage-related hazards may have constant probability of occurrence, but their effects could be cumulative such that the magnitude of failure may increase with time. It should be emphasized that each case should be evaluated individually, based upon details of design and characteristics of a particular site. The Hazard Index (Appendix K) is designed as a method of relative ranking of the degree of risk at a given site, and of calculating risk factors at various points during the life of a site.

4.2 CAES POTENTIAL FAILURE MODES IN HARD ROCK

The failure modes associated with CAES in hard rock are:

- o Cavern Collapse
- o Loss of Volume Due to Water Inflow (unbalanced CAES)
- o Loss of Pressure

4.2.1 Cavern Collapse--Scenario: Collapse Due to a Natural Seismic Event

The potential risk associated with CAES caverns will naturally be higher for areas with high seismic activity than for areas with low seismic activity. The probability of seismic activity in the continental U.S. is discussed by delineating areas into seismic zones 0, 1, 2, and 3. This delineation is commonly used to establish seismic design criteria; the following maximum ground accelerations are associated with the zones: Zone 3 - 0.33g, Zone 2 - 0.16g, Zone 1 - 0.08g, and Zone 0 - 0.04g. In Zone 3 (defining areas close to a major active fault) the maximum ground acceleration is estimated to be approximately 0.50g. Underground structures are, in general, much safer than above-ground structures for a given intensity of shaking. The stability of underground excavations under seismic loading is discussed, and the literature reviewed in Appendix A. From experience, it has been noted that only a few cases of minor damage to underground excavations were observed for surface accelerations up to 0.25g. It may be expected that structural damage to a CAES facility from seismic excitation will be low, due to site selection, investigation, and design criteria, and because of the inherent resistance of underground openings to seismic damage.

4.2.2 Cavern Collapse--Scenario: Collapse Due to Induced-Seismicity

It is likely that frequent cycling at high temperatures and pressures may affect seismic event occurrence, especially if the CAES reservoir is located near a fault or shear zone. If the system is a balanced one, the presence of water will affect the pore pressure within the rock, making slippage more likely. This, coupled with frequent changes in pressure, may cause fault activation.

This has been documented at injection sites in the Denver area. Excess and deteriorating stocks of war chemicals at Rocky Mountain Arsenal, near Denver, were disposed of some years ago by pumping them at high pressure into deep drilled wells. Later research showed that these pressurized injections had induced local earth tremors or seismicity ranging in strength up to 5.5 on the Richter scale.[1] This method of disposal was accordingly halted. The well at the Arsenal was 12,000 feet deep. The head or pumping pressures ranged up to 1,700 pounds per square inch (psi). Pressures at the well bottom ranged up to 6,000 psi (or 415 bars) and are estimated to have been 5,640 psi (389 bars) when the tremors started.

Subsequent experiments to try to create controlled earthquakes were made by pressure flooding an oil field at Rangely in northwestern Colorado.[2] The maximum pressure involved was 4,550 psi (314 bars). The critical fluid pressure, above which earthquakes were triggered, was calculated to be 3,730 psi (257 bars). Depths of fluid-holding voids in the natural formation down to 7,500 feet were observed.

Small-scale, induced seismic activity could have significant effects on CAES systems. Movement along fault planes caused by the pressure cycling may only give rise to minor roof falls; however, it may lead to significant increases in permeability, possibly resulting in leakage of air along new or reopened discontinuities. Obviously, sites containing a number of major faults will not be considered; however, a site devoid of minor faults or major discontinuities is rare, and the possibility of induced-seismicity is present at most sites to some degree. Proximity to known seismic zones is a major site selection criterion. (For an additional discussion of induced seismicity see Appendix J.)

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[1]See Healy, J.H., W.W. Rubey, D.T. Griggs, and C.B. Raleigh, "The Denver Earthquakes," Science, vol. 161, No. 3848, 27 Sep. 68, pp. 1301-1310.

[2]Raleigh, C.B., J.H. Healy, and J.D. Bredehoeft, "An Experiment in Earthquake Control at Rangely, Colorado," Science, vol. 191, 26 March 1976, pp. 1230-1237.

4.2.3 Cavern Collapse--Scenario: Collapse Due to Faulting

The siting of CAES caverns in areas of high tectonic activity would be undesirable due to the likelihood of encountering faults, shears, and intense jointing in the rock formation. These types of geologic features would not only present problems with cavern stability, but would drastically increase the probability of air leakage and water inflow. A detailed investigation of the geologic conditions at a particular site will be undertaken to properly evaluate the site in detail, thus highlighting early the feasibility of a site. It is highly unlikely that a CAES scheme will be located near a major fault. The consequences of collapse due to faulting could in some cases be averted if remedial action, such as support and reinforcement, was implemented immediately upon discovery.

4.2.4 Cavern Collapse--Scenario: Collapse Due to High Tectonic Stress

In-situ material stresses will always be present in rock at depth, because these stresses are required in order to maintain equilibrium, i.e., to support the overburden. Horizontal stresses will also be present, and if the region has been subject to tectonic activity, these stresses could exceed the vertical ones. The horizontal stresses may vary from one-third to twice the vertical overburden pressure. Care must be taken in designing the openings, in order that the cavern can withstand such stresses. In CAES caverns excavated by conventional room-and-pillar mining techniques, it will be important that the extraction ratio be kept at a level that will not overload the supporting pillars. Pillar failure due to overloading can occur by exceeding the load carrying capacity of the pillar. The factors influencing the pillar behavior in addition to the extraction ratio are the rock mass compressive strength, the depth of overburden, and the induced stresses (thermal included) due to the air storage itself. Pillar failures could have several implications. Collapse of a single pillar would cause the applied loads to be redistributed to adjacent pillars to be overloaded, thereby causing a progressive failure of the entire cavern. Failure of the pillars due to overloading or due to excessive yielding would result in closure of the opening. This closure would ultimately result in subsidence of the ground above the cavern. Proper design of the cavern will minimize the possibility of pillar failures.

4.2.5 Cavern Collapse--Scenario: Collapse and Pressure Loss Due to Internal Pressure and Temperature Loads

Siting of a CAES cavern at shallow depths may not produce compressive tangential stresses generated by the internal pressurization of the cavity. In such a case, if net tensile stresses are allowed to develop, then the danger of a blowout due to a roof failure could arise. The combined effect of both pressure and temperature cycling should be throughly evaluated. As the depth of overburden above the cavity increases, the compressive stresses around the cavity increase. These compressive stresses cannot be allowed to approach the compressive strength of the rock, or failure around the cavern becomes highly probable. Milne et al. (1977) have recommended a lower bound compressive strength of 130MPa for rock surrounding the cavity to accommodate the structural and thermal stresses likely to be induced.

4.2.6 Cavern Collapse--Scenario: Collapse Due to Cyclic Loading Fatigue

Rock materials are known to have reduced strength in both tension and compression when subjected to successive cycles of loading and unloading. As the number of cycles increases, the fatigue strength decreases. Assuming a 30 year design life for a CAES cavern operating on a daily cycle of pressurization-depressurization, the cavern would undergo approximately 11,000 cycles. Haimson (1974) has shown that the failure stress for Westerly Granite cycled in a tension-compression mode in tension was only 40 percent of the uniaxial static tensile strength. This observation emphasizes that strengths can be substantially reduced under cyclic loading conditions. However, depending upon the strength properties of the host rock, the stress conditions around the unpressurized cavern and the air stroage pressure, the stresses induced in the rock due to cyclic loading may never reach a sufficient mangitude to produce fatigue failure, even for the number of cycles being considered. The present knowledge of cyclic loading in crystalline rocks is described in a brief review in Appendix B.

4.2.7 Loss of Volume Due to Water Inflow (Unbalanced CAES)--Scenario: Surface Flooding

The potential for flooding a CAES cavern from surface water sources depends not only upon the presence of surface water, but also upon the abilities of the CAES surface facilities to seal the shafts, etc. It can only be assumed that the design will incorporate adequate precautions against influences such as flooding. Thus, the possibility of flooding of shafts for both the compensated and uncompensated systems should be minimal due to their design.

4.2.8 Loss of Pressure--Scenario: Blowout Due to Loss of Integrity Between Well Casing and Grout

Smith et al. (1978) have pointed out that a casing failure occurs initially when temperature-generated compressive stresses exceed the yield strength of the casing resulting in permanent deformations of the casing. Subsequent cooling relieves the compressive stress and the induced deformation may create tensile stresses if the casing returns to a lower temperature. This tensile stress may cause failure in the casing joints by fracture or pullout.

The response of cement grout to elevated temperatures is also of concern. There are two components to the thermal problem: (1) the elevated temperature itself and the potential for cements other than the silica-based ones to dehydrate and lose integrity, and (2) the establishment of a radial thermal gradient across the sheath. The first area appears to be manageable with the proper type of cement. The second problem may require that the injection temperature be raised gradually over many cycles. This would warm the cement sheath by conduction and possibly eliminate any high thermal stresses to be generated within the sheath. The loss of integrity of the casing-grout system should therefore be thoroughly evaluated in the design process, and casing and grout materials compatible with the anticipated air storage temperature selected.

4.2.9 Loss of Pressure--Scenario: A Blowout Due to Champagne Effect

In CAES caverns to be operated under the water-balanced scheme, a unique mechanism called the champagne phenomenon could occur between the compressed air and the balancing water. Milne et al. (1977) have described this phenomenon as outlined below.

> During cavern charging, air would be pumped into the underground cavern displacing water from the cavern into the vertical shaft and from there, into the compensating reservoir. During power generation, air would be withdrawn from the cavern and water from the compensating reservoir would flow back into the cavern. Because of the high air pressure in the cavern, some of the air in the cavern would be forced into solution at the air-water interface. If the normal charging/discharging cycle were interrupted for several weeks or more, the water could become saturated. Consequently, during subsequent cavern charging, saturated water would be forced up the water shaft and air would come out of solution, forming a two-phase, champagne-like bubble-water mixture. This bubble mixture could, under certain conditions, lead to unstable loss of head and blowout of the cavern.

Additional research is being conducted regarding the effects, scope, and preventive means for avoiding this hazard. The analysis herein represents the dimensions of the "Champagne Effect" phenomenon to the extent they are realized in current engineering literature. The updated scientific data base which is likely to evolve from any findings of the current research programs will have to be reflected in the loss rate estimates, as listed for hard rock in Table 5-2. The risks can be minimized by employing varous design schemes as outlined by Milne et al. (1977).

4.2.10 Loss of Pressure--Scenario: Pressure Loss Due to Excessive Air Leakage Through Rock Mass

Walia and McCreath (1977) have pointed out that because air has a low viscosity, it will leak through a rock mass of relatively low permeability. Methods for reducing permeability, such as grouting and the installation of water curtains, are quite expensive (Bergman, 1977). An acceptable air loss for CAES caverns is about two percent of the total contained volume of air per day. A total leakage rate of three to four percent would probably require costly measures to prevent excessive leakage from and water inflow into the storage cavern. Massive igneous plutonic and metamorphic rocks along with some limestones and dolomites are likely to meet the low-permeability requirements. Fracture permeability derived from joints, fractures, and other fissures in the rock will usually control the total permeability of a crystalline rock mass.

Geologic studies should be made to site the CAES cavern in rock masses that will not exceed the acceptable permeability limits of 10^{-6} cm/sec for water. In evaluating the likelihood of encountering excessively high permeabilities for any particular cavern site, a thorough investigation is a prerequisite for making a reasonable assessment of the risks involved. Field permeability data for fractured hard rocks, varying with depth, are given in Appendix B.

4.2.11 Loss of Pressure--Scenario: Air Loss and Possible Collapse Due to Cycling Deterioration of Rock Mass

The existence of elevated temperatures, readily available free oxygen and carbon dioxide and liquid phase water in a CAES cavern create the ideal environment for chemical weathering reactions (Smith et al., 1978). The key factors in this weathering environment are the high-temperature and water-saturated air. An additional concern for high-temperature CAES schemes pointed out by Smith et al. is that thermal/chemical alterations could perturb matrix permeability, corrosion potential and/or scaling potential.

If caverns are excavated in rocks containing inherent weakness, such as closely spaced cleavage and foliation planes, or thinly bedded sedimentary deposits, the weaknesses are susceptible to deterioration. Cyclic changes in humidity combined with cyclic temperature and pressure variations can cause decay, alteration, or deterioration of such weaknesses, leading to increased permeability, and air loss. The thermomechanical cyclic fatigue was discussed above in the scenario on Collapse Due to Cyclic Loading Fatigue.

4.3 UPH POTENTIAL FAILURE MODES IN HARD ROCK

Underground pumped hydro differs structurally from present pumped storage schemes only in that the lower reservoir is situated underground. It is therefore considered only a minor extension of existing technology. The major difference between the underground cavern and the present structures is the moderate depth (possibly 1500-1800m) at which some schemes are contemplated. Since the in-situ stress field increases with depth, the major problem area will be the underground reservoir (cavern) stability. The potential failure modes of a UPH cavern also differ only slightly from CAES in hard rock and the scenarios giving rise to these failure modes are similar. The major difference between the two is the cyclic thermal and pressure loading experienced in the case of CAES in hard rock. The following failure modes are possible for a UPH facility:

- Underground Reservoir Collapse
- Loss of Volume Due to Water Inflow

4.3.1 Underground Reservoir Collapse--Scenario: Collapse Due to a Natural Seismic Event

This scenario and its impact on this failure mode are the same as CAES in hard rock, with the exception that, in this case, daily or weekly inspection of the underground reservoir may be possible, whereas in CAES this is unlikely.

4.3.2 Underground Reservoir Collapse--Scenario: Collapse Due to Induced Seismicity

The possibility of such a scenario occuring for UPH is approximately the same as present underground hydro or pumped hydro plants, since the fluid pressure is contained in the pressure tunnel and is not associated with the lower reservoir.

4.3.3 Underground Reservoir Collapse--Scenario: Collapse Due to Faulting

The same as CAES in Hard Rock.

4.3.4 Underground Reservoir Collapse--Scenario: Collapse Due to High Tectonic Stress

The same as CAES in Hard Rock.

4.3.5 Loss of Volume Due to Water Inflow--Scenario: Groundwater Flooding

The possibility of groundwater flooding of the underground reservoir in UPH is greater than in CAES-hard rock, since the latter uses greater-than-atmospheric pressures, thus resisting water inflow. Except for this point, the case of UPH in hard rock is similar to that of CAES.

4.4 CAES POTENTIAL FAILURE MODES IN POROUS MEDIA

The condition of the rock mass is extremely important for the success of CAES-aquifer schemes. Two criteria must be satisfied: first, the aquifer must be sufficiently permeable for the air to pass freely through pores; and secondly, the aquifer must be capped by rock of sufficiently low permeability for air not to escape. Field exploration to determine the characteristics of a potential aquifer site is both difficult and expensive. The techniques involved in the field exploration of aquifers are described in Appendix H. The failure modes associated with aquifers are:

- Decrease of Permeability
- Loss of Air
- Environmental Damage to Surface Aquifers
- Inefficient Air Recovery

4.4.1 Decrease of Permeability--Scenario: Clogging of Pore Space

In CAES schemes in aquifers, the potential for a reduction in permeability and the associated loss of storage volume due to clogging of pores is significant, particularly as the number of storage cycles increases. Smith et al. (1978) have noted the potential for microscopic-level spalling and the subsequent production of mobile fine particles. These particulates could potentially cause constrictions in the available pore space and lead to decreased porosity and effective permeability. Differential thermal expansion, deterioration of cement bonds between grains and fragmentation of grains at sharp (high stress) grain contacts could result in collapse of the granular structure itself as well as the production of particles. Conversely, the high mass flow rates and cyclic nature of a CAES facility could cleanse an aquifer matrix and improve porosity and permeability.

4.4.2 Decrease of Permeability--Scenario: Change in Permeability Due to Temperature Changes

Results of an experiment by Nelson (1975) show that the permeability of a single fracture in sandstone depends on temperature. It increases to a maximum at about 50-70° C and subsequently drops. This particular sample was unconfined in this experiment, but the author concludes that confinement could in itself lead to a decrease in permeability.

4.4.3 Decrease in Permeability--Scenario: Change in Permeability Due to Chemical Changes

The introduction of oxygen into a previously low-oxygen environment may cause aquifer damage. Aerobic bacteria and the different oxidation potential of water may cause minerals to change oxidation states and precipitate out of solution. For example, iron may be converted to the ferric state and precipitate. This behavior can cause the blocking of pores, subsequent permeability reduction, and reduction in flow. The full extent of this problem is not well defined, but these difficulties should be considered in aquifers of high mineral content.

4.4.4 Loss of Air--Scenario: Cap-Rock Leakage

It is extremely difficult to determine the tightness of the cap-rock during the site investigation stage and gas storage wells have been abandoned because minor faults have later been detected (WGI: Brandywine Project). As described in Appendix H, there is usually a critical pressure which a cap rock can withstand before allowing air to pass through. It is impossible to determine this pressure by in-site tests, since over-pressurization may cause permanent damage to the cap-rock by opening up leakage paths which may not close again. In the case of storage wells, from which natural gas has been removed, it can be assumed safe to repressurize to at least the original discovery pressure.

Even when a well has been successfully completed, there exists the risk that the repetitive cycling will cause the cap-rock to fatigue, possibly giving rise to air leakage. Leakage may therefore occur after several years of successful operation. This was the case at one natural gas storage site which operated successfully for twelve years, but withdrawal in the thirteenth year showed that most of the gas had escaped (see Appendix I).

4.4.5 Loss of Air--Scenario: Air Loss Due to Pumping Effect

During repeated cycling, gas is withdrawn from the near-well zone but significant quantities are left around the periphery. During the injection stage, this "edge gas" is displaced a little farther outwards. Eventually it is displaced, so far as to be "lost" from the well. The failures of two natural gas storage wells have been at least partially attributed to this effect. If this effect is noticable after five or six annual cycles, it may constitute a serious hazard over the thousands of cycles of a CAES plant.

4.4.6 Loss of Air--Scenario: Air Loss Due to Umbrella or Fingering Effect

When the vertical permeability of a reservoir is significantly lower than the horizontal permeability (e.g., when shale partings or interbeads are present), the gas bubble may not develop its intended thickness, but may flow out in a thin zone immediately beneath the cap rock, resulting in gas escaping from the area of closure. When recognized, this can often be controlled with the proper injection techniques.

4.4.7 Loss of Air--Scenario: Air Loss Due to Regional Groundwater Flow

Maintenance of the air cushion may be difficult due to regional groundwater flow gradients. Under certain conditions, regional groundwater drift in confined aquifers can cause stored gases or other fluids to be convected away from the intended storage area. This can cause inefficient recovery conditions. A case of treated water storage in Louisiana documented a 25 percent recovery efficiency after six days of storage. This poor performance is attributed to pre-existing groundwater flow patterns.

4.4.8 Loss of Air--Scenario: Blowout

If the well is too shallow or the cap-rock is not thick enough, it is possible for the well to rupture and "blow out". The necessity of siting the well at sufficient depth for the water pressure to contain the air greatly reduces this hazard, but may not completely stop air leakage. Slow leakage of air through the cap-rock in one case pressurized a shallow sandstone only a few hundred feet below the surface. Eventually this sandstone blew out, creating a crater around the well head. The well head then failed, allowing the well to blow.

4.4.9 Loss of Air--Scenario: Blowout Due to Loss of Integrity Between Well Casing and Grout

This is discussed in the sections on CAES in Hard Rock and Salt.

4.4.10 Environmental Damage to Surface Aquifers--Scenario: Operational Difficulties Due to Regional Groundwater Flow

Regional groundwater flow through an aquifer can cause operational problems by deforming the bubble and convecting it away from the wells (i.e., translation of the stored air).

4.4.11 Inefficient Air Recovery--Scenario: Incomplete Water Displacement and Air/Water Mixing

It is essential that the near well area be kept free of interstitial water, for the efficient operation of the air recovery cycle. This will be achieved by ensuring that only dry air is pumped into the well. If the water remains in the pores, the flow of air will be inhibited and recovery hindered. Accumulation of water near the well can significantly disrupt the air flow rates required for the system operation.

A second problem called coning arises when air is withdrawn too rapidly from the well. This is caused by the air and water mixing and being drawn together out of the well. Too rapid a withdrawal rate can also lead to reduced pore pressures because the water-drive is not sufficient to fill the pore space vacated by the air. The loss of "support pressure" can lead to compaction and damage to the aquifer matrix. Total system shutdown may result.

Environmental Damage to Surface Aquifers

Leakage of air into surface aquifers can seriously disrupt local water supplies. Even slight pressurization of shallow aquifers can cause artesian flow in water wells, and the appearance of new springs. This has been observed on several occasions in connection with the repressurization of oil reservoirs. Even without pressurization, accumulation of air or gas can cause wells to go dry.

4.5 CAES POTENTIAL FAILURE MODES IN SALT

The following failure modes are possible for a CAES plant in salt:

- Cavern Collapse
- Loss of Volume
- Groundwater Contamination
- Pressure Loss Due to Blowout
- Collapse of Surface Structures

As stated earlier, every mode will not apply to any particular site, and judicious site selection will reduce many of the risks. Indeed, salt appears to be a highly favorable medium in which to construct a CAES plant, based on assessment of failure modes.

Failure modes will only be described and discussed insofar as they differ from their occurrence in hard rock.

4.5.1 Cavern Collapse--Scenario: Collapse Due to a Seismic Event

The probability of seismic activity in the continental U.S. is discussed in the scenario for CAES in Hard Rock, Section 4.3.2. As stated earlier, the risk of damage to underground structures from seismic activity is generally small. This is especially true in salt because salt contains generally fewer fractures or planes of weakness along which motion can occur. There is no evidence of compressed air energy storage giving rise to induced seismicity; however, there is only a single plant in operation. For low-pressure cycling it appears unlikely that induced seismicity will occur.

4.5.2 Cavern Collapse--Scenario: Closure and Failure Due to Creep

Possible consequences of creep deformation in salt that is subjected to temperature and stress loading are creep-rupture and creep-closure. The creep properties of salt are highly dependent on temperature and pressure. The relevant properties of salt for CAES systems are discussed in detail in Appendix D. Provided the cavern is designed correctly (i.e., depth of cavern, thermo-mechanical properties of salt, magnitude of pressure and temperature cycling are balanced to minimize cavern closure), no significant closure should be expected. Deep cavities, however, have been known to close at rates of up to 30 percent per year. If closure of the cavern was significant, additional solution-mining could reinstate capacity.

4.5.3 Cavern Collapse--Scenario: Temperature and Pressure Cycling Effects on Salt

Temperature and pressure cycles can affect the stability of CAES cavities constructed in a salt medium. In CAES salt cavities, there will be a daily cycling of temperature and pressure that can mechanically affect the cavity stability, closure rate, etc. Investigations carried out at the Huntorf facility showed that maximum rate of depressurization of 10 atm/hour and cycling between 10° C and 800°C was within the safe limits.

4.5.4 Cavern Collapse--Scenario: Unstable Cavern Shape

The solution-mining of a salt cavern is a relatively simple and cheap process (see Appendix F) but requires much expertise on the part of the contractor to obtain the optimum shape. The leaching process is controlled by altering the inlet and outlet levels and flow rate of the water/brine. Anisotropy and heterogenecity in the properties of the salt can lead to accelerated leaching in one direction and retard leaching in another, giving the cavern a "bad" shape, i.e., a shape which is sub-optimal for withstanding tectonic and cycling stresses. All of the four known instances of cavern collapse (see Appendix D) have occurred during brine solution-mining and are believed to have resulted from uncontrolled leaching of the salt near the top of the dome. The thicknes of the cavern roof was in each case less than 300 feet. Insoluble material within the salt can also collapse during solution-mining, causing damage to piping. The rounded cylindrical shape of ideal caverns is, in practice, difficult to obtain. The shape of the caverns at Huntorf clearly demonstrates the irregularity that is often achieved by solution-mining. If the solution-mined cavern's shape is poor, (e.g., elongated horizontally), it may lead to eventual collapse due to a possible roof fall.

4.5.5 Loss of Volume--Scenario: Loss of Volume Due to Flooding

Although salt can, for practical purposes, be considered impermeable, it is possible for water to penetrate the salt by dissolving it. Many salt domes are surrounded and overlain by aquifers. Shafts sunk through aquifer layers and into the salt can act as channels for the migration of water and the subsequent dissolution of the salt. Lenses of sandstone containing water can be encountered during mining in salt domes or bedded salt deposits. If water penetrates the walls of the cavern, flooding can result. At worst, this can lead to total loss of the chamber. More generally, it will lead to a loss of useful volume for air storage and may lead to leaching of the cavern walls. This latter effect may be negligible if the water is saturated with salt when it enters the cavern.

4.5.6 Groundwater Contamination--Scenario: Disposal of Saline Solution

It is necessary to dispose of large quantities of saline solution produced by the leaching of the caverns. If this is pumped into fresh water aquifers and eventually drawn upon for town supplies, it would constitute an environmental hazard. This problem will be solved at the site selection stage, since an environmental study would most likely be undertaken before a site is selected.

4.5.7 Pressure Loss Due to Blowout--Scenario: Overpressurization of Cavern

Cyclic temperature loading of the well can lead to loss of integrity between the well casing and the cement grouting. This scenario is expanded upon in the section of CAES in Hard Rock and similar comments apply here.

4.5.8 Collapse of Surface Structures--Scenario: Surface Subsidence

The construction of an underground chamber causes movements and induces stress changes in the surrounding rock mass. These movements can give rise to subsidence of the ground surface above the opening. The following factors influence the magnitude and nature of subsidence above solution-mined areas:

- Properties of bedded and domal salt
- Location, size, depth, and shape of the proposed opening
- Faults, shear zones, bedding planes, and discontinuities
- Presence of other openings
- Initial stress state

Two modes of failures include compressive yielding and failure under tensile stresses. Failures in the vicinity of an opening do not have significant effect on surface subsidence associated with sinkholes and ground breakage can occur. Generally, failure does not propogate to the surface, and it is necessary to predict the subsidence that can occur from the creation of solution cavities.

4.6 HAZARD INDEX CONCLUSIONS

Any particular site will be described by a unique set of geological, design, and structural characteristics. An analytic technique has been developed which may be used to apply the parameters of a general nature, produced in this risk assessment, to the large variation in possible site-specific details. The use of such a tool will enable analysts to examine insurability, and to rank caverns of particular design, size, geometry, and depth, which could be situated within a given set of geologic, seismic, and hydrologic conditions. When cavern design features or other site-specific factors vary from their original description, a new index can be determined. Such an approach has been applied to the long-term stability of tailing dams by Nelson and Shepherd (1978). This approach is modified below to allow for establishing such a hazard index. Applied to the analysis of Failure Modes, Section 4.0, this "Hazard Index" can generate quantified rankings of the risks associated with compressed air energy storage in underground salt or hard rock caverns, or in aquifers, on a relative basis.

A methodology for comparative evaluation of CAES and UPH schemes, on the basis of a weighted score of all potential modes of failure, has been developed. The weighted scoring produces an ordinal ranking which designates undesirable outcomes with correspondingly low values. With appropriate coefficients, the algorithm may be used to generate a multiplier (greater than or equal to one) for adjusting the rates in Section 5.3 according to the Hazard Indexed risk rating for any particular site.

4.6.1 Hazard Index Assessment for Hard Rock--CAES

No design (conceptual or otherwise) for a CAES scheme in hard rock is presently available; it has been necessary, therefore, to propose an idealized CAES scheme, a base case to use in discussion for all three geologic structures. The base case considered for hard rock is of the following configuration and geological setting:

a) location in seismic activity areas denoted by zones 0, 1, or 2;
b) no major faults or shear zones nearby;
c) rock type granite or granite gneiss;
d) rock quality, excellent, average minor joint spacing 1m, major joint spacing 3m, uniaxial compressive strength of core 130MPa, rock mass permeability 5×10^{-6} cm/sec;
e) depth 700-1000m;
f) operating maximum pressure 1500 psi; and
g) maximum air temperature 15°C above rock-ambient.

It has been assumed that this generic CAES scheme will undergo competent site selection, design, construction and operation methods, and that monitoring activities will occur throughout the development process. A qualitative assessment of hazards for the hard rock-CAES base case are given in Table 4-1 for the failure modes of cavern collapse, loss of volume and loss of pressure for both the balanced and unbalanced schemes. The various scenarios considered were: a) natural seismic event; b) induced seismic event; c) tectonic activity such as faulting; d) high tectonic stresses; e) internal fluid pressure generating tensile stresses; f) effects of cyclic thermal and pressure loading; g) groundwater flooding; h) loss of well casing and grout integrity; i) air leakage through the rock mass; and j) champagne effect for the compensated system. In Table 4-1, the likelihood, magnitude and consequences of a scenario giving rise to a particular failure mode are described.

TABLE 4-1

POTENTIAL FAILURE MODES OF CAES IN HARD ROCK (BASE CASE)

FAILURE MODES / SCENARIOS	CAVERN COLLAPSE			LOSS OF VOLUME			LOSS OF PRESSURE		
	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure
NATURAL SEISMIC EVENT	Zone 1 0.08g earthquake at surface. Zone 2 0.16g earthquake at surface.	Minor to no damage to cavern. (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	Zone 1 0.08g earthquake at surface. Zone 2 0.16g earthquake at surface.	Minor to no damage to cavern. (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	Zone 1 0.08g earthquake at surface Zone 2 0.16g earthquake at surface	Minor to no damage to cavern. (Possible small rock-falls only)	Cleanup required in routine inspection shutdown
INDUCED SEISMIC EVENT	Unknown	Possibly small if no major discontinuities present	Could be extremely serious	Unknown	Possibly small if no major discontinuities present	Could be extremely serious	Unknown	Possibly small if no major discontinuities present	Could be extremely serious
FAULTING	Low due to site selection criteria	Small in the absence of geological structural weaknesses	Could be serious	Low due to site selection criteria	Small in the absence of geological structural weaknesses	Could be serious	Low due to site selection criteria	Small in the absence of geological structural weaknesses	Could be serious
HIGH TECTONIC STRESS	Moderate possibility of presence. Likelihood low due to site selection & design criteria	Significant	Possible total or operational shutdown	—	—	—	—	—	—
INTERNAL PRESSURE GENERATING TENSILE STRESS	Low due to design criteria	Significant	Possible total or operational shutdown	Low due to design criteria	Significant	Possible total or operational shutdown	Low due to design criteria	Significant	Possible total or operational shutdown
CYCLIC TEMPERATURE PRESSURE AND HUMIDITY EFFECTS	Unknown	Significant	Possible total or operational shutdown	Unknown	Significant due to washing out joint filling	Serious could lead to operational shutdown and remedial measures (grouting)	Unknown	Significant due to washing out joint filling	Serious could lead to operational shutdown and remedial measures (grouting)
GROUNDWATER FLOODING	—	—	—	Low to moderate due to site selection design criteria	Moderate to significant	Intermittent pumping or shutdown for repair.	—	—	—
LOSS OF INTEGRITY BETWEEN WELL CASING AND GROUT	—	—	—	—	—	—	Low to moderate due to monitoring and design	Moderate to significant	Possible shutdown and repair
AIR LEAKAGE THROUGH ROCK MASS	—	—	—	Low to moderate due to site selection & design	Moderate to significant	Could be moderate to significant if requiring grouting or water curtain.	Low to moderate due to site selection & design	Moderate to significant	Could be moderate to significant if requiring grouting or water curtain
CHAMPAGNE EFFECT (COMPENSATED CAES)	—	—	—	Low due to design criteria	Small due to design	Minor	Low due to design criteria	Small due to design	Minor

4.6.2 Hazard Index Assessment for Hard Rock--UPH

The base case considered here is of the following configuration and geological setting:

a) located in seismic activity areas denoted by zones 0, 1, or 2;
b) no major faults or shear zones nearby;
c) rock type granite or a granite gneiss;
d) rock quality excellent average minor joint spacing low, major joint spacing 3m, uniaxial compressive strength of core 5 x 10^{-6} cm/sec;
e) depth 1000m; and
f) operating head 1000m.

From present knowledge, qualitative estimates have been made on the hazard index of particular scenarios of various failure modes, as input data and background knowledge to professionals in the insurance industry. This generic UPH scheme should undergo competent site selection, site investigation, design, construction and operation procedures monitoring activities throughout development. Qualitative assessments of hazards for the hard rock-UPH base case are given in Table 4-2. For the failure modes of cavern collapse and loss of volume, the various scenarios considered where: a) natural seismic event; b) induced seismic event; c) tectonic activity such as faulting; d) high tectonic stresses; and e) groundwater flooding. In Table 4-2, the likelihood, magnitude, and consequences of a scenario giving rise to a particular failure mode are described.

4.6.3 Hazard Index Assessment for Porous Media

The preliminary design criteria from PNL, Section 3.4.1, has been used for the aquifer base case, using the following configuration and geological setting:

a) located in seismic activity areas denoted by zones 0, 1, or 2;

TABLE 4-2

POTENTIAL FAILURE MODES OF UPH IN HARD ROCK (BASE CASE)

SCENARIOS \ FAILURE MODES	CAVERN COLLAPSE			LOSS OF VOLUME		
	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure
NATURAL SEISMIC EVENT	Zone 1 0.08g earthquake at surface. Zone 2 0.16g earthquake at surface.	Minor to no damage to cavern (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	Zone 1 0.08g earthquake at surface Zone 2 0.16g earthquake at surface	Minor to no damage to to cavern. (Possible small rock-falls only)	Cleanup required in routine inspection shutdown
INDUCED SEISMIC EVENT	Low	Possibly small if no major discontinuities present	Could be extremely serious	Low	Possibly small if no major discontinuities present	Could be extremely serious
FAULTING	Low due to site selection criteria	Small in the absence of geological structural weaknesses	Could be serious	Low due to site selection criteria	Small in the absence of geological structural weaknesses	Could be serious
HIGH TECTONIC STRESS	Moderate possibility of presence. Likelihood low due to site selection & design criteria	Significant	Possible total or operational shut-down	—	Blank	—
GROUNDWATER FLOODING	—	Blank	—	Low to moderate due to site selection design criteria	Moderate to significant	Intermittent pumping or shut-down for repair.

b) no major faults or shear zones nearby;

c) rock type sandstone with shale cap rock;

d) depth 500-1000m;

e) operating maximum pressure 1500 psi;

f) maximum air temperature 100°C;

g) permeability and porosity 1 x 10^{-3} cm/sec and 15% respectively; and

h) cap rock thickness 10m, cap rock permeability 1x 10^{-9} cm/sec.

As in hard rock, qualitative estimates of the Hazard Indices for aquifers of particular scenarios of various failure modes were made. Hazard Index assessments, especially in the case of aquifer utilization, are strongly dependent on site-specific data. Similar assumptions were made for aquifers as were made for the hard rock scheme, i.e., a site will undergo competent site selection, site investigation, design, construction and operation procedures, and monitoring activities, throughout the process. A qualitative assessment of hazards for the base case are given in Table 4-3 for the aquifer failure modes of decreased permeability and storability, loss of air, and environmental impact. The various scenarios considered were: a) clogging of pores; b) cyclic loading; c) chemical and biological reactions; d) air/water mixing; e) cap-rock leakage; f) pumping effect; g) umbrella and fingering of storage; h) translation of stored volume; i) well casing and grout integrity; and j) blowout.

4.6.4 Hazard Index Assessment for Salt

The configuration of the Huntorf facility provided the model for developing the base case. For purposes of insurance analysis, Huntorf provides the only available history of operations of a CAES facility; additional sites will have specifications peculiar to them. The technical parameters used for the base case, however, are considered to be representative of those in salt cavities generally, and to establish a useful framework for comparison of individual sites. The base case considered here is of the following configuration and geological setting:

TABLE 4-3

POTENTIAL FAILURE MODES FOR CAES IN AQUIFIER (BASE CASE)

SCENARIOS \ FAILURE MODES	DECREASE OF PERMEABILITY AND STORATIVITY			LOSS OF AIR			ENVIRONMENTAL DAMAGE		
	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure
CLOGGING OF PORE SPARE	Unknown	Moderate to severe	Possible reduction in efficiency and capacity. Could eventually lead to abandonment.	—	—	—	—	—	—
CHANGE IN PERMEABILITY DUE TO CYCLIC TEMPERATURE, PRESSURE & HUMIDITY EFFECTS	Unknown	Moderate to severe	Possible reduction in efficiency and capacity. Could eventually lead to abandonment	—	—	—	—	—	—
CHEMICAL/BIOLOGICAL REACTION	Unknown	Difficult to assess at this time	Difficult to assess at this time	—	—	—	—	—	—
AIR/WATER MINING	Low due to site investigation and design	Moderate	Loss of capacity and Low efficiency	Low	Small to moderate	Possible modification of operational procedure	—	—	—
CAPROCK LEAKAGE	—	—	—	Low to moderate due to site selection, and in-site investigation	Moderate to significant	Possible abandonment of well	Low to moderate	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to blovout.
PUMPING EFFECT	—	—	—	Unknown	Moderate to significant	Loss of capacity	Unknown	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to blovout.
UMBRELLA OR FINGERING EFFECT	—	—	—	Low to moderate due to site selection investigation and design	Moderate to significant	Loss of capacity	Low to moderate	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to blovout.
TRANSLATION OF STORAGE	—	—	—	Low due to site selection	Small to moderate	Loss of capacity and possible abandonment of site	Low	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to blovout.
BLOWOUT DUE TO LOSS OF INTEGRITY BETWEEN WELL CASING AND GROUT	—	—	—	Low to moderate	Moderate to significant	Possible operational shutdown with remedial measures. Could lead to abandonment.	Low to moderate	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to cratering and damage to surface plant
BLOWOUT	—	—	—	Low due to site selection	Moderate to significant	Probable shutdown and possible abandonment	Low	Moderate to significant	Possible pressurization of overlying aquifers. Could lead to cratering and damage to plant

a) located in seismic activity areas denoted by zones 0, 1, or 2;
b) no major faults or shear zones nearby;
c) rock type domal salt;
d) salt quality excellent and uniform;
e) depth 700-1000m;
f) operating maximum pressure 1500 psi; and
g) maximum air temperature 15°C above rock-ambient.

Qualitative estimates have been made on Hazard Indices of particular scenarios from various failure modes in salt. These generic hazard indices have been determined as input data and background knowledge for professionals in the insurance industry. It was assumed that the salt scheme will undergo competent site selection, site investigation, design, construction and operation methods and procedures, along with monitoring activities, throughout the process. The qualitative assessment of hazards for the base case are given in Table 4-4 for the salt failure modes of cavern collapse, loss of volume, loss of pressure, and environmental impact. The scenarios considered were: a) natural seismic event; b) closure due to creep; c) tectonic activity such as faulting and/or diapiric movement; d) effect of cyclic thermal and pressure loading; e) solution-mining; f) groundwater inflow; h) loss of well casing and grout integrity; and i) blowout. In Table 4-4, the likelihood, magnitude, and consequences of a scenario giving rise to particular failure modes are summarized.

TABLE 4-4

POTENTIAL FAILURE MODES OF CAES IN SALT (BASE CASE)

SCENARIOS \ FAILURE MODES	CAVERN COLLAPSE			LOSS OF VOLUME			LOSS OF PRESSURE			GRANDWATER CONTAMINATION		
	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure	Likelihood of Failure	Magnitude of Failure	Consequences of Failure
NATURAL SEISMIC EVENT	Zone 1 0.08g earthquake at surface Zone 2 0.16g earthquake at surface	Minor to no damage to cavern (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	Zone 1 0.08g earthquake at surface Zone 2 0.16g earthquake at surface	Minor to no damage to cavern (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	Zone 1 0.08g earthquake at surface Zone 2 0.16g earthquake at surface	Minor to no damage to cavern (Possible small rock-falls only)	Cleanup required in routine inspection shutdown	—	—	—
CLOSURE DUE TO CREEP	Low to moderate due to design & site selection	Moderate to significant	Possible abandonment of cavity	Low to moderate	Small to moderate for high pressure, low temperature	Possible resolution to achieve original volume	—	—	—	—	—	—
TECTONIC/DIAPIRIC MOVEMENT	Low due to site selection	Small	May be moderate to significant	Low	Small	Moderate	—	—	—	—	—	—
CYCLIC LOADING	Unknown	Moderate to significant	Possible abandonment of cavity	Unknown	Small to moderate for conservative pressure & temperature variations	Possible resolution to achieve original volume	—	—	—	—	—	—
SOLUTION MINING	Low due to site selection, design and monitoring	Moderate to significant	Possible abandonment of cavity	—	—	—	—	—	—	Low due to site selection and environmental impact studies	Moderate	Moderate depending on monitoring
WATER INFLOW	—	—	—	Low to moderate	Small to moderate	May require intermittent pumping. Possibly serious requiring abandonment	—	—	—	—	—	—
BLOWOUT DUE TO LOSS OF CASING INTEGRITY	—	—	—	—	—	—	Low to moderate	Moderate to significant	Possible operational shutdown with remedial measures could lead to abandonment	—	—	—
BLOWOUT - AIR LEAKAGE	—	—	—	—	—	—	Low to moderate	Moderate to significant	Possible operational shutdown with remedial measures could lead to abandonment	Low to moderate	Moderate to significant	Possibly serious

5.0 A RISK ANALYSIS OF UNDERGROUND ENERGY STORAGE SYSTEMS

5.1 TERMS OF THE RISK ANALYSIS

5.1.1 Types of Loss

The levels of risk attributable to different types of underground energy storage systems are best assessed by comparing their similar and dissimilar features, using current systems to establish baseline values. The comparison should make as clear as possible both the factors and the events that can give rise to a financial loss, and those that can affect the size or extent of such a loss. Financial loss is pertinent to an insurance risk assessment since insurers indemnify their clients only by payment of money. An insurer usually has the option of repairing or replacing insured property that is lost or damaged, but this simply diverts a money payment from the insured to the source of the repairs; the insurer still meets its obligation by payment of money. Sources of financial loss, therefore, are considered in this analysis. Risk elements will be examined that present a novel financial exposure relative to conventional electric utility underwriting conditions and thus give rise to questions of insurability.

A loss may occur as the result of several types of events:

- Direct property damage.

- Losses from operation interruption, which may be of different levels:

  1) An entire business process or operation may be interrupted, for which the loss of profit plus necessarily continuing expenses is usually considerable; or

  2) The operation of one or more machines or pieces of equipment may be interrupted, resulting in an "outage," for which an arbitrary or fixed value per unit time is usually established in advance. Outages and business interruptions

may be caused by either incidents on an insured's own premises, or by incidents on the premises of others that cut off some necessary service to the insured.

- An event on an insured's premises or elsewhere may be traceable to its negligence. Others can sue to recover any damages they may suffer from such an event.

These and any other financial losses are the only types of events that are considered in this analysis.

5.1.2 Approach to the Risk Analysis

There are three principal questions to be asked in a risk assessment:

1) What kind of losses can occur?
2) How frequently can each kind be expected to occur?
3) When a particular incident occurs, what is the probable extent, amount, or proportion of loss?

The results of a risk assessment will be more valuable if degree of reliability can be stated. If the assessment is based on actual loss data and on data which accurately measure the extent of exposure to loss, the degree of reliability can be stated with relative precision. With such a measure of reliability, the results of the assessment may be used to judge the extent to which a contingency allowance must be added in order to keep the underwriting or business risk sufficiently small.[1] The less the amount of available data, or the greater the uncertainty regarding the completeness of those data, the less reliable will be both the results of a risk assessment and the measure of its degree of confidence. The relative size of any contingency allowance required, therefore, will accordingly increase.

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[1]A contingency allowance is also called a premium loading factor, and is added by the underwriter to compensate for the novelty of a risk exposure.

Very little actual loss or exposure data are available for the relatively new types of energy storage systems for which risks are being assessed. The assessments are thus based in large measure on engineering, geological, and underwriting judgment. The degree of reliability is, of necessity, in part measured subjectively. A paucity of data makes the furnishing and use of reliability measures more important to prospective insurers.

The data needed for performing the risk judgments of CAES and UPH technologies were designed by relying upon experience in the field of insurance, and were then confirmed through talks with executives and underwriters of major domestic and London-based insurance organizations. The insurance representatives were selected for questioning both from those presently active in underwriting insurance risks for electric power utilities and from other industries involved with technologically innovative methods. In the absence of key information on a particular technology (e.g., loss histories), a risk assessment of that technology will be increasingly dependent on comparative evaluations, such as: (1) adjustments to existing rate schedules; or (2) information regarding insurance experience with apparently similar risks. Further discussion of the information needs of insurance underwriters is found in Section 6.1. The degree to which these coarse factors are truly analogous to accurate descriptions of the new technology determines the extent to which the third component of a risk assessment, actuarial judgment, must be asserted. A subjective element is present to some extent in most major insurance-related decisions and is also represented in the generic findings of this risk assessment. The biasing effect of subjective judgment is maintained at a minimal level by referencing the judgment only to data drawn from the current rate schedules of the insurance industry. These types of references are noted in the text.

5.1.3 Technical Basis for Risk Analysis

The following summaries, based on the findings reported in Chapter 3.0, Technical Description, and Section 4.3, Failure Modes, are utilized as the foundation of the risk and actuarial assessments.

Underground energy storage systems have been categorized for the purposes of actuarial analysis according to three major characteristics:

1) Geologic configuration of the cavity.
2) Scheduled cycle for energy storage and utilization.
3) Size of pressure differentials in the system.

Only fluids that are economic free goods, such as air and water, are considered. Essentially pure -- at least non-saline -- water will be used, in order to minimize problems of corrosion and other possible adverse chemical reactions with pumps, passages, reservoirs, other property, and persons. The types of cavities to be used for underground energy storage are found in three geologic structures:

1) Natural or human-made caverns in hard rock; also used for Underground Pumped Hydro storage.
2) Solution-mined salt domes.
3) Aquifers.

The technically possible types of stored energy systems are, therefore:

1) Balanced compressed air storage in hard rock.
2) Balanced compressed air storage in a salt dome.
3) Unbalanced compressed air storage in hard rock.
4) Unbalanced compressed air storage in a salt dome.
5) Unbalanced compressed air storage in an aquifer.
6) Underground pumped water storage in hard rock.

Pressure in a "balanced" storage cavity is kept nearly constant by use of a column of water to offset the pressure of the air that is pumped in, while the unbalanced system lacks this compensating component. The hazards involved in balanced and unbalanced systems do not appear to be different enough to require separate discussion. As a practical matter, it is accordingly necessary to make separate risk assessments of only four different types of systems, numbers 1, 4, 5, and 6 above.

The findings of the Failure Modes Analysis make clear that the geotechnical risks associated with the proposed CAES and UPH schemes may be viewed as belonging in two classes: (1) those risks associated with the actual construction of the underground structures; and (2) those associated with the operation phase of an energy storage system.[2] The distinction between the two classes is the amount of data available on the performance of the different formations in each phase of development.

There are a great deal of expertise and data available regarding the construction requirements for the different CAES/UPH facilities (i.e., excavation in hard rock). Underground construction for energy storage facilities will be considered as falling within the limits of present technology, even though greater depths than are currently excavated are involved. Therefore, the insurance coverage for construction operations will require no unusual provisions.

In contrast, certain unknowns regarding the operations phase are presently being investigated and include: behavioral response of the geologic formations to the stresses of daily temperature, pressure, and humidity fluctuation over an operating span of 30 years; stability criteria for facility operations; and other quantitative analyses describing optimum system features. While the areas of long-term risk can be defined and possible failure modes specified, the reliability of the assessments of the probability and consequence of a failure are necessarily goverened by the present experience and knowledge in the area of material response. Technical assessments of the operating characteristics of underground energy storage in each geology have been based on the track records of similar uses of the three geologic formations: petroleum products' storage in mined salt caverns; natural gas storage in aquifers; and storage of solid and liquid commercial products, petroleum and natural gas products, and highway and mining development in both natural and human-made hard rock formations.

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[2]Appendices C, E, G, H, and I describe the history and experience to date with both the construction and operation of varying types of facilities in mined salt deposits, aquifers, and hard rock formations.

5.1.4 Loss Incidents with Similar Risks

A comprehensive risk assessment relies, to a great extent, upon loss statistics of the exposure being studied. Loss history information is essential in determining the insurability of CAES and UPH. A thorough review of the information needs for underwriting may be found in Section 6.1. In the risk assessment of a technology as new as underground energy storage systems, however, the absence of a loss record necessitates substituting loss incidents from a variety of technologies which pose similar risks. Table 5-1 shows the losses referred to in this risk assessment. Notably few major incidents occurred with pressurized gas storage. The largest incident, flooding of the powerhouse of a pumped storage facility, was reimbursed by the insurer, with minor significant effects on subsequent policy terms. Further detail of loss reimbursements for these incidents provided a sketch of the loss history in "similar technologies."

5.2 INSURANCE LOSS RATES AND ADJUSTMENTS FACTORS

The first task required in a Risk Assessment of a fluid energy storage system is the classification of the potential hazards and perils (Section 3.3; Section 4.6) in a format that is handy for insurance underwriting and rating. Depending upon the specific set of conditions prevailing at a particular site (Appendix K), various modes of geotechnical cavern failure may be possible, as described in Chapter 4.0. The Risk Assessment reduced the lengthy list of untoward events that may occur to a smaller number of generalized, major perils and hazards. A list of the elements included in the definition of each peril or hazard is provided in the following text.

Using the existing rate structure, loss statistics from similar technologies, and adjustments based on actuarial judgments, the hazards were represented as the expected annual financial loss to which the utility will be exposed, per $1,000 investment. The results, in terms of Physical Damages risks, are summarized in Section 5.2.2. The assessment of Interruption of Operations rates is presented in Section 5.2.3 in the form of multipliers that will be applied to Property Damage loss rates. The components of liability risks are described in Section 5.2.4, along with the evaluation of loss rates.

TABLE 5-1

LOSSES TO SIMILAR TECHNOLOGIES

TYPE OF FACILITY	INCIDENTS	AMOUNT OF LOSS	INSURED AMOUNT	PHASE
Natural Gas Storage	Blowout	Gas lost: $800,000 Loss control: $1-1/2-$2 MM Total loss: 3% of property value	Replacement Value - $100 MM	Operation
Natural Gas Storage	Fire and explosion - 4 - property damage 2 - employee injury	Damage: 4 each incident over $25,000	Fire - $50 MM	Operation
LPG Storage	Fire	Damage: $30,000	Covered by retention - $250,000	Operation
Underground Power House	Flood	$9 MM	Approximately $40 MM (equipment value)	Construction
Above Ground Pumped Hydro	Pipes burst as a result of a boiler economizer freeze up	$100,000	Probably covered by deductible $100,000-$2 MM, depending on the equipment	Operation
Above Ground Pumped Hydro	Slight fracture in the reservoir	$50,000	Probably covered by All Risk Builders Risk Deductible - $100,000	Construction
Hydroelectric	Crane destroyed	$90,000	Probably covered by their deductible - $100,000	Construction
Hydroelectric	4 generator fires	Largest loss: $1/3 MM	Named Peril - $200 MM	Operation

The result of the Risk Assessment at this level may suffice to warrant rejection of a site as an insurable facility, or to reduce the apparent risk exposure to tolerable levels.

5.2.1 Potential Hazards and Perils

The findings of the Failure Modes Analysis are summarized in the following categories:

1. Earthquake
   The structural effects of seismicity, and cost approximations for various levels of earthquake-resistance in facilities are described in Appendix A.

2. Induced Seismicity
   Liquids, very high induced pressures, high existing tectonic stresses in the natural rock, and considerable depths of liquid penetration were all involved in projects at Rocky Mountain Arsenal and at Rangely, Colorado, as described in Section 4.3.4. This combination of elements is not included in any of the contemplated energy storage systems. Accordingly, the probability of artificial seismicity being caused by any form of liquid energy storage system seems quite small. The probability of such tremors being caused by operation of a dry compressed-air system also appears to be negligible.

3. Flooding
   Loss rates for flooding damages from rising surface waters have been developed by the Federal Insurance Administration, which manages a flood insurance program for several thousand communities.[3] Another type of flooding to which cavities can be subject is leakage of subsurface water through floor, walls, or roof. Since the federal flood insruance program is not

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[3]Section 6.3, Alternatives to Commercial Insurance, discusses the National Flood Insurance Program as a type of government-sponsored insurance.

intended to cover this hazard, preventive measures assume unusual importance. The risk assessment of flood hazards has been conducted assuming that appropriate preventive devices, as specified by engineering and design analysis of the requirements for the particular facility locations, will be implemented in cavity design (see Section 5.3).

4. <u>Loss of Volume: Wall or Roof Failure</u>
   a. Static failure
   b. Dynamic failure

5. <u>Uncontrolled Increase in Volume of Storage Cavity</u>
   Air stored under pressure may be lost in ways other than collapse or blowout of the cavity. Some of the losses of this type, outlined in Section 4.3, remain unexplained even though they have resulted in severe costs, including necessary abandonment of gas storage sites. These types of loss include:
   a. Decrease in the volume of air recovered, below the volume injected. This may start after a storage facility has been operating satisfactorily for several years.
   b. Sudden or gradual opening of pores in walls or roof.
   c. Changes in surrounding groundwater flow in aquifers, which leads to large pressure drops.

6. <u>Failure of Pressure Containers, Joints, and Seals</u>
   The principal types of pressure containers, joints, and seals that can fail are:
   a. Cavity.
   b. Subsidiary containers (casing or piping, vertical conduits, inlet and outlet shafts, underground machinery housings, or service passages to underground equipment).
   c. Joints and seals (pumps, pipes and conduits, turbines and generation machinery, access passages, and equipment shaft seals).

7. Mechanical Failure of Equipment

Special hazards that apply to equipment used for pumped-water installations underground are:

a. Mechanical abrasion or damage from non-dissolved or airborne solids.

b. Chemical corrosion.

c. Machinery breakdown.

5.2.2 Loss Assessments: Physical Damage

The foregoing summary of perils that may affect a fluid energy storage installation provides a basis for a numerical assessment of property loss potential. The estimated yearly loss rates-per-thousand are listed in Tables 5-2, 5-3, and 5-4. These are, of necessity, average figures; it is estimated that about 90 percent of CAES/UPH installations will have loss rates that fall between one-half and twice the figures shown, and that 99 percent will have loss rates that fall between one-tenth and 10 times the figures shown.

Each of the three tables covers one of the three major geologic types of storage cavity. The variance in the loss rates indicated in Tables 5-2 to 5-4 is largely due to differences in the contingency factor introduced to allow for the relative degree of novelty of the risk exposure in each geologic setting. The rates are loaded such that the appropriate allowance in each case varies from the 5 percent customary in insurance rate filings to as much as 50 percent in specific instances. This loading does not provide for expenses, profits, or special situations. Contrary to the usual insurance rating practice, whereby only a single average contingency factor is used to represent the range of novelty of the risk elements being rated, the study has made special effort to represent the full range of foreseeable loss rates, with the greatest precision possible in indicating the individual risk exposures presented by each failure mode in the geologic settings.

To adapt the tabular figures to a specific installation or site, one first must select the appropriate table and the pertinent portions of that table. One can use the Hazard Index algorithm (Section 4.1) to adjust these

TABLE 5-2

Risk Assessment of Perils to Property--Hard Rock Cavities
(Dollars)

Perils	Yearly Loss Rate per $1,000 Value Compressed Air Earthquake* Zone 1	 Zone 4	 Pumped Water Earthquake* Zone 1	 Zone 4
1. Earthquake	.70	.20	-	-
2. Seismicity induced from operations				
a. No induced pressuer	-		.01	
b. Compressed air in dry cavity, or balanced by water column	.05		-	
c. Compressed air in closed cavity partly filled with liquid	.10		-	
3. Flooding				
a. Rising surface waters	10.00		10.00	
b. Leakage through floor, walls, or roof	1.00		1.00	
4. Loss of volume from wall or roof failure				
a. Roof collapse	.50		.40	
b. Pillar or wall collapse	.10		.20	
c. Gradual roof or wall subsidence	.10		.10	
d. Lateral shift or creep of parts	.05		.05	
5. Uncontrolled increase in volume				
a. Opening of pores or creation of other openings	.20		.10	
b. Changes in groundwater flow patterns	.10		.10	
6. Failure of pressure containers, joints, or seals				
a. Cavity blowout	.10		.01	
b. Leakage through existing openings	.20		.01	
c. Water blowout	.20		.01	
d. Joint failure	1.00		.50	
e. Seal failure	1.00		.50	
7. Mechanical failure of equipment				
a. Abrasion or breakage	Use Boiler Manual Rates		Use Boiler Manual Rates	
b. Chemical corrosion				
c. Breakdown				

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuinness Associates.

TABLE 5-3

Risk Assessment of Perils to Property--Salt Domes or Cavities
(Dollars)

Perils	Yearly Loss Rate per $1,000 value Compressed Air Earthquake* Zone 1	Zone 4
1. Earthquake		
a. No water or other liquid present	.70	.20
b. Partly filled with liquid	.80	.30
2. Seismicity induced from operations		
a. Compressed air in dry cavity	.01	
b. Compressed air in closed cavity partly filled with liquid	.10	

	Natural Void	Dry Mined & Pillared	Solution Mined
3. Flooding			
a Rising surface waters	10.00	10.00	10.00
b. Leakage through floor, walls, or roof	2.00	3.00	6.00
4. Loss of volume from wall or roof failure			
a. Roof collapse	3.00	4.00	20.00
b. Wall or peripheral collapse or major rock fall	1.00	2.00	5.00
c. Gradual roof or wall subsidence	1.50	7.00	10.00
d. Lateral shift or creep of parts	1.00	2.00	5.00
5. Uncontrolled increase in volume			
a. Opening of pores or creation of other openings	2.00	4.00	10.00
b. Changes in groundwater flow patterns	1.00	1.00	2.00
6. Failure of pressure containers, joints, or seals			
a. Cavity blowout	.10	.10	.20
b. Leakage through existing openings	.20	.20	.50
c. Joint failure	1.00	1.00	1.00
d. Seal failure	1.00	1.00	1.00
7. Mechanical failure of equipment	Use	Use	Use
a. Abrasion or breakage	Boiler	Boiler	Boiler
b. Chemical corrosion	Manual	Manual	Manual
c. Breakdown	Rates	Rates	Rates

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuiness Associates

TABLE 5-4

Risk Assessment of Perils to Property--Aquifers
(Dollars)

Perils	Yearly Loss Rate per $1,000 Value Compressed Air Earthquake* Zone 1	Zone 4
1. Earthquake		
a. Porous rock	.70	.20
b. Porous sand or other small particles semi-suspendible in water, partly filled with liquid (resonance or plastic effect)	1.25	.40
2. Seismicity induced from operations		
a. Air pressure confined to porous rock or particulate material	.05	
b. Air pressure zone overlying materially fractured or faulted hard rock	.15	
3. Flooding (damage to surface installations)		
a. Rising surface waters	10.00	
b. Leakage into aquifer	-	
4. Loss of storage volume from wall, roof, or aquifer failure		
a. Roof caprock failure	.75	
b. Plugging of pores	2.00	
5. Uncontrolled increase in volume		
a. Opening of new pores or creation of other openings	5.00	
b. Changes in groundwater flow patterns	2.00	
6. Failure of pressure containers, joints, or seals		
a. Caprock blowout	1.50	
b. Lateral blowout (umbrella effect)	1.50	
c. Joint failure	1.00	
d. Seal failure	1.00	
7. Mechanical failure of equipment		
a. Abrasion or breakage	Use Boiler Manual Rates	
b. Chemical corrosion		
c. Breakdown		

*Excluding the ten West Coast states and Hawaii, which have higher rates.

Source: Adapted from data provided by John S. McGuinness Associates.

average figures for known departures from those provisions for loss prevention (Section 5.3) and for known departures from average geologic conditions at the site being considered. Such detailed analysis will be necessary in order to conduct a full actuarial assessment of any particular site.

5.2.3 Loss Assessments: Interruption of Operations

Physical damage to installations and equipment can give rise not only to repair or reconstruction costs but also losses due to reduction of income and extra expense caused by interruption of operations. The items for which coverage is usually available are listed in Table 5-5.

Machinery insurance premiums are typically quoted in dollars per unit or object, rather than as loss rates. A high proportion of such premiums is devoted to expense since all insured objects are inspected, and some must, by law, be inspected at least once yearly. The percentages shown in Table 5-5 are thus only roughly appropriate for machinery insurance. Actual premiums are available from the industry rate manuals, however, for just about any object.

5.2.4 Loss Assessments: Liability Hazards

Underground energy storage systems present few hazards of third-party loss that are not faced commonly by public and private power utilities. CAES and UPH systems offer no hazards that are not already encountered in connection with underground mines, oil fields, sulfur extraction, subway construction, dam construction, and possibly some chemical extraction and production.

A limited number of insurers specialize in underwriting the liability exposures of very large industrial firms or of particular types of unusually hazardous operations such as petroleum extraction, underground mining, underground or underwater construction, or chemical processing. The expertise of these insurers and the operating and loss experience of these types of firms are directly applicable to underground energy storage systems. Much of this expertise is exhibited in the rate filings of major insurers and of rating organizations such as Insurance Services Office.

TABLE 5-5

LOSS RATE ADJUSTMENT FACTORS FOR INTERRUPTION OF OPERATIONS COVERAGE

	Percent of Physical Damage Rate*
Business Interruption, during the period required to restore the damaged installation to operating condition:	
Gross earnings:	
Including ordinary payroll	70
Excluding ordinary payroll	80
Extra Expense:	
Of securing power from alternate sources	200
Debris removal	200
Other	200
Outage or loss of use of specific items of equipment, for a specified number of days or weeks, at a specified rate per unit time	varies

* The assumed physical damage and machinery insurance rates are those which are based on an amount of insurance equal to at least 80 percent of the full value of the insured property.

Source: Adapted from data provided by John S. McGuinness Associates.

Determination of liability hazards requires identifying the pertinent data from these sources. The key liability hazards which are connected with construction and operation of fluid energy storage systems are listed in Table 5-6, together with relevant risk and rating estimates.

Table 5-6 differs from Tables 5-2 to 5-5 in that gross insurance rate estimates, not simply loss-cost estimates, are presented. These liability rate estimates are approximately one and one-half times the pure loss-cost estimates. The rates assume a limit of $25,000 per occurrence for bodily injury liability and $5,000 per occurrence for property damage liability. Coverage of $10,000,000 per occurrence will increase the bodily injury rates by a factor of 10 for operations, and by a factor of 20 for products liability. The respective property damage factors are about 4 for operations and 8 for products.

Different bases of premium calculation apply to different types of operations and different products exposures. These bases are specified in the table.

5.3 LOSS PREVENTIVE MEASURES

Reports from geologists and engineers have provided certain measures for avoiding loss incidents. These reports have considered factors such as:

- The measured characteristic of the different materials from which the storage cavities may be formed.
- Design features of man-made cavities, reservoirs, and conduits.
- Operational procedures.

The risk assessment discussed in this report is based, generally, on the assumption that these preventive measures will be implemented. In the absence of particular measures for reducing the apparent loss potential, adjustments to the rates in Section 5.2 will be required, as indicated by the new Hazard Index value that will be generated.

TABLE 5-6

Risk Assessment of Liability Hazards for Underground Energy Storage Installations
(Dollars)

	Type of System		OPERATIONS: Basic Rates				OPERATIONS: Surcharges: All Areas			PRODUCTS -OR- COMPLETED OPERATIONS		Basis of Premium[1]	
			Bodily Injury Liability		Property Damage Liability		x	c	u	Most States			
	Compressed Air	Pumped Water	Urban	Other	Urban	Other	Explosion	Collapse	Underground Damage	B.I.L.	P.D.L.	Operations	Products
Construction of Installation													
Excavation	x	x	2.40	1.60	.99	.94	2.25	incl.	.50	.39	.26	Payroll	Receipts
Mining, not surface	x	x	.16	.12	.10	.043	.05	-	-	-	-	Payroll	-
Liquid spoil (brine), sale or disposal	x		-	-	-	-	-	-	-	.07	.10	-	Mft[3]
Solid spoil, sale or disposal	x	x	-	-	-	-	-	-	-	.09	.05	-	Sales
Irrigation or Drainage System Construction	x		.81	.53	.45	.43	.55	-	.10	.15	.14	Payroll	Receipts
Tunneling	x	x	.81	.53	.45	.43	2.25	incl.	.50	.40	.28	Payroll	Receipts
Core Drilling	x	x	.87	.51	.63	.54	-	-	-	.09	.05	Payroll	Receipts
Drilling	x		.87	.51	.63	.54	-	-	-	.25	.11	Payroll	Receipts
Concrete Construction--including foundations, making, setting up, or taking down falsework, forms, scaffolds, or concrete distributing apparatus	x	x	1.70	1.10	.28	.28	-	-	-	.25	.10	Payroll	Receipts
Dam or Reservoir Construction		x	2.00	1.70	.80	.75	1.70	incl.	.25	.25	.10	Payroll	Receipts
Levee Construction	x	x	1.60	.66	.76	.73	-	-	-	.15	.14	Payroll	Receipts
Millwright Work--erection or repair of equipment or machinery	x	x	.96	.72	.35	.34	-	-	-	1.00	.27	Payroll	Receipts
Operation of Completed Installation													
Electric Light or Power Firms:													
Companies	x	x	2.10	1.90	.45	.27	.25	incl.	.25	-	-	Payroll	-
Rural Electrification Administration Cooperatives	x	x	4.80	3.70	.99	.72	.25	incl.	.25	-	-	Payroll	-
Blowout or cratering from pressure cavities	x		-	-	-	-	-	-	-	.05	.10	-	Mft[3]
Chemical, dust, or noxious gas pollution of air	x		-	-	-	-	-	-	-	.05	.03	-	Mft[3]
Chemical pollution of surface water		x	-	-	-	-	-	-	-	.02	.01	-	Mft[3]
Chemical pollution of underground water	x	x	-	-	-	-	-	-	-	.02	.01	-	Mft[3]
Collapse or subsidence of land surface on others' property:												-	Mft[3]
Salt dome: natural void	x		-	-	-	-	-	-	-	.07	.40		
Salt dome: dry mined & pillared	x		-	-	-	-	-	-	-	.06	.12		
Salt dome: solution mined	x		-	-	-	-	-	-	-	.20	2.00		
Other	x	x	-	-	-	-	-	-	-	.05	.10		
Operation and existence of reservoirs		x	-	-	-	-	-	-	-	incl.	incl.	-	Mft[3]

[1]Bases of premium are $1,000 of payroll, $1,000 of receipts and thousand cubic feet of volume or capacity

Source: Adapted from data provided by John S. McGuinness Associates.

The loss preventive measures discussed below fall within one or more of the following categories: (1) siting; (2) design and construction; (3) equipment specifications; (4) operational procedures; and (5) monitoring procedures and maintenance provisions.

Siting

The success of any CAES or UPH scheme will require that the site of the plant meet specific and stringent requirements. One criterion which must be met is that the geology be suitable for the construction of such caverns. In choosing a site, the following natural hazards should be avoided:

1) High seismic activity;

2) High tectonic stresses;

3) Highly fractured or faulted rock;

4) The presence of aquifers in the proposed cavern area; and

5) High permeability of rock mass.

In the case of salt and aquifer storage schemes still other requirements must be met. For salt caverns there must be a large mass of preferably homogeneous salt whose purity and crystaline structure meet appropriate standards. Important also is the proximity of a saline aquifer, salt marsh, or other suitable receptacle in which the saline solution produced during the solution-mining of the cavern may be disposed without causing environmental damage.

In the case of aquifer storage there must, of course, be an aquifer with good cap-rock above to seal it with adequate closure and proper geometric configuration.

Other siting factors within the control of planners and designers are more general in applicability. These include:

- Placement of buildings, equipment and machinery, and other concentration of capital value within a radius that includes the area most likely to be affected by incidents in the underground structure should be minimized.

- Both the location of the site and the use of emission control measures must be considered in order to limit the incidence of adverse environmental effects, such as particulate emissions (alkaline metals, salt, silica and rock dust); localized meteorological alterations caused by water vapor release; minerals dissolved from the floor of a surface reservoir; and other environmental pollutants.

Design and Construction

- Construction and design standards promulgated by the U.S. Department of Energy and other authorities should be fully met, including design safety factors. For example, a dynamic tensile strength (under pressure cycling) of only 40 percent of the static tensile strength is posited for some types of hard rock. Using a design safety factor of 3, design calculations for cavern walls and pillars would be based on not over 13 percent (i.e., roughly one-third of 40) of the static strength.

- Compressed-air caverns and all associated structures and equipment should be floodproofed against at least 100-year floods and preferably against 500-year floods.

- Damping should be sufficient to prevent damage from vibration to penstocks and other water conduits.

- Provisions must be made for rapid access to undergound and other installations that:

  - Permit operating and emergency personnel (e.g., fire-fighting and loss control) to reach all areas and to enter, take temporary refuge if necessary, and leave safely.

- Permit removal, repair, and reinstallation of all equipment.

- Cavern pillar design must be based on recognition of potentially high tectonic stresses present at the proposed construction depths.

- Sensitive system components and underground equipment should be compartmentalized by electrical fusing, bulkheads and watertight doors, valves and cutoffs, and other means sufficient to localize loss or damage.

Equipment Specifications

- Turbine blades, pumps, and other mechanical parts contacting water or salt-laden air should be constructed of a type of metal alloy capable of resisting corrosion and pitting from all chemicals likely to be encountered in solution at the site.

- Provisions should be made for adequate drainage and pumps to remove water from power houses.

- Fire-preventive and protective devices and measures (e.g., automatic sprinklers, carbon-dioxide systems, and other fire extinguishing devices; fire resistive constructin; etc.) should be maintained that are sufficient to qualify a site for Highly Protected Risk status by insurers.

- Emission control devices, as described under Siting, must be in place.

Operational Procedures

- The rate of pressure change in compressed air systems should be controlled, below some maximum limit.

- The operating temperature in compressed air systems should be maintained within a range appropriate for the given site.

- Security provisions should be made (e.g., fences, patrols, no trespassing signs, guards at entries, check-in and check-out registers, etc.) against public or unauthorized intrusion into reservoirs, power houses, and other parts of an installation.

- Adequate means should be made for selecting and training operating personnel in order to minimize human error.

Monitoring Procedures and Maintenance Provisions

- Monitoring instrumentation (e.g., hard rock creep meters, strain meters, magnetrometers, seismometers, and tiltmeters) should be installed on the surface and/or in the cavity of a facility located in any of the nine westernmost continental states or in any other state in earthquake insurance rating zones 1 or 2 (these approximate seismic zones 3 and 2).

- Trash racks, screens and other related devices should be installed and properly maintained to ensure protection of equipment, passageways and other installations from stone fragments, silt, dust, and other foreign matter capable of causing excessive wear, breakage and other damage or impairment of function.

- A program of regular maintenance and periodic physical inspections of the physical plant (including reservoirs) should be instituted to ensure detection of leaks, deterioration, and other possible causes of loss.

- Automatic alarm and safety shut-off devices (including blowout diaphragms and cut-off valves to contain or safely channel compressed air blowouts) which cover as much of the system as practicable and are designed to offset as far as possible the effects of human error should be installed.

5.4 ANALYTIC TECHNIQUES FOR REDUCING RISK

The size, shape, materials, and other characteristic of the cavities used for energy storage very tremendously. The enormous variation in cavity characteristics gives rise to a correspondingly wide range in the degree of uncertainty abut probably loss costs. Uncertainty is lowest in a fully man-made, hard rock cavity with the following characteristics: uniform galleries; evenly-spaced pillars and other members of known and tested dimensions; condition and materials; the use of monitoring and other measuring devices; known (bore-tested) capping and overburden; and located in an area in which seismic activity is known to be low. It is perhaps highest in an aquifer or naturally void salt dome from which no cores have been taken and no seismic tests have been made; the size and shape and supports of which are at best vaguely envisioned; in which no instrumentation has been installed; and which is located in a zone of high seismic activity. A view of a best case and a worst case such as this suggests an approach to measuring the quality and completeness of information that is available for conducting a risk assessment of a specific site.

If the quality or degree of completeness of available information is known, a more dependable allowance for contingencies can be made. For example, if little information is available but it is known that the data at hand are among the most important that are needed, a lower contingency factor is needed than would be the case either if definitely less important data were available, even in much greater quantity, or if the relative importance of the available data were completely unknown.

5.4.1 System Optimization Flow Analysis

Many of the risks associated with the construction and operation of energy storage schemes will be minimized by the proper site selection and design procedures. An outline of a typical system optimization procedure is shown in Figure 5-1.

The earliest time that a utility could reasonably approach an insurance company for insurance of a proposed CAES or UPH project is after the Preliminary Design Phase. At this time the utility will have performed a geological exploration of the proposed site and have prepared a design plan based on the results of this survey. In assessing the risks associated with the utility's plan, an insurance company should be satisfied that all the possible failure modes associated with the proposed design have been addressed, and satisfactory answers found to potential problems.

5.4.2 A Structural Engineering Approach

The geologic analyses make clear the difficulties in estimating the probabilities of loss and the probable degree of error in such estimates, particularly in efforts to extend general, theoretical information to specific cases. An analytic approach such as that used in structural engineering may be of help in reducing these difficulties. This technique will not supply missing information; but if applied in the analysis of cavities contemplated for underground energy storage, the type and extent of missing information that is needed for a complete engineering analysis will be determined. Structural engineering expertise should assist in judging the relative importance of this information to the accuracy of a full risk assessment. Based on this actuarial judgment, an evaluation can be made of the extra risk arising from lack of information and the size of contingency loading required to offset that extra risk. Computer programs have been produced to perform structural analysis of this sort.[4]

A structural engineering technique can be used for an analysis of the cost-effectiveness of probes, tests, borings, or other investigations of a site. It can often provide a single uniform procedure for comparative analysis of all types of sites, providing insurance underwriters with a good idea of the appropriate size of contingency loading-- a greater degree of imprecision in the estimate requires a larger contingency loading.

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[4]See, for example, R. Steklasa, "Wide Interest in Building by Computer Data System," The Financial Post, 19 May 1979, p. 16.

It is helpful to outline examples of the information that might be pertinent to a structural engineering analysis of an underground energy storage facility. This is a partial list of the types of data and information required:

a. Structural materials and their characteristics:

(1) Kind(s) of rock, shale, and other material surrounding the cavity;

(2) Formation integrity: presence or absence of faults and fissures, homogeneity or heterogeneity of key elements such as cap-rock and walls, degree of porosity, resistance to fatigue and to changes in temperature and pressure;

(3) Compressive, tensile, and shear strengths; elasticity, unit weight, stiffness, and other measurable characteristics of each natural present in significant quantity, and;

(4) Quality of water used in a balanced compressed air system, and availability of chemical additives that could reduce, at affordable cost, the air-dissolving capacity of the water; form a barrier film at the water/air interface; or otherwise reduce the likelihood of a blowout from the "champagne effect".

b. Dimensions and arrangement of materials:

(1) Length of clear spans of salt dome ceilings or of roofs of other cavities;

(2) Regularity of shape and thickness of cap-rock over cavities, e.g., whether an upillared roof is actually a hemispherical dome or is generally flat, or whether cap-rock extends in a solid and generally uniform mass well beyond the edges of the cavity it covers, and;

(3) Relation of the thickness, uniformity, stiffness, and strength of rock or other load-bearing elements to their spans and loads.

c. Degree of interdependence between various structural elements of a cavity, and the consequent probability of a complete versus partial collapse or failure.

A particular site will produce analytic requirements more extensive and of greater detail than indicated here. Nonetheless, this concept will reduce the apparent risk of utilization of the site by informing the insurer of outstanding data needs, and the relative importance of the lacking knowledge to a thorough risk assessment.

5.4.3 Network Analysis

By now it should be safe to assume that in constructing an underground energy storage facility, both the client utility organization and the general contractor will ensure that progress is controlled by a network analysis. The procedure used may be the critical path method (CPM--a deterministic approach). The considerable advantages of these network-analysis methods to control routing and scheduling of work, as well as costs, are well documented, as are the methods for their utilization.

It would be beneficial, however, to subject site analysis (including the structural engineering analysis portion thereof) to CPM or PERT time and cost control. A comprehensive basic network would result from a cooperative endeavor to perfect it by use on the first few projects to be undertaken. Thereafter the developed network would be available for all future projects. Its use would contribute much to ensuring that all cost-effective information had been obtained on each project. This should in turn minimize the risks due to imperfect information that would be faced by the utilities, contractors, and insurers. Similarly, uneconomic information searches, in which less value is added to the outcome of a decision than the costs incurred in securing it, would be in large measure avoided.

6.0 INSURANCE IMPLICATIONS

6.1 CONDITIONS OF UNDERWRITING ANALYSIS FOR ELECTRIC POWER UTILITY RISKS

Electric Utility Insurance

The conditions of operating an electric power utility comprise a unique set of risks which give rise to demand for accordingly unique insurance coverage. Electric utilities are a class of underwriting opportunity for which special forms and coverages have been developed by the insurance industry over the years. Briefly, among primary factors which set the industry apart are:

1. Relatively high values at risk and equipment with extremely high unit values.

2. Large and specially designed machinery having extensive replacement time.

3. Generally low hazard occupance, but with localized areas of heavy fire loading consisting of hydraulic systems, hydrogen coolant, cable insulation, lubricant, and fuel storage.

4. Lack of standby or reserve generating capacity in the event of emergency shutdown.

5. Generally remote locations lacking adequate public or private emergency response facilities.

These factors have led in the past to the underwriting of utilities, whether publicly or privately owned, on either a subscription-type manuscript policy in which several insurance companies participate or on a layered basis with substantial primary self-retention on the part of the insured. A specialized segment has evolved from the larger international insurance industry, consisting of firms whose business includes underwriting the unusual operating risks of electric utilities. Such specialization of underwriters is the case with reinsurance of electric utility risks, as well as with direct insurance.

Given the development of a viable market for primary insurance for CAES and UPH systems, it may be presumed that an appropriate reinsurance market would be established simultaneously. Using the preceding technical and actuarial sections of the report as the basis for comparison of CAES/UPH systems with similar technical risks (the similar risks which were examined are described subsequently in this chapter), it appears likely that the necessary insurance and reinsurance facilities can be implemented by the present private-sector insurance underwriting framework. The London markets will most likely take the lead role in defining any reinsurance market that finally develops for CAES/UPH risks. The impetus contributed by the group of utility insurers located in Bermuda may be somewhat less, but participation by Bermuda underwriters at all levels will be nonetheless important in the dimensions of the insurance policies which are ultimately available. Further, it is reasonable to expect that the aggregate capacity of both the primary and reinsurance markets will ultimately be adequate to accommodate the forecasted scale of implementation of CAES and UPH systems.

The inherent insurability of CAES and UPH systems does not appear to be an impediment to commercialization of these systems over the long term. In a short-run perspective, the problem facing utility risk managers attempting to procure insurance coverage for CAES/UPH investments will be similar to that commonly involved with insuring other novel technical risks. The market may initially be somewhat limited to captive or specialty insurers and surplus lines, broadening gradually to maintain a size consistent with the accumulated loss data regarding such facilities. The size and types of underwriters engaging this sort of risk at any given time will largely determine the brokering requirements for CAES/UPH coverage, i.e., whether adequate insurance coverage may be obtained through excess lines and layering or by direct insurance with adequate reinsurance of a shared risk or other type.

Analysis Framework

The scope of this study includes the underwriting factors that distinguish electric power generating utilities from other industries. Moreover, it has proved useful to further sub-categorize electric utility risk management concerns under two headings, containing (1) coverages which a utility might pursue to protect from the ordinary property and casualty risks of a plant or other operating investment, and (2) the modified or extraordinary insurance policies that an electric utility would want in order to be protected from the novel loss exposure presented by technically innovative operations. The insurance policies so indicated are of concern in this report if, in the former case, the terms or scope of the coverage for the ordinary operating risks is affected by use of a CAES/UPH system. For the latter, the focus of the study has been on identifying the insurance policies demanded by these novel situations. Risk managers of some major electric utilities which are considering installation of CAES or UPH systems expressed some additional concerns of a utility-specific nature, and these were addressed as well in the insurance analysis.

Data Needs for Underwriting

Risk management programs at electric utilities vary with the corporate policies as implemented by risk managers at each company. As the insurance coverage thereby requested varies in levels, scope, and intent, so the decisions of potential insurers with regard to underwriting a given risk and in terms of the premium structure which is levied will depend upon the operating records and the prevailing conditions at individual utilities. The basic information required pursuant to underwriting decisions is virtually a common standard throughout the insurance industry. Faced with a novel risk exposure, the relative importance of the different bits of information required by underwriters varies according to the apparent composition and degree of the new risk; greater depth of information regarding certain aspects of the system being insured may seem called for. Nonetheless, the schedule of areas in which information will be required is fairly constant.

The schedule is headed by a requirement for quantitative historical loss records of the technical system which is to be insured. Statistical loss records of operation of either CAES or UPH technology are effectively sparse for the purposes of this report. There are no operating UPH facilities; the only active CAES facility (see Appendices F and G) had been in existence for only a few months at the time such data were incorporated in the analysis. The implications of these data were, nonetheless, included in the actuarial assessment described in Chapter 5.0. Most insurance policies are based on well established rate schedules which reflect actual loss records for the appropriate risk category over a significant period of time. The untried status of the underground energy storage technology, however, imposes information requirements different from standard electric power utility exposures.

Traditional information sought by insurers for first-of-a-kind technologies such as CAES and UPH includes:

- o Utility risk management histories and regional data.

  Although historical loss data may not be available for a proposed technology, loss statistics will be compiled for the applicant company's operations. The company's experience with insurance and operating losses and its track records managing new technologies both influence underwriting judgment. Loss data for the geographic region that will host the new installation will be reviewed, to enable underwriters to generate profiles of historical patterns in the area of natural perils (floods, earthquakes, etc.).

- o Corporate financial data.

  Corporate financial background data (e.g., assets, revenues, payroll, debt) are used to establish certain insurance rates.

- o Extensive technical data on the proposed installation.

  Technical or theoretical data will not replace and do not always constitute a temporary substitute for loss experience. Evidence of a thorough technical assessment, however, will be necessary. Such an assessment for CAES or UPH should specify the following:

  - Siting and Geological
    - Site selection procedures

- Site and generating facility location (e.g., flood or earthquake zones
- Theoretical material behavior estimates
- Geological specifications (including data on the integrity of the overburden)
- Age of the cavity (if not human-made)

- Engineering and Equipment
  - The effects of air impurities on equipment (particularly relevant to CAES in salt domes)
  - Data on subsidence, underground hydrology, explosion factors
  - Geodetic and flood surveys
  - Design or equipment characteristics unique to CAES/UPH

- Operations
  - Program plan for maintenance and monitoring
  - Safety factors (e.g., adequate fire protection, emission controls, alarm systems)
  - Security

The terms of insurance policies available for use with new technologies will be most favorable if the prospective client has demonstrated to the underwriter a thorough understanding of the new concept both technically and in terms of the corporate loss exposure.

Insurance for Similar Technical Risks

An absence of loss histories is characteristic of new technical risks, in which case insurability will be determined by an analytic comparison of the new exposure with technical risks which are apparently similar. In the absence of loss data, a realistic substitute must be identified in order to encourage the availability of insurance for the new risk. The risks presented by underground energy storage systems are unusual not so much because any one component of the technology is unique as because the technology presents a unique combination of elements. These elements are:

1. Physical location of properties at risk in underground geologic structures.

2. Storage of gas at significant pressures underground, or high heads for hydroelectric operations.

3. Stresses imposed on natural and installed facilities by regular, frequent cycling of storage fluids.

CAES and UPH are not unusual, in other words, owing to any one or two of the aspects of underground construction, nor because geologic caverns will be used for storage vessels, nor even due to the use of large differentials in the elevations of water basins at either end, or of storage pressures used; all are familiar processes to both underwriters and to engineers. Technologies have been employed for several years, one or the other of which demonstrates each of these system components.

The list of similar technologies which were examined in order to facilitate the insurance assessment on a comparative basis includes:

1. Pressurized storage of natural gas in geologic formations
2. Conventional hydroelectric facilities
3. Pumped hydro storage
4. Coal mining and tunneling

The insurance policies used for these operations reflect to a large degree the accumulated loss records and summarize inherent risks of the technology involved, all loaded appropriately for insurers' risks, costs, and profits. The experience of corporate risk managers in obtaining insurance, the events of negotiations, and conversations with the underwriters and brokers involved with the similar technical risks provide a realistic background upon which to assess the risks and insurance provisions necessary for CAES and UPH.

<u>Natural Gas Storage.</u> Utilities engaged in the storage of natural gas deploy the product in several types of underground structures, including:

aquifers, salt domes, excavated cavities, abandoned coal mines, and depleted gas and oil wells. Table 6-1 lists some of the facilities used this way in the U.S., in terms of cavity-type, storage pressures, and cavity depths. The companies surveyed were selected because the gas is stored at pressures equal to or exceeding the pressures forecast for energy storage system use, and because system cycling can occur on a daily or even hourly basis. Although the physical and chemical properties of stored gas vary markedly from those of compressed air, important points of similarity of loss exposure remain.

All of the gas storage facilities were covered by conventional gas utility insurance, included under the utility's blanket or All Risk policy.[1] Underground storage was considered by the gas utilities to present less of a liability loss exposure than did other gas operations, with velocity and rate of flow on extraction considered to be more important risk engineering variables than the frequency of cycling. Coverage typically extends only to plant assets, excluding the product. Terms of coverage for natural gas storage policies are summarized in Table 6-2.

Hydroelectric Facilities. The similarities between underground pumped hydro and conventional hydroelectric facilities span the plant, equipment, and design characteristics. Heads are lower for the conventional mode, but operating specifications such as turbine RPM and machinery specifications are of standard design.

A significant number of utilities in the U.S., particularly those with a large number of hydroelectric facilities, are part of public utility systems, i.e., either state- or municipally run. Several public utilities were contacted in order to determine any special insurance requirements for such operations. Contacts with these utilities revealed no significant differences between their insurance programs and those of the private sector.

[1] A thorough review of gas utility insurance programs may be found in 1978 Insurance Practices in the Gas Utility Industry, prepared by the American Gas Association.

TABLE 6-1

NATURAL GAS STORAGE INSTALLATIONS 1/

COMPANY/LOCATION	CAVITY TYPE	STORAGE PRESSURE (psi)	DEPTH (ft)
Illinois Power Co.	aquifer	852,1346	2140,3250
Natural Gas Pipeline of America (IL)	aquifer	1085,1145	2260,2505
Peoples Gas, Light & Coke Co. (IL)	aquifer	1750	4100
Central Illinois Public Service	aquifer	1300	2700
Midwestern Gas Transmission Co. (IL)	aquifer	1300,1975,2000	792,794,820
Northern Indiana Public Service	aquifer	1100	3020
Citizens Gas & Coke Utilities	aquifer	810	2050
Indiana Gas Co.	aquifer	730	1500
Texas Gas Transmission Corp. (KY)	aquifer	870	2025
Northern Natural Gas (NB)	aquifer	850,1350	NA
Gas Co. of New Mexico	aquifer	1150	2350
Mountain Fuel Supply Co. (UT)	aquifer	1090,1100	1831,2445
Washington Natural Gas Co.	aquifer	855,1275 psig @ -2200'	2531,3157
Mountain Fuel Supply Co. (WY)	aquifer	1676	3479
Southeastern Michigan Gas Co.	salt cavity	1200	2250
Trans-Continental Gas Pipeline Corp. (MS).	solution mined cavern	4000	6200
Saskatchewan Power Corp.	salt cavity	2500,2200,2000,3000	3947,3578,3345,5370
Michigan Consolidated	depleted gas wells	630-2000	1003-3670
Consolidated Gas Supply (PA)	depleted gas wells	710-4200	1493-6674

NA - Not Available

1/ Installations listed have storage pressures over 700 psi

Source: "Survey of Underground Gas Storage Facilities in the U.S. and Canada." Prepared by the American Gas Association, Washington, D.C. 1978.

TABLE 6-2

CURRENT INSURANCE COVERAGE FOR NATURAL GAS STORAGE FACILITIES

	NAMED PERIL	DIFFERENCE IN CONDITIONS 1/	CASUALTY 2/
LIMITS	$10-$20 MM	$2-$30 MM	$50 MM
RETENTION	$10,000-$500,000	$50,000-$250,000	$250,000-$500,000
PREMIUMS 3/	$25,000-over $1 MM		$50,000-over $1.5 MM

1/ D.I.C. coverage is frequently combined with Named Peril to form an All-Risk policy.

2/ Includes CGL and Workers' Compensation.

3/ Premium estimates from "1978 Insurance Practices in the Gas Utility Industry." Prepared by The American Gas Association.

A federal system such as the Tennessee Valley Authority self-insures both its property and liability exposures. Two municipalities, Los Angeles and Seattle, have chosen not to purchase property insurance for their dams or power houses. Liability coverage for the hydroelectric facilities is included in each city's general liability policy.

The State of Vermont owns a dam, and a private utility owns and operates the generating plant. Vermont does not have liability coverage which is structure-specific; however, the dam is covered as part of a state-wide policy. The private utility has standard commercial insurance for the generating plant but is in no way responsible for the dam. Another state agency, the Power Authority of the State of New York, insures its three hydroelectric facilities (and one fossil plant) under a master contract policy. This is a subscription-type policy underwritten by 18 insurance companies. The Power Authority only self-insures for physical loss or damage to earthen dykes. Their policies contain no exculsions with regard to dam collapses, floods, or earthquakes. The Sacramento Municipal Utility District (S.M.U.D.) obtained business interruption and extra expense coverage in addition to standard commercial utility insurance.

Property exposures for these technologies (as well as for CAES and UPH) are associated with the larger equipment mandated by higher heads, and with the threat of flooding in power houses. Current insurance coverage for hydroelectric and pumped storage facilities is specified in Table 6-3.

Pumped Storage. Pumped energy storage (including above-ground pumped hydro) is a precursor of UPH. Pumped storage installations are generally of two types: (1) those using both pumped water and natural run-off for generation; and (2) those which generate power by recirculating the water between lower and upper reservoirs.[2] Pumped storage facilities may be introduced in "any location where there is a difference in elevation between two areas that are suitable for creation of reservoirs and sufficient water is available to

[2]Federal Power Commission, 1977. Hydroelectric Plant Construction Cost and Annual Production Expenses, Nineteenth Annual Supplement, 1975, p. X.

TABLE 6-3

CURRENT INSURANCE COVERAGE FOR HYDROELECTRIC AND PUMPED STORAGE FACILITIES

	NAMED PERIL	DIFFERENCE IN CONDITIONS 1/	BOILER AND MACHINERY	CASUALTY 2/
LIMITS	$200 MM - $3 B		$15-$50 MM	$30-$50 MM
RETENTIONS 3/	$100,000 - $500,000		$100,000 - $2 MM	$150,000 - $500,000
PREMIUMS	.03-.08/$100 insured value		Premiums are a function of the equipment's age and size	NA

NA = Not Available

1/ D.I.C. coverage is frequently combined with Named Peril to form an All-Risk policy.

2/ Includes CGL and Workers' Compensation.

provide for initial reservoir filling and water make-up."[3] The basic rationale behind the two technologies is similar, i.e., using water power for peaking capacity by converting low-cost, off-peak pumping energy to high value peaking energy. The Cabin Creek pumped storage facility owned by Public Service Company of Colorado has a design head of 1,226 feet; which is within the range of heights estimated for UPH sites.[4] Another similarity is the use of reversible pump/turbine, motor/generator units.

Coal Mines and Tunneling. Companies engaged in underground construction are knowledgeable about the special risks associated with such work. Insurance for the underground part of those installations covers equipment only. As with the gas product stored underground, neither the coal in coal mines, nor the subway tunnels, *per se*, are insured. Distinguishing the construction and operating phases is of special importance in insurance for the companies involved in underground construction. During construction, the property coverage allows for restoration (to the original condition) or reimbursement, in the event of a cave-in. Once the facility is operational, this is no longer available, and only actual property damage is covered. The terms of coverage are generalized in Table 6-4.

Insurance Experience at the CAES Facility in Huntorf, West Germany

Construction. The above-ground installations, those relating to the construction of the underground caverns as well as the power house and machinery, were covered by standard all risks insurance provided by the contractors. Underground operations were covered by an "adapted" all risks policy. No coverage was sought for perils involving geotechnical risks (cave-in) because neither the engineers nor the contractors were required to guarantee the "operational quality" of the completed caverns.

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[3]Harza Engineering Co., 1977. Underground Pumped Hydro Storage and Compressed Air Energy Storage, An Analysis of Regional Markets and Development Potential. Prepared for Argonne National Laboratory, ANL-K-77-3485-1, p. I-18.

[4]"Design head" is the hydraulic head under which a turbine is designed to operate at maximum efficiency.

TABLE 6-4

CURRENT INSURANCE COVERAGE FOR
COAL MINING AND UNDERGROUND CONSTRUCTION 1/

CONSTRUCTION PHASE

	ALL-RISK, BUILDER'S RISK	WRAP-UP 2/
LIMITS	Generally equivalent to the replacement value	$15-$50 MM
RETENTIONS	$10,000 - $250,000	Up to $1 MM
PREMIUMS	.08-.26/$100 insurable value	NA

OPERATIONS PHASE

	NAMED PERIL	DIFFERENCE IN CONDITIONS	BOILER AND MACHINERY	CASUALTY 3/
LIMITS	$30-$300 MM	$10-$25 MM	Vary by size and value of equipment	$25-$50 MM 4/
RETENTIONS	$50,000-$1 MM	Approximately $500,000	$50,000 - $250,000	NA
PREMIUMS	NA	NA	NA	NA

NA = Not Available

1/ Many of the coal mining operations contacted were subsidiaries of some of the nation's largest steel corporations. In most cases, such companies choose to self-insure for both property and casualty and perhaps carry an excess policy beyond a certain point.

2/ Includes CGL and Workers' Compensation.

3/ Includes CGL and Workers' Compensation.

4/ Several companies felt their casualty coverage was inadequate and hoped to obtain more.

Operations. Huntorf maintains conventional property coverage (including Fire and Boiler and Machinery). No coverage has been sought for operating losses (i.e., Business Interruption or Extra Expense) resulting from a fire, breakdown or loss of pressure in the caverns. Coverage for power house machinery was granted "at usual terms" for only the first year of operation (during which the manufacturer's warranty is in effect). Following inspection and operations review at the plant, the policy terms were to be revised as appropriate. This caution was due to the prototype aspects of some of the machinery.

Terms of Coverage. Nordwestdeutsche Kraftwerke, AG (NWK) added the Huntorf CAES plant to existing policies for Fire and Boiler and Machinery coverage. The insurer, Haftpflichtuerband Fuer Industrie, stated that their previous experience with underground operations had been good. No unusual requirements or risk reduction methods were imposed.

Risk Perception. The risks perceived for construction included possible loss of sections of free-hanging pipe. (To avoid this hazard, pressures must be reduced prior to pipe manipulation to prevent a blowout.) Concern was expressed that during operations, the turbine blades could be damaged by high salt content of the emergent air. Threats to the integrity of the turbine blades can be determined by inspection (required by the guarantee) of the equipment after the first year's operation.

Accident and Claims History. The installation at Huntorf involved a 5-year period of redevelopment of a salt cavity which had been used previously for gas storage. No claims were made during construction. One incident, the result of variance from operating standards for above-ground equipment, delayed commissioning of the facility for 18 months. The incident was unrelated to the underground installations and their operation. Costs for one claim have not exceeded DM 40,000 (about $20,000).

6.2 MODEL INSURANCE PROGRAM

Utility Risk Management

The insurance coverage presently maintained by the research utilities is sufficiently flexible to allow adjustments to meet the needs of most new operations. The in-house risk analysis capability of electric utility companies is considerable at present and undergoes a continual process of upgrading and improved sophistication. Generally, it appears that the risk management programs of utilities demonstrates great confidence on the part of utility executives and risk managers in the reliability of their existing facilities, and in the security of these facilities even with minimal insurance coverage. Many utilities obtain commercial insurance as a last resort, preferring, on the basis of computer-run systems integration and risk assessment techniques, to assume a large part of the risk of operations. In other cases, risk managers indicated that they would be able to obtain all desired coverage for their exposures through present carriers, and they envisioned no necessity for substantial modification of their insurance programs to accommodate a CAES/UPH risk. Moreover, none of the utilities involved with CAES/UPH research anticipates that the formation of an insurance pool will be necessary to accommodate the exposure of CAES/UPH systems. From all such evidence, the levels of the CAES/UPH insurance requested by utilities should not overburden industry capacity.

Although levels of risk retention vary for each case, electric utilities generally prefer to assume a great portion of their operating risk. Casualty deductibles may be as high as $1 million or more, although a limited number of utilities prefer "first dollar coverage," that is, insurance policies with no deductible. The level of risk retained in Named Peril and Difference in Conditions coverage normally ranges around $250,000-$500,000, although variances from these figures are common.

Boiler and Machinery insurance at experience-adjusted manual rates is available to cover all common types and uses of pumping and generating equipment. The manual rates for pumps of the large capacity and power suitable for pumped hydro energy installations apparently assume above-ground installation, however. Manual rates for deep-well pumps and pump units appear only for a range up to about 1,000 horsepower and for depths to about 1,000 feet. Deductibles for Boiler and Machinery policies are set individually for each unit, as high as $1 million for the most costly piece of equipment.

Coverage for CAES/UPH Facilities

The availability of conventional insurance coverage for generating and transmission operations will be minimally affected by use of CAES or UPH components. This forecast is based on the experience of electric utility insurers with technologies which exhibit technical similarities to CAES or UPH (e.g., underground construction; pressurized storage of substances underground). The underwriters who were most positive about this viewpoint were those already familiar with the geologic configurations involved (e.g., had provided coverage for petroleum storage in salt domes, for natural gas storage in hard rock or aquifers, or for existing pumped storage facilities), or whose previous experience involved underwriting new technical risks.

From all indications, the risk exposure presented by CAES/UPH installation will not impede the insurability of the technology. A comparison of the coverages sought by the three research and other interested utilities with the coverages deemed appropriate and reasonable by the insurance industry shows very few differences. Broken down into separate phases of construction and operation, these conventional insurance programs might include:

1. Construction
   - All Risks Builders Risk (property)
   - Casualty
     - Comprehensive General Liability (CGL)
     - Workers' Compensation

2. Operations
   - Property
     - Named Peril
     - Difference in Conditions (D.I.C.)
     - Boiler and Machinery

- o Casualty
  - CGL
  - Workers' Compensation

During the construction phase, CGL and Workers' Compensation may be written in the form of a "wrap-up" policy. In states prohibiting such arrangments, an "owner controlled" or other alternate program might be used. Errors and Omissions in Design coverage for architects and engineers is available, though requirements for this insurance remain at the discretion of project owners. Casualty coverage during the operating phase may be added as an extension of the current policies carried.

Stressing that CAES/UPH technologies are not inherently uninsurable, ultimate availability of particular policies to individual utilities will nevertheless depend in part on the accessibility of such policies to the electric generating utility industry as a whole. Several types of coverage not generally available to utilities may be sought by individual utilities for CAES/UPH systems. The availability of such insurance could make investment in CAES or UPH plants more attractive, although there is no indication that these policies being made available are a prerequisite to CAES/UPH installation. It is likely, therefore, that the availability of these policies would not demonstrably deter investment decisions by utilities.

One utility expressed interest in coverage for the risk associated with the utility's inability to complete cavern construction and commence operations, based on the utility's judgment that the costs associated with not completing a facility were greater than those associated with the risk of failure or collapse of the cavity once operations had begun. This threat is considered a business or venture risk by the insurance industry and, notwithstanding changes in practice of the insurance industry, is therefore uninsurable.

Liability coverage in the event of a brownout or a blackout was described as a type of coverage that would further attract utilities to CAES and UPH. Brownout/blackout exposures are considered by underwriters as risks inherent to the electric power utility business. This narrow premium base makes the risk uninsurable; the loss potential associated with the brownout/blackout exposure is large, and the risk exposure is ill-defined. Even if insurance for this peril were available, the price would be very high. The general attitude of electric utility representatives was that blackout risks were a familiar part of utility operations, and that this coverage was not a definitive factor in investment decisions.

Utilities have expressed interest in indemnification for two other types of loss, the availability of which may have an important bearing on CAES/UPH investment decisions generally. One is coverage for the physical integrity of an energy storage cavity. Insurance has been obtained by one company for coverage of the risks of the ability of a cavity to hold stored natural gas products which are cycled on a seasonal basis at pressures only slightly above hydrostatic pressure. This policy covers the cavern, well heads, all associated equipment, and any loss due to a cavity's inability to perform the function for which it was designed. If the cavern is not able to store the product, the policy reimburses any costs of repair or replacement of the facilities up to the original cavern investment cost, which is used as the limit of the policy. Such existing policies will require certain important adjustments in order to conform to two additional requirements of the CAES or UPH energy storage systems: (1) CAES will utilize storage pressures of approximately 1000 psi; and (2) cycling of stored energy will be conducted on a daily or weekly schedule.[5] These two features would be known to the underwriter of a cavern-integrity policy. Insurance is currently available for underground facilities storing methane and ethane at pressures as high as 1900-2000 psi; separate coverage is available for facilities which practice more frequent cycling. Insurance policies also have been written for operations combining two of these three conditions (cavern integrity; pressurized storage; product cycling). There is no evidence that the commercial insurance industry is unwilling to write a policy combining all three.

[5]UPH cavern cycling stresses are less than 50 psi. At these relatively low pressures, the greatest cycling stress in UPH systems is in surge pressure and abrasive action of the water.

A second insurance policy uncommon in the electric utility industry is insurance for interruption of operations and extra expense. Availability of this coverage at reasonable rates will be an additional encouragement to utilities considering use of underground energy storage systems. Business Interruption coverage is rare, and it is expensive to obtain. This insurance is frequently not sought by utilities that expect to be able to recover through rate increases the higher costs of purchasing electricity within a power grid. One power utility has obtained a Business Interruption clause in their Property Damage coverage. The policy indemnifies the insured against losses incurred from any interruption of business, including coverage for extra expenses arising from machinery breakdown. The technologies' innovative status creates problems in obtaining such coverage for CAES and UPH. Insurance companies providing business interruption and extra expense policies require additional information possibly not included in the standard property policy, and most important, not always available when a facility comes on line.

6.3 ALTERNATIVES TO COMMERCIAL INSURANCE

The status of insurance made available for underground storage systems could result from one or from a combination of factors. In the recent history of casualty insurance underwriting, the industry encountered a succession of large claims arising out of product liability, medical malpractice, and automobile operators liability insurance exposures. The industry consequently attempted to reduce that exposure in which the potential was prominent for very large liability losses. New exposures were minimized, and non-essential coverages were eliminated. Such a series of losses could occur at any time, which would imply meager findings for utilities attempting to generate insurance interest in innovative operating conditions. Judicial decisions have tended to allow that any ambiguities in insurance contracts are swayed in favor of the claimant.

An insurance company will provide coverage, assuming that technical and actuarial standards are met, only if adding such a facility does not overextend the company's internally-allocated proportion of exposure to risks of that nature. A utility's record must also be good. One bad experience may be enough to discourage an underwriter of utility accounts, to the extent that a utility with an inferior loss record may find a difficult time obtaining coverage in either foreign or domestic markets.

The eventual responses by insurance companies to the CAES/UPH risk will vary, depending on the determinations of eligibility of particular sites for coverage. It seems unlikely that a utility would select an uninsurable site for CAES or UPH investment, especially considering the general sophistication of electric utilities in engineering and risk management areas. It is nonetheless conceivable that the terms of an offer of insurance may not be compatible with the structure of a utility's risk management program or philosophy. Alternatively, the insurance industry, typically cyclical in terms of the levels of commitment that can be made to risks of various natures, may be unable to respond at all, due to externally regulated reserve requirements. In such circumstances, a knowledge of the alternatives to commercial insurance will be useful.

The alternatives to commercial insurance that might be possible without government participation include: self-insurance; multi-utility risk sharing such as captive insurers or an insurance industry pool; and a trust fund or mutual assessment association. Those options requiring government sponsorship include government insurance, or statutory liability limitation.

Self-Insurance

Self-insurance is defined as a firm's accepting a level of risk for which the firm has sufficient assets to cover the particular liability. Self-insurance or self-retention is feasible, to some degree, for almost all firms, and is practiced by most utilities in the form of a self-insured retention. Self-insurance may be less adequate than commercial insurance, however, in that commercial insurance can be written on a "per occurrence" basis, while all self-insurers would not be prepared to cover more than a small number of accidents per year.

The costs of self-insurance begin with the costs of the expected value of losses not covered by insurance. There are additional costs associated with the following factors:

1) Insurance premiums are tax deductible, whereas the liability loss is tax deductible only if it actually occurs.

2) Exposure to a major loss could force a utility to engage in very high cost, short-term borrowing that might dangerously reduce working capital.

3) Most companies and most individuals are risk avoiders and prefer small certain income to a higher average but more uncertain income.

4) The cost of loans is larger in the absence of adequate insurance, and credit will generally be more difficult to obtain.

It is obvious that in most cases the perceived costs of self-insurance are greater than the insurance premiums for an equivalent risk. Two exceptions to this may be applicable to utilities. First, a utility may be large enough that a given type of risk can be treated as an expected operating cost. Many large firms self-insure for Workers' Compensation, since that can become a relatively predictable expenditure. Several of the large coal and steel companies self-insure to a certain level, carrying only excess or umbrella coverage for disasters. The second exception may occur as a result of the uncertainty of the risks involved. The premiums quoted may be so conservatively estimated or include such a stiff loading factor that a utility might feel it would be cheaper to self-insure than to accept the high risk estimates of the insurance industry.

Multi-Utility Risk Sharing

o Captive Insurance

Captive insurers, insurance companies established either by large companies, groups of companies, or trade associations specifically to meet their needs, are a source not only for reinsurance, but also for coverage which is currently either unavailable or too expensive from commercial insurance companies. A captive may both provide a means for reducing soaring insurance costs and may, by being set up in tax havens like Bermuda, offer tax breaks on premiums and a chance to accumulate investment income tax-free.

- Insurance Industry Pool

  An insurance pool, if the insurance industry could be persuaded to form one, would consist of a joint undertaking by a number of insurance companies to participate in meeting claims against the utilities buying insurance from it. Participating insurance companies would determine, in advance of joining, the percentage of total risk each would be willing to accept. Such pools normally act to provide liability insurance and currently exist for the liabilities associated with nuclear hazards, marine oil spills and aviation accidents. The advantage of a pool from the insurer's point of view is that it provides a convenient mechanism whereby a large number of insurers can each be responsible for only a small fraction of the risk.

  A pool such as the Nuclear Energy Liability-Property Insurance Association (NEL-PIA) provides both liability and property insurance. The operators of nuclear facilities and their supplies are covered for any liability they may incur as a result of bodily injury or property damage resulting from a nuclear accident. The property insurance covers damage to the property of nuclear facility owners. The pool has a specialized engineering and underwriting staff and insurance treaty arrangements with current premiums of under $16 million.

<u>Trust Funds</u>

An industry-wide trust fund could be considered as an alternative to insurance, particularly for liability insurance. Such a fund would be financed out of contributions from utilities and would be administered by a fiduciary organization formed for the purpose. The organization would accumulate contributions, invest its funds, and pay meritorious claims against participating utilities.

There would be two problems with providing insurance by this approach. The first is that during its initial years, the narrow financial base upon which it would rest would only provide partial coverage. After a period of years, however, a large financial reservoir would eventually accumulate that would provide the necessary resources to handle large losses. The second problem involves the insurance laws of many states which expressly prohibit any organization from providing insurance or services analogous to insurance unless it is a fully qualified insurance company.[6]

Mutual Assessment Associations

The formation of a multi-utility mutual assessment association would depend to a large extent on industry initiative. It would be advantageous for utilities inasmuch as (unlike a multi-utility trust fund) the funds required to implement the assessment system would not be much larger than the amount of the losses of the utility. If no losses were incurred, no assessments would be required. One disadvantage involved with such associations centers around the institutional or legal problem that certain states simply prohibit them. Another problem might be the dependence for success of the association on the voluntary cooperation of the utility industry members. A mutual assessment approach may not represent sufficient proof of "insurance," thus creating an impediment to debt financing. The efforts of the New York Stock Exchange to protect the public from the bankruptcy of Exchange members is an example of an industry-based mutual assessment association. This type of scheme is apparently, for the reasons cited, not effective in situations requiring insurance.

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[6] See, e.g., McKinney's Consolidated Laws of New York, Title 27, Insurance Law, §40; Deerings California Code, §700.

Government-Sponsored Insurance

States and the federal government have offered insurance or reinsurance in such diverse areas as flood damage, ghetto fire and property, hurricanes, and workers' compensation. The number of utilities installing underground energy storage systems may be so small, however, that a state or federal program would require either a substantial loading factor or a commitment of the governments' own funds if a large loss occurred. The "National Swine Flu Immunization Program" of 1976 contained a provision that provided insurance in case of an injury or death resulting from the program. The State of Ohio has an exclusive state insurance fund to provide workers' compensation insurance. The advantages of such an arrangement are: (1) the rates of the state fund are significantly less than those of private insurers; (2) a state-administered fund would have lower operating expenses than a private company; and (3) more and more private insurers are giving up workers' compensation insurance.

The National Flood Insurance Program, administered by the Federal Emergency Management Administration, was created by the Congress in order to reduce annual flood losses through more careful planning and to provide property owners with affordable flood insurance protection. Once a community qualifies for the sale of flood insurance, a policy may be bought from any licensed property insurance agent or broker. From existing estimates, loss rates are available or can be developed for virtually any location in which an underground energy storage installation might be sited. The federal program makes available only a limited amount of insurance on one risk, an amount that would probably be less than the limit of loss which a public utility would retain as its own risk in the form of a deductible. Such a rate would therefore most likely be a measure of the degree of hazard retained by the owning utility rather than the basis for an insurance premium, although special coverage might be arranged in the private "surplus lines" markets.

Government-Enforced Liability Limitation

It is extremely unlikely that the commercialization of CAES and UPH would necessitate government-initiated liability limitation. The most well-known example of the government stepping in to limit liability is the Price-Anderson

Act, which limits private liability for accidents resulting from the operation of federally licensed nuclear power plants. The Act establishes "a liability ceiling of $560 million beyond which neither the licensees nor the government must compensate the victims of such an occurrence."[7] Such government involvement has proven extremely controversial, and in fact, in 1977 there was a District Court decision declaring that the Price-Anderson Act was an unconstitutional deprivation of due process and equal protection.[8] This decision was reversed and the constitutionality of the Act was upheld by a 1978 Supreme Court ruling.

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[7]Environmental Law Institute, "Judges as Statesmen: U.S. Supreme Court Jumps Standing Hurdles to Uphold Price-Anderson Act," in Environmental Law Reporter, Vol. VIII, August 1978, p. 10162.

[8]Carolina Study Group v. AEC, 510 F.2d 796, 5 ELR 20181 (D.C. Cir. 1975).

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APPENDIX A

SEISMIC STABILITY OF UNDERGROUND CAVERNS

1.0 INTRODUCTION

The effects of earthquakes on underground cavern stability has been the subject of far less study than the response of surface structures such as tall buildings and power stations. However, there have been several documented instances of underground structures being involved in earthquakes, as well as analytical and numerical studies of the elastic response of caverns to seismic waves. Analysis of the seismic stability of underground openings must focus upon:

- Past experience of underground cavern performance under seismic loading,
- Likely ground motions the cavern will experience,
- The response of caverns due to seismic excitation.

In studies of blasting vibrations, particle velocity is commonly employed as a damage index. In earthquake engineering, however, the peak ground acceleration is, by far, the most widely accepted index for comparing a structure's performance under seismic excitation. Detailed studies indicate that structural damage is a function of the number of cycles or duration of shaking, ratio of structural frequency to input frequency, and structural damping, as well as peak acceleration.

2.0 LIKELY GROUND MOTIONS

There are three types of waves which can be experienced by an underground cavern, (a) P-waves, (b) S-waves, and (c) Rayleigh surface waves. In most cases, the response of a cavern is analyzed assuming the earthquake is a pure shear (S) wave travelling vertically upwards. However, depending on the depth and the stratigraphy, this type of ground motion may not give rise to the worst case of seismic loading of the cavern. Therefore, all three types of waves will be considered here. A number of factors that could affect response and thus damage, other than peak surface motions, require details of the earthquake time-history at depths which are generally not known and must be determined by attenuation relationships. Most attentuation relationships have been derived from measurements made at surface stations located on a wide range of ground conditions, both soil and rock, without differentiation between the different geological conditions. Because of site amplification effects, this lack of discrimination in correlations is a serious disadvantage when dealing with tunnels located at depth in rock. Therefore, it is important to determine the stratigraphy and material properties at a specific site to derive the motions that occur at depth.

The design spectrum for surfaced concrete structures from the NRC Regulatory guide is shown in Figure A-1. One method of determining spectral input for seismic design is to assume the input has the same shape as given in Figure A-1, but the magnitude of maximum acceleration is less. This technique is obviously approximate and actual measured dynamic response measured at depth would be ideal. However, measurements in underground excavations for dynamic response are limited. Figure A-2 illustrates spectral response measure in the Colony Mine due to a nuclear explosion being detonated nearby.

Two empirical methods for determining input spectral are: One assumes different shapes for the frequency distribution curves for regions of different seismicity, whereas the other takes all regions to have frequency distribution curves of the same shape. The first method is based on a seismic probability in the region under consideration and the maximum intensity of shaking are normally taken as shown in Table A-1 for various earthquake magnitudes.

TABLE A-1
MAXIMUM ZONAL ACCELERATIONS

Zone	Max^{m}Accelerant$_{n}$%ng	Richter Magnitude
3 (near a great fault)	50	8.5
3 (not near a great fault)	33	7.0
2	16	5.75
1	8	4.75
0	4	4.25

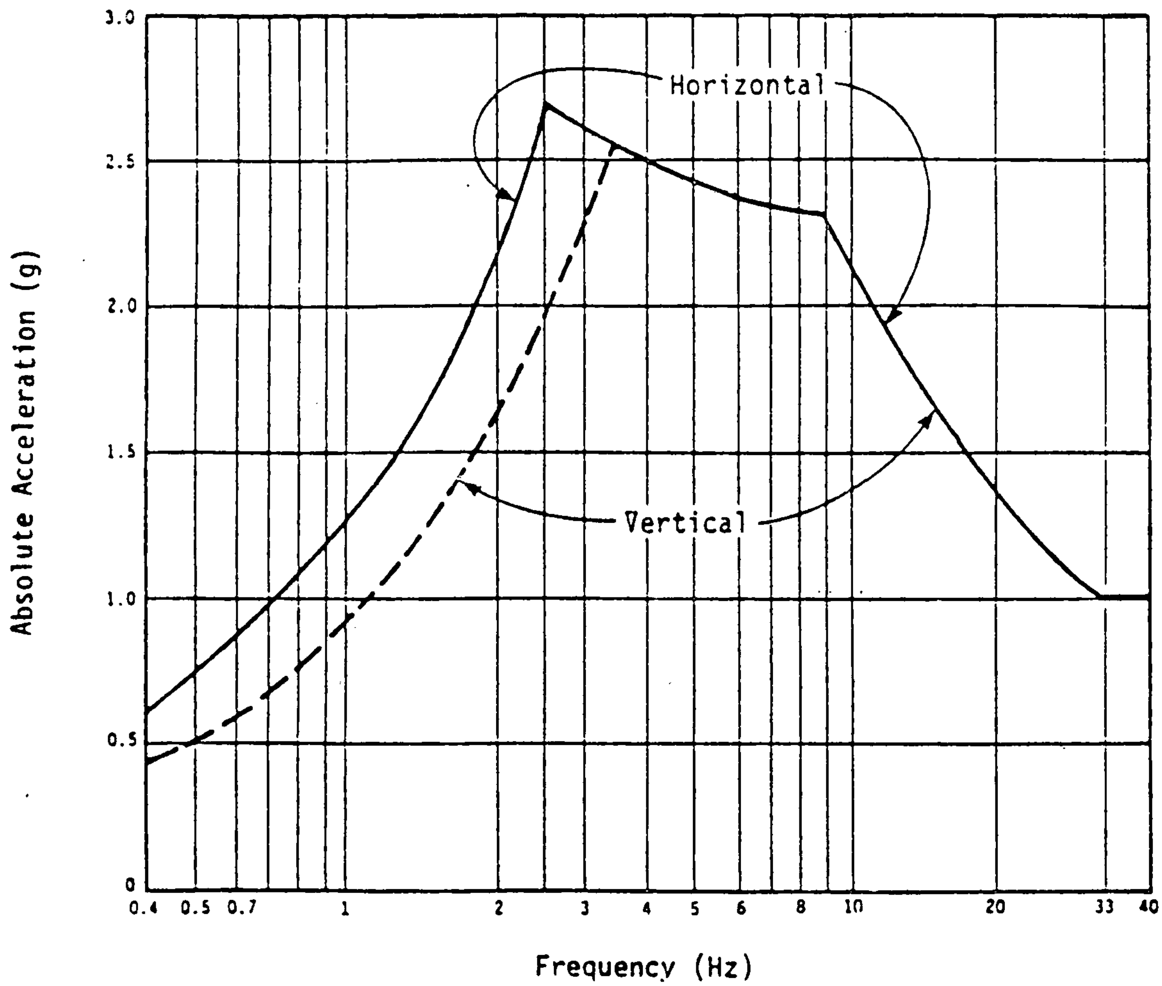


FIGURE A-1. NRC regulatory guide 1.60 response spectra at 7% damping

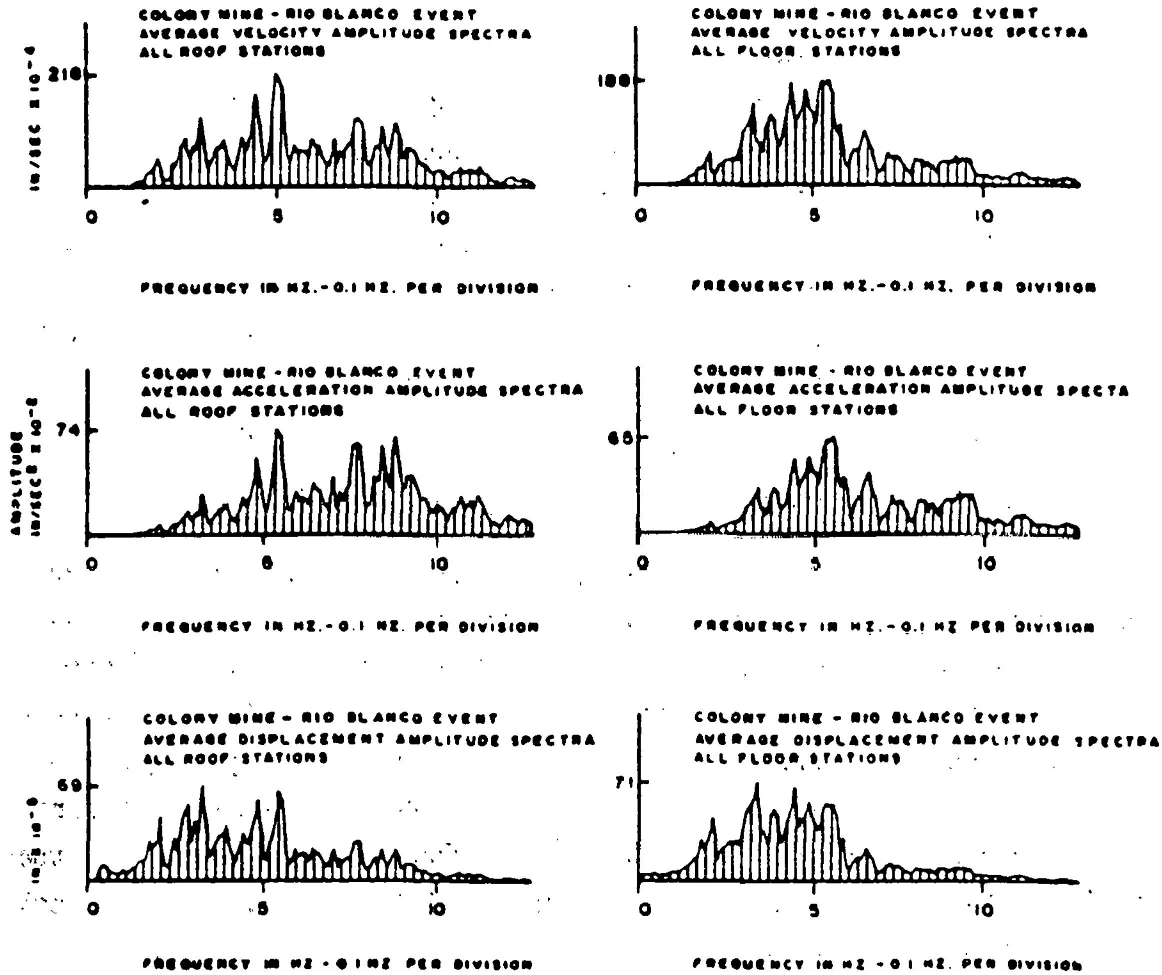


FIGURE A-2. Average spectral response for the roof and floor from the Colony Mine (Munson, 1975)

The second approach assumes that earthquakes of all magnitudes are possible in any region of the world. This approach assumes the frequency distribution to be the same in all regions. With this ideal frequency distribution, there is no upper bound for magnitude. As a practical matter, however, a lower bound must be set for meaningful probability. For example, in California it seems most unlikely that an earthquake having M > 8.5 will occur; hence, when making probability calculations, the probability for M > 8.5 can be considered to be negligible. This, then, specifies a "negligible probability" to be applied when considering regions of lower seismicity than California.

3.0 PAST EXPERIENCE OF CAVERN PERFORMANCE

The impact of seismic excitation on underground cavern performance can only be determined from observing cavern response during earthquakes. Figure A-3 summarizes the basic data from the case histories as reported by Dowding and Rozen (1977). Three levels of response were distinguished, as shown in Figure A-3, without regard to geologic media or lining. NO DAMAGE implies post shaking inspection revealed no apparent new cracking or falling of stones. MINOR DAMAGE DUE TO SHAKING included fall of stones and formation of new cracks. DAMAGE includes major rock falls, severe cracking closure.

The three levels of response are stratified with respect to the calculated peak surface motions. There are no reports of even falling stones in unlined tunnels or cracking in lined tunnels up to 0.19g. Up to 0.25g, there are only a few incidences of minor cracking in concrete lined tunnels. Between 0.25g and 0.52g, there was only one partial collapse and it was associated with landsliding and brick lining failure.

Figure A-4 summarizes two relationships involving tunnel damage. First, the observed damage is compared to Modified-Mercalli (MM) intensity levels for aboveground structures. Secondly, the damage level is correlated to Richter magnitude and distance between epicenter and tunnel location. The "No Damage Zone" with acceleration up to 0.19g, is equivalent to Modified-Mercalli (MM) VII-VIII; the "Minor Damage Zone" with acceleration up to 0.5g is equivalent to MM VIII-IX.

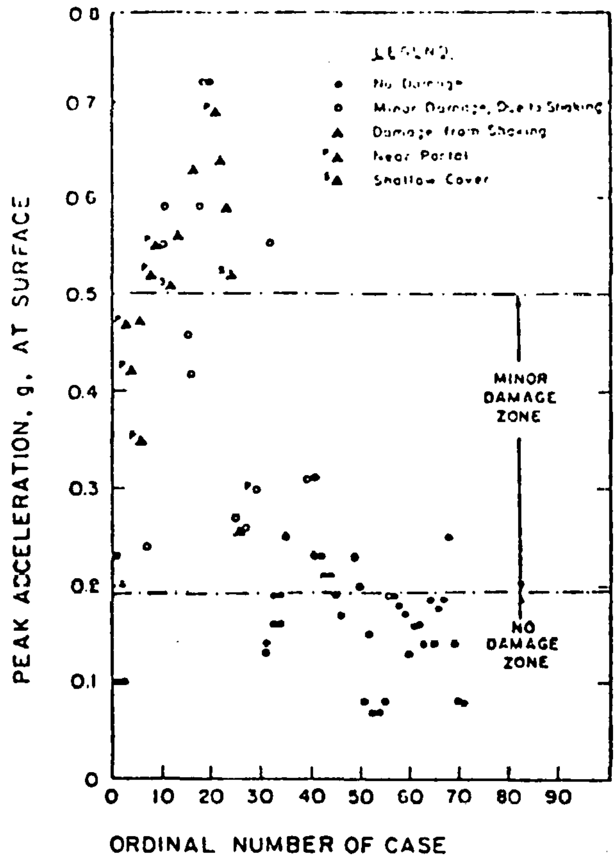


FIGURE A-3. Calculated peak surface accelerations and associated damage observations (Dowding and Rozen, 1978)

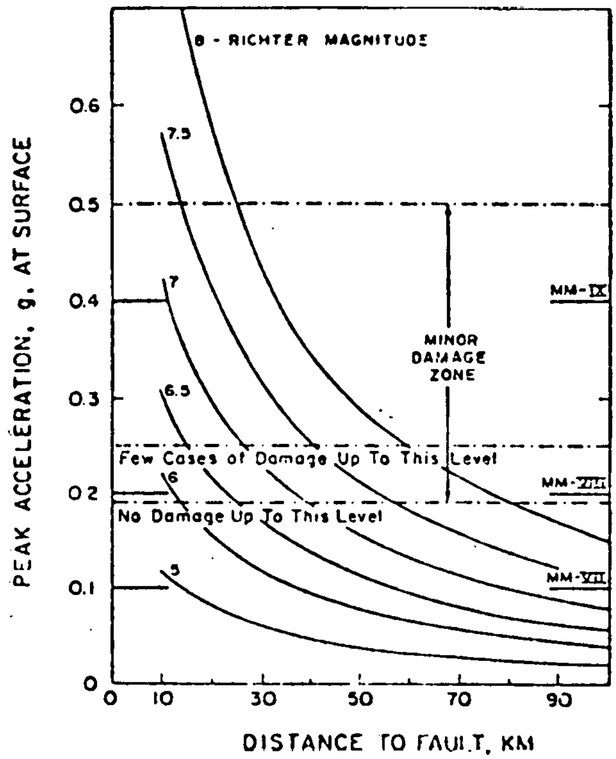


FIGURE A-4. Comparison of modified mercalli intensity of surface motions and observed damage (Dowding and Rozen, 1978)

The following conclusions were drawn by Dowding and Rozen (1978) and are listed below:

- Collapse of tunnels from shaking occurs only under extreme conditions. It was found that there was no damage in both lined and unlined tunnels at surface acceleration up to 0.19g. In addition, very few cases of minor damage due to shaking were observed at surface acceleration up to 0.25g.
- Tunnels are much safer than aboveground structures for given intensity of shaking. While only minor damage to tunnels was observed in MM-VIII to IX levels, the damage in aboveground structures at the same intensities is considerable.
- More severe, but localized damage may be expected when the tunnel is crossed by a fault that displaces during an earthquake. The degree of damage is dependent on the fault displacement and on the conditions of both the lining and the rock.
- Tunnels in poor soil or rock, which suffer from stability problems during excavation, are more susceptible to damage during earthquakes, especially where wooden lagging is not grouted after construction of the final liner.
- Lined and fully grouted tunnels will only crack when subjected to peak ground motions while unlined tunnels are subjected to rock falls.
- Tunnel deep in rock are safer than shallow tunnels.
- Total collapse of a tunnel was found only when associated with movement of an intersection fault.

Blume and Associates (1978) have undertaken an investigation into facility hardening studies for the N.T.S. Terminal Waste Storage Program. This study included determining costs of hardening the underground excavations against seismic and nuclear dynamic loading.

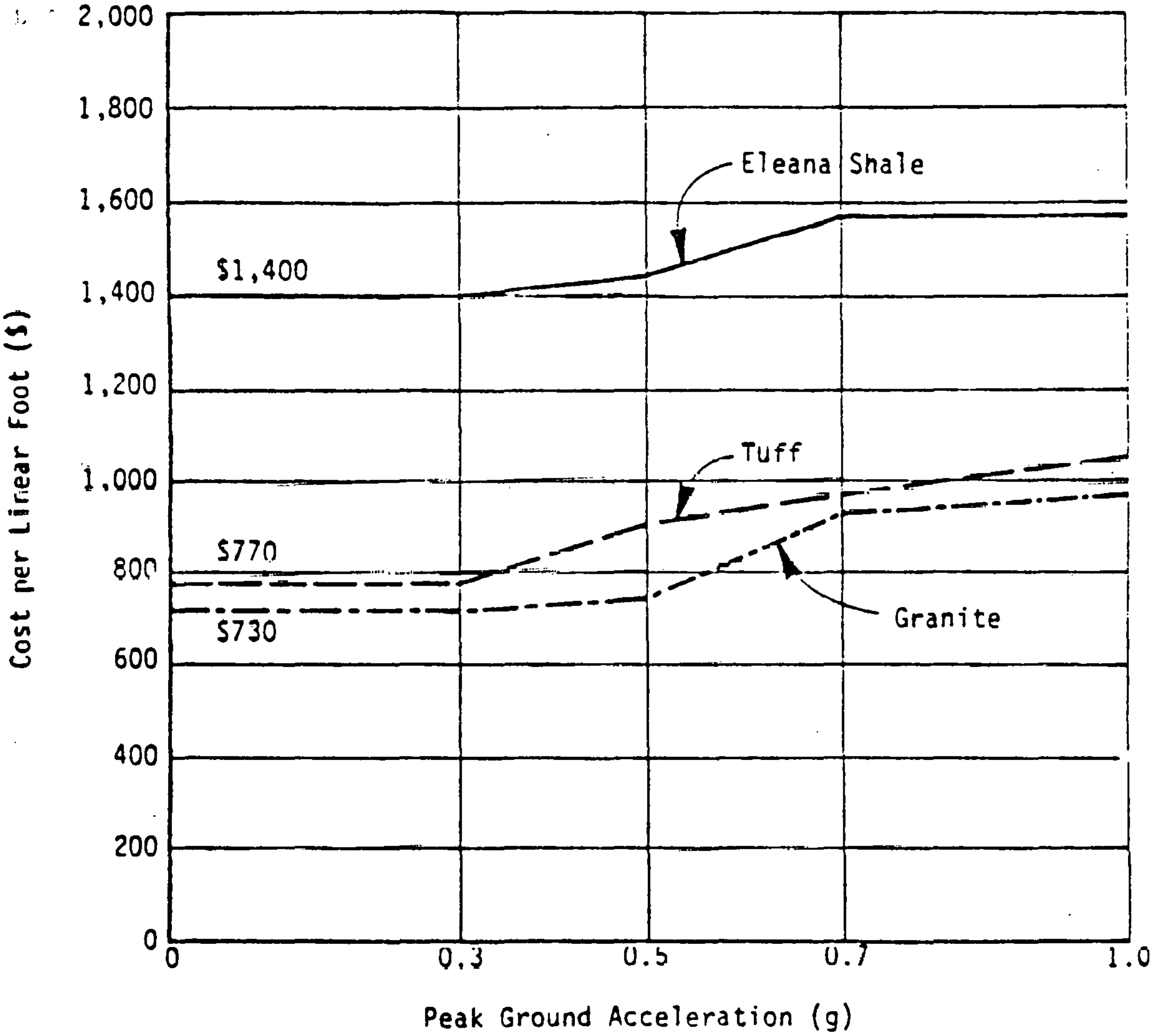
A summary of percent increased costs of hardening the underground escavations against peak ground accelerations up to 1.0g are given in Table A-2. The total estimated costs for the tunnels per linear foot are plotted in Figure A-5 as a function of peak ground acceleration.

TABLE A-2*

SUMMARY OF ESTIMATED HARDENING COSTS AS PERCENTAGE INCREASE

	Cost Increase Per Linear Foot (%)					
	Tunnels			Four Shafts Combined		
PGA Range (g)	Granite	Tuff	Shale	Granite	Tuff	Shale
0.0 to 0.3	0	0	0	0	0	0
0.0 to 0.5	3	18	2	1	1	1
0.0 to 0.7	27	26	13	1	1	1
0.0 to 1.0	34	35	13	1	1	10

*Blume & Associates, 1978.



NOTE: These dollar amounts should be used only in the context of this report. They are relative figures and may vary significantly.

FIGURE A-5. Summary of estimated tunnel cost per linear foot (Blume & Associates, 1978)

REFERENCES

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APPENDIX B

RELEVANT PROPERTIES OF HARD ROCKS FOR CAES SCHEMES

1.0 INTRODUCTION

In this appendix, hard rocks will consist of crystalline rocks such as granites, gneiss, etc. Granites are commonly light-colored, coarse-grained igneous rocks, consisting mostly of alkali feldspar and quartz. In this appendix, only granite, in which the alkali feldspar comprises more than two-thirds of the total feldspar present will be discussed in detail. At present, the material behavior of hard rocks under the loading conditions to be experienced in a CAES cavern are, as yet, undetermined. The main difference in the loading experienced in a CAES scheme to other underground caverns is the daily cyclic loading. The mechanical, thermal and hydrological properties of the rocks for both an intact specimen and the rock mass must be determined in order to properly design CAES schemes in hard rock. The U.S.D.O.E. is in the process of letting a contract through PNL (Pacific Northwest Laboratories) in order that the necessary material properties are investigated under CAES conditions. Dr. Loscutoff of PNL is in charge of technical administration of this contract and another contract for the numerical modeling of CAES schemes in hard rock, awarded to RE/SPEC. It is appropriate at this time to include a brief review of the understanding of intact and rock mass behavior under cyclic loading conditions of pressure temperature and humidity. Since the hydraulic properties of a rock mass are important in the acceptability of a site for CAES siting, a brief review of their variability in hard rock is presented. The following review has been taken directly from the paper by G. Hocking, titled "Parametric Cyclic Thermal and Pressure Analysis of Underground Openings in Crystalline Rock," presented at the CAES Technology Symposium, Pacific Grove, Asilomar, California, May, 1978.

2.0 REVIEW

Intact mechanical and thermal properties of some U.S. granites are listed in Table B-1. This table was compiled from approximately fifty

TABLE B-1

INTACT PROPERTIES OF SOME U.S. GRANITIC ROCKS

Rock Type	Young's Modulus ($x10^4$MPa)	Poisson's Ratio	Porosity (%)	Compressive Strength MPa	Tensile Strength MPa	Coeff. of Linear Thermal Expansion ($x10^{-6}/^oC$)	Specific Heat ($x10^3 J/Kg^oC$)	Thermal Conductivity (W/m^oC)
Barre Granite	7.2	0.22	0.4	234.	7.6	8.1	1.0	2.37
Colville Granite (slightly altered)	1.1	0.20	2.36	65.	3.2	9.0	1.0	2.42
Pikes Peak Granite	7.1	0.31	0.25	226.	11.9	9.0	1.0	2.41
St. Cloud Gray Granodiorite	7.1	0.25	0.08	282.	7.0	--	--	--
Coarse Grain Granite (Big Thompson Project)	2.7	0.12	1.0	72.	3.6	8.1	1.0	2.42
Rion Granite	5.3	0.25	--	202.	9.3	8.0	0.98	2.42
Raymond Granite	3.7	0.25	0.8	180.	8.9	8.1	1.0	2.42

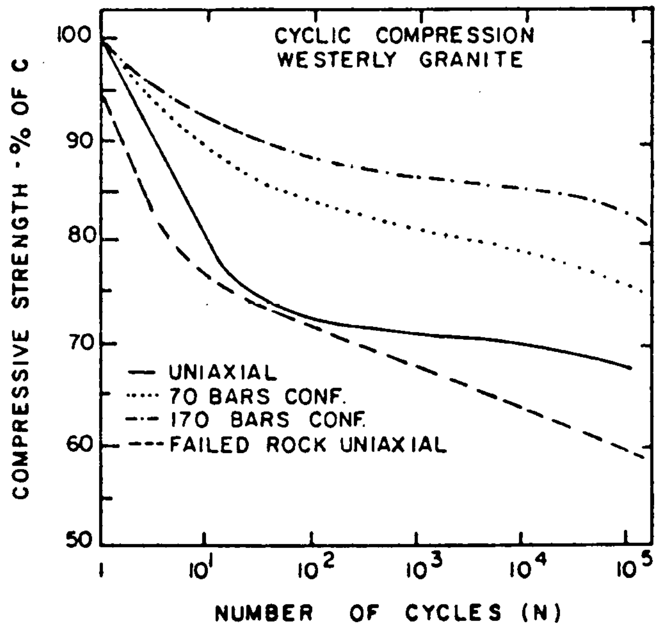

FIGURE B-1. Cyclic uniaxial and triaxial compression in terms of respective monotonic compressive strengths (C) for Westerley granite (Haimson, 1974) references in a recent literature survey by Dames & Moore for the Office of Water Isolation. The compressive and tensile strengths and elastic parameters quoted in Table B-1 are for single loading of the samples at a maximum rate of 6.67 MPa/sec. In CAES schemes, the pressure and/or thermal loading on the rock is cyclic; either due to the variation in the chamber air pressure in unbalanced schemes or the wetting-drying process in balanced schemes. Haimson (1974) has undertaken cyclic uniaxial and triaxial compression cyclic tests on Westerley granite. The reduction in compressive strength of Westerley granite with the number of load cycles is illustrated in Figure B-1 for both uniaxial and triaxial conditions. Even though the load cycles were rapid, approximately 1 cycle/sec., the results do indicate the effect of cyclic loading on rock compressive strength. The compressive strength (C) of Westerley granite for a loading rate equivalent to 1 cps was found to be 320., 412., and 485. MPa at confining pressures of 0., 7., and 17. MPa, respectively.

Haimson also undertook cyclic tension and tension-compression loading conditions resulted in the greatest reduction of rock tensile strength with loading cycles. The reduction in the tensile strength of Westerley granite versus number of loading cycles is illustrated in Figure B-2 for both cyclic tension and tension-compression loading modes. The uniaxial tensile strength (To) of the Westerley granite at a loading rate equivalent to 1 cps was found to be 11. MPa. Typical stress-strain and strain-time curves recorded during tension compression cyclic loading of Westerley granite are shown in Figure B-3. It is important to note from this diagram the different effects the tension and compression have on rock. As the load shifts from compression into tension, there is a sharp drop in modulus indicating the opening of the previously closed microcracks. The additional drop in the tensile modulus between the first and last cycles is around 30%, which is considerably higher than in other loading types. It is perhaps this excessive "softening" which makes tension-compression the most damaging cyclic loading. Photomicro-graph studies of selected specimens removed from the testing machine at different stages of cyclic loading indicated that cyclic fatigue

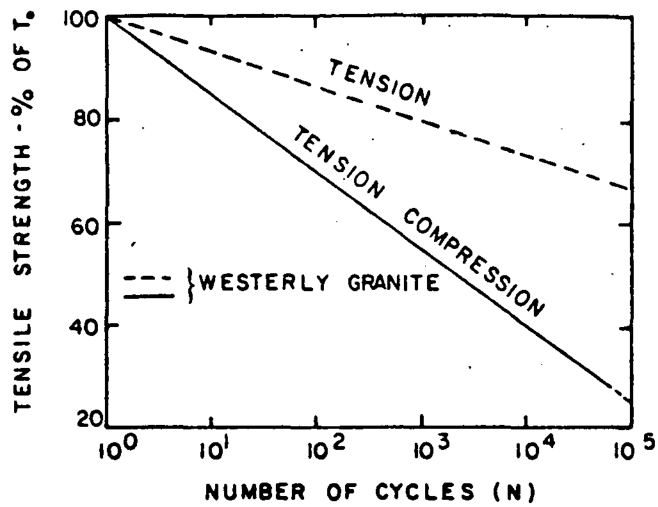

FIGURE B-2. Cyclic uniaxial tension and tension-compression in terms of respective monotonic tensile strengths (T_0) for Westerley granite (Haimson, 1974)

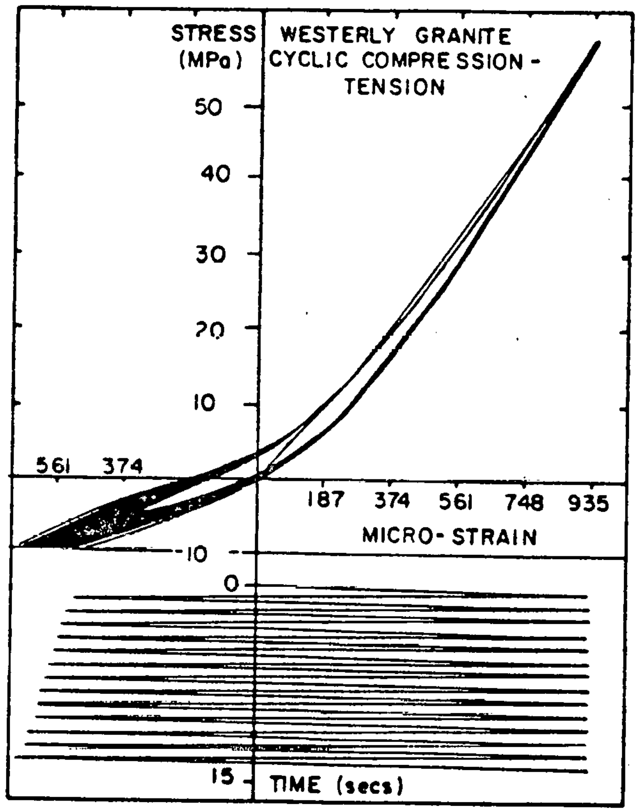

FIGURE B-3. Typical stress-strain and strain-time curves recorded during tension-compression cycling of Westerley granite
(Haimson, 1974)

was a result of a microfracturing process. Haimson noticed that fabric changes in uniaxial compression appeared to be dominated by grain boundary loosening and intergranular cracking in the first few cycles, followed by a pseudo-stagnant crack extension period, and finally resulting in crack coalescence and fatigue failure. The entire process of cumulative damage was noticed to be evenly distributed throughout the entire specimen. On the other hand, fatigue tensile failure is greatly dependent on the presence of critical flaws, thus resulting in little to no formational warning of fatigue tensile failure. Similar conclusions were found by Montoto (1974) from cyclic loading of Barre granite at cyclic rates varying from 0.5 to 2 cycles per second. Scanning electron microscope (SEM) studies clearly indicated microcrack development and coalescence under cyclic loading. Although the above described tests were at a significantly higher cyclic loading rate than is to be expected in a CAES system, the results do indicate the trend of fatigue strength behavior of granite.

Although there is data available on the behavior of granites at elevated static and cyclic temperatures, most of the information is at moderately high temperatures (150°C). In proposed CAES systems, the maximum range of temperatures within the cavern is approximately from 10 to 70°C. Long-term cyclic thermal loading behavior of granite rocks within this temperature range is not readily available in the literature except for application to CAES. Studies have been conducted in France (Mailhe et al., 1977) on the behavior of various rocks under the effect of alternating thermal shocks, for assessing the suitability of rocks for a CAES facility. The experiments were undertaken by an automatically controlled apparatus whereby a large number of immersion and heating cycles could be undertaken. The samples were placed in a watertight tank heated to the desired temperature, then flooded with cold water (16°C), the tank being emptied after a few minutes and the cycle repeated. Up to a maximum of 24 cycles per day could be effected with maximum temperatures ranging from 50 to 300°C. Increased microcracking was assessed by measuring the air permeability of the samples after each new cycle. Thus, the critical number of cycles at a particular maximum temperature that a rock developed irreversible microcracking phenomena, followed by substantial acceleration, could be determined. This deterioration of the rock is illustrated in Figure B-4 for granite from Brittany under cyclic thermal shock loading as described previously. From further tests on the coarse granite subjected to successive cycles under thermal shock conditions from 16 to 91°C, only a slight change in air permeabilities was noticed even after 1,000 load cycles.

The effect of water and air on rock strength of granites is two-fold; (a) an immediate noticed reduction in strength upon degree of saturation (Waversik, 1974), and (b) long-term chemical and physical deterioration through air and water exposure. The short-term phenomena has been studied in moderate depth, and data is readily available. For example, Westerley granite has a noticeable reduction in uniaxial compressive strength of 0.85 when fully saturated compared to air dried (Waversik, 1974). The long-term deterioration reaction depends on the specific deterioration liability of mineral constituents and on the surface areas in contact with water. The effect of weathering and its associated changes in the mechanical properties of granites have been measured both in the laboratory and the field. However, the time dependent process of weathering at elevated stress levels, e.g., rock around an underground cavern subjected to wetting and drying processes, is not generally discussed quantitatively in the literature.

Most of the above discussion has been restricted to intact granite specimens involving microcracking and not considering the effect of joints. The behavior of a granite rock mass is greatly dependent on the spacial distribution and strength properties of joints present. The behavior of models of jointed rock media have been studied in physical experiments under cyclic loading (Brown and Hudson, 1974). The models consisted of plaster blocks assembled into a loading frame and loaded cyclically to determine the compression fatigue strength locus. Discrete discontinuities in granite rock masses have been studied in detail in conventional rock shear experiments (Schneider, 1974). The shear strength characteristics of discontinuities subjected to shear displacement reversal have been investigated in detail; however, low cyclic force controlled shear loading has not been a subject of major investigation. The shear fatigue failure strength of rock discontinuities must be available in order that the progressive weakening of rock masses subjected to cyclic loading can be modeled.

In crystalline rock masses where the joint sets are mainly responsible for the transport of fluid and where the porosity is very low, conventional field methods of measuring rock mass permeability have been successfully applied to rock masses where the permeability is approximately 10 cm/sec. For values of permeability below this order of magnitude, alternative in-situ tests have been devised, such as the pulse test, to measure low permeabilities in crystalline rock masses. Field observation of permeability and fluid pressure in crystalline rocks are generally not made consistent with respect to scale. Therefore, attempts at generalizing field permeability data in crystalline rocks must be viewed with a certain amount of skepticism. Some data available on rock mass permeabilities of crystalline rocks in both the U.S. and Sweden are illustrated in Figure B-5 along with the depth of the specific test (Maini and Hocking, 1977). The decrease in permeability with depth is clearly apparent in this diagram; however, whether the permeability of a crystalline rock mass will ever decrease to an asymptotic value of the intact material is doubtful. This diagram illustrates that a crystalline rock mass at a depth of 700m could be found that has a permeability less than 10^{-6} cm/sec. and possibly be of the order of 10^{-7} cm/sec.

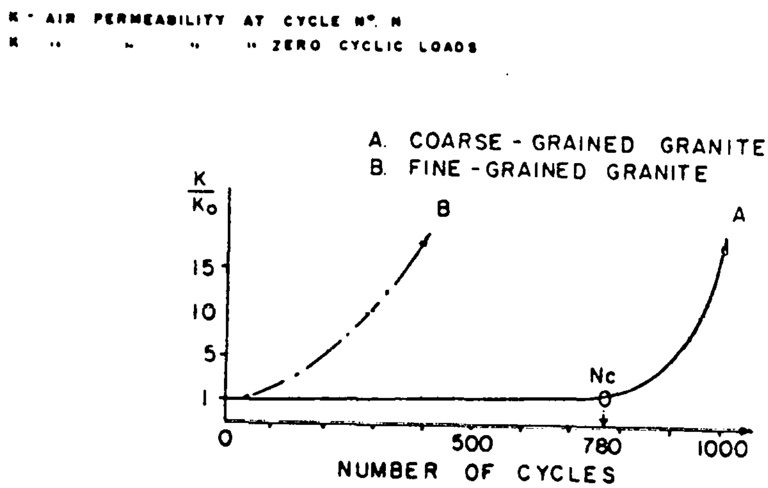

FIGURE B-4. Evolution of the critical number N_c for granite rock types with thermal cycles from 10 to 180°C (Mailhe et al., 1977)

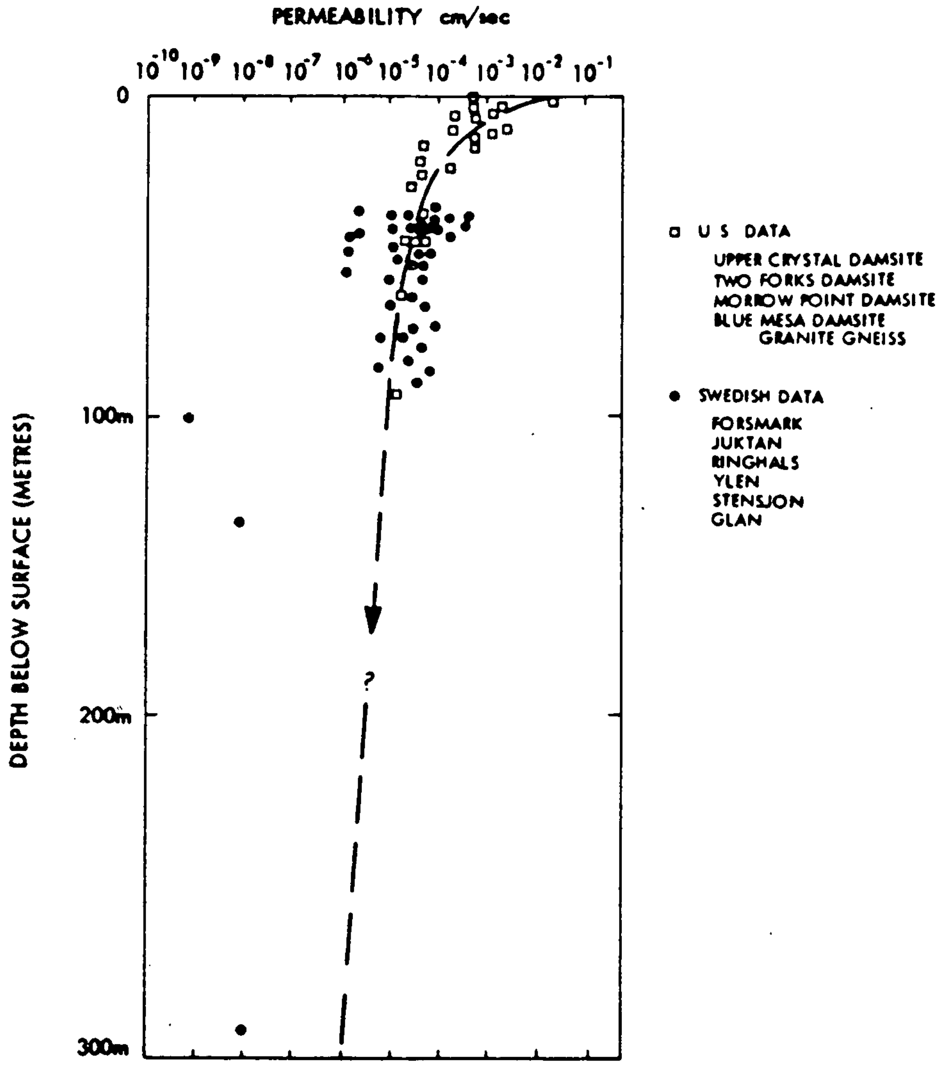

FIGURE B-5. Plot of permeability data with depth for granite rock masses (Maini and Hocking, 1977)

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APPENDIX C

LARGE PERMANENT UNDERGROUND OPENINGS

1.0 INTRODUCTION

Large permanent underground openings include all openings with dimensions greater than 15m and expected to have a functional life of over ten years. These distinctions exclude tunnels, shafts and most aspects of underground mine openings except for underground crushing stations and some large maintenance areas. Table C-1 lists the size of some large permanent underground hydroelectric generator rooms. Hoek (1975) lists the dimensions and rock conditions for many large permanent openings throughout the world.

TABLE C-1

TYPICAL LARGE UNDERGROUND OPENING

Project Name	Hall Dimensions LxWxH (Meters)	Depth (Meters)	Rock Condition
Drakensberg (Natal RSA)	193 x 16, 3 x 45	150	Horizontal series of sandstones and silt-stones and mudstones.
Poatina (Tasmania, Australia)	92 x 13, 7 x 26	152	Horizontally bedded mudstone. Horizontal stress approximately twice vertical.
Portage Mountain (Canada)	271 x 20, 4 x 44	61	Interbedded sandstone shale and coal measure dipping 15°. Horizontal stress approximately twice vertical.
Churchill Falls (Canada)	300 x 25 x 45	308	Diorite, gneiss. Horizontal stress approximately twice vertical.
Boundary (Washington, U.S.A.)	147 x 23 x 54	203	Good quality bedded limestone and dolomite.

2.0 DESIGN PROCEDURES

The procedures adopted in the design of large underground openings follow the basic steps outlined below:

- preliminary geological reconnaissance
- preliminary estimate of opening size and shape based on functional requirements
- preliminary site selection
- conceptual design - optimize opening shape
  - orientation
  - size
  - location
- detailed geological investigation
  - structure
  - stress
  - strength
  - water conditions
- pilot excavation, rock instrumentation and monitoring
- final design - support and reinforcement
  - optimize shape
  - orientation
  - specify construction method and sequence
- field input during construction
  - detailed geology
  - support performance
  - rock monitoring
- design modification

The site evaluation and site selection procedure for these structures is elaborate because of their large dimensions, long life and high capital cost. Often, exploratory shafts and/or drifts are an integral part of the site selection process. The location and orientation of these structures is a design variable resulting in the avoidance of faults and regions of poor ground.

The significant component of the design procedure is that the design process does not stop until the structure is fully constructed. This is necessary because the complete definition of the geology, jointing, faulting and groundwater conditions cannot be achieved until after excavation. This unusual design procedure (i.e., unusual in comparison to the design and construction of most aboveground structures) requires flexibility in the contractual procedures with the constructing contractor.

3.0 DESIGN VARIABLES

The variables in the design of a large underground opening are:

- Location, selected so that the excavation will be in the best quality rock within functional constraints on location.
- Orientation could be selected to minimize the impact of regular geological features such as inclined bedding, jointing and in-situ stress.
- Excavation shape and size should be optimized to minimize excavated material, but to provide adequate functional space without excessive rock reinforcement or support requirements.
- Support or rock reinforcement method. Rock bolts, grouted cables, shotcrete, reinforced concrete, etc., provide a wide variety of reinforcement and support types to select from.
- Excavation method. Conventional drill and blast, smooth wall pre-split, post-split blasting methods and non-blasting techniques using tunnel boring machines or wire sawing could be used.

No generally accepted set of design guidelines is used in selecting acceptable shapes, sizes, support requirements, etc. Instead, large permanent underground openings are designed on the basis of experience, comparison with other projects of similar size and rock conditions and stress analysis. Most designs are accompanied by an extensive array of instrumentation to monitor rock movements, stress change in the rock, and loading in the reinforcements to check that design assumptions are acceptable. The following is a brief summary of suggested design guidelines.

4.0 DESIGN GUIDELINES

1. Location

Away from weathered or altered zones, at depth sufficient to provide adequate confinement for fallout of roof blocks. Avoid fault or highly fractured zones. Avoid contacts between two rock types.

2. Orientation

- Major axis of opening within 15 to 30^{0} of the major horizontal stress direction, if a significant difference exists between the two horizontal stresses.
- Major axis along the bisection line of the intersection angle between two dominant joint directions (bedding or foliation partings included), Selmer-Olsen and Brock (1977).
- Major axis perpendicular to the stress of a single major joint set.

3. Excavation shape and size

- Elliptical or circular form best, minimize sharp protrusions or cuts, Selmer-Olsen and Brock (1977), suggest the guidelines shown in Figure C-1.
- High flat walls avoided if possible.
- Adjacent rooms should be separated by a pillar of width at least equal to the room height, minimum width 5m (16 ft.).
- One dimension, room width, should be minimized. The compilation of large underground openings by Hoek (1975) included only three with spans over 30m (100 ft.). All excavations were relatively shallow. Support costs increase approximately as the square of the room spans.

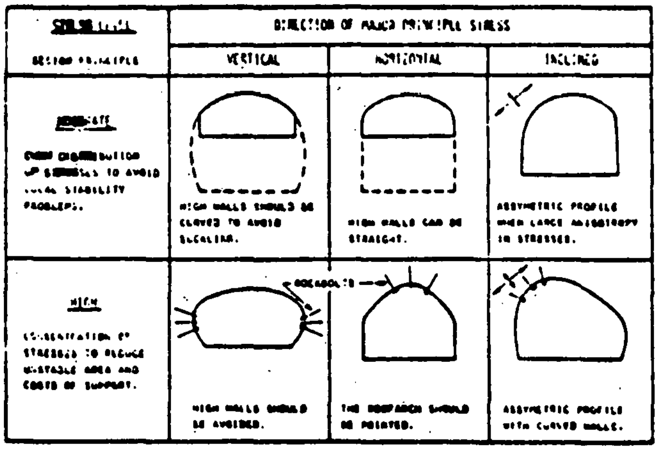


FIGURE C-1

Design Principles for Underground Openings in Rocks at Varying Stress Levels and with Varying Direction of the Major Principle Stress when this is Normal to the Length Axis of the Opening. (Selmer-Olsen and Broch, 1977)

4. Excavation sequence is dictated by rock conditions and support method. Two specific examples of excavation sequencing are given in Figure C-2 and C-3. Application of support after all mining is impractical in such large openings. Placement during construction ensures load transfer to the reinforcement or supports as deformations accompany subsequent excavation.

5. Support or rock reinforcement. The need for support or reinforcement can be assessed from the rock quality, in-situ stress field, opening dimensions by application of numerical method, analysis of wedge fallouts and numerical modeling. The rock classification systems can be a useful guide for the selection of support requirements.

The support pressure P as defined in Figure C-4 (Cording et al., 1971) has been used extensively in the design of large underground structures, and helps to quantify the support function. Its origin is in the design of artificial support, steel sets, etc., but can be used in the selection of rock bolt patterns and shotcrete linings. The support pressure has been found from compilation of several case examples to be well-correlated with room span and rock conditions. Cording and Mahar (1978) note that:

$$P = n B \sigma - C$$

where n = factor dependent on rock conditions
B = ream span
σ = rock density
C = pressure reduction term to simulate the effect of cohesion in the rock mass

The variation of n with rock quality is shown in Figure C-4. As the room span increases, not only does the number of bolts increase to maintain the same pressure over the increased room span, but also either the bolt strength must be increased or a reduction in spacing is required to provide the additional pressure. In shotcreting, as the span increases, the thickness of the shotcrete must, too.

Figure C-5 shows the support pressure in wall and the roof of some large underground openings, Cording et al. (1971). Values of n

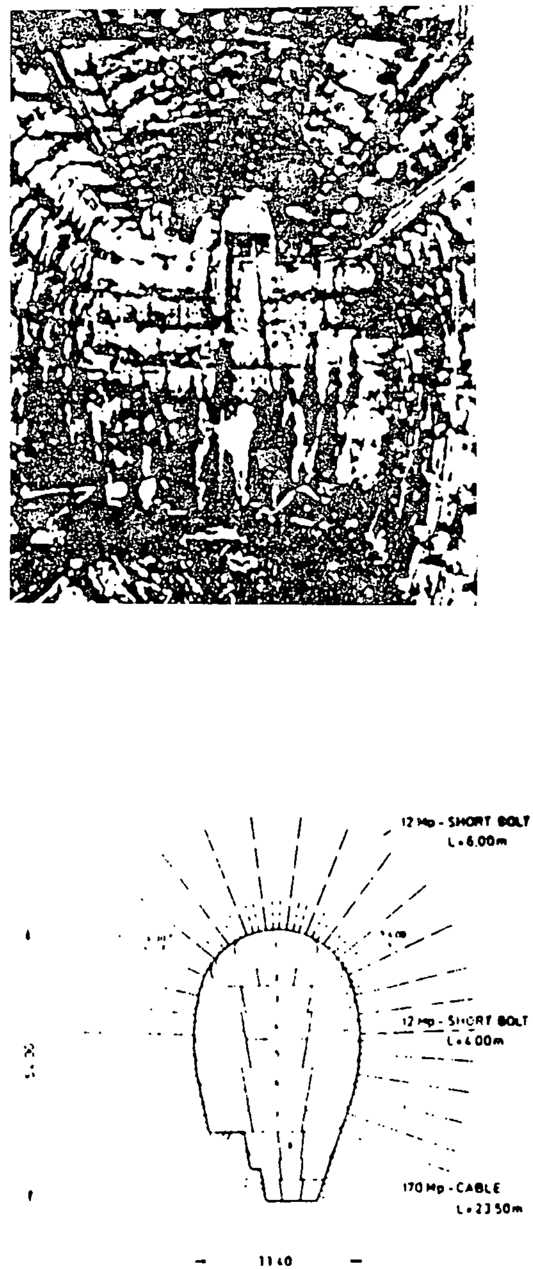


FIGURE C-2

Underground Power Station Waldeck II;
Sequence of Excavation and Support
(Muller and Spaun, 1977)

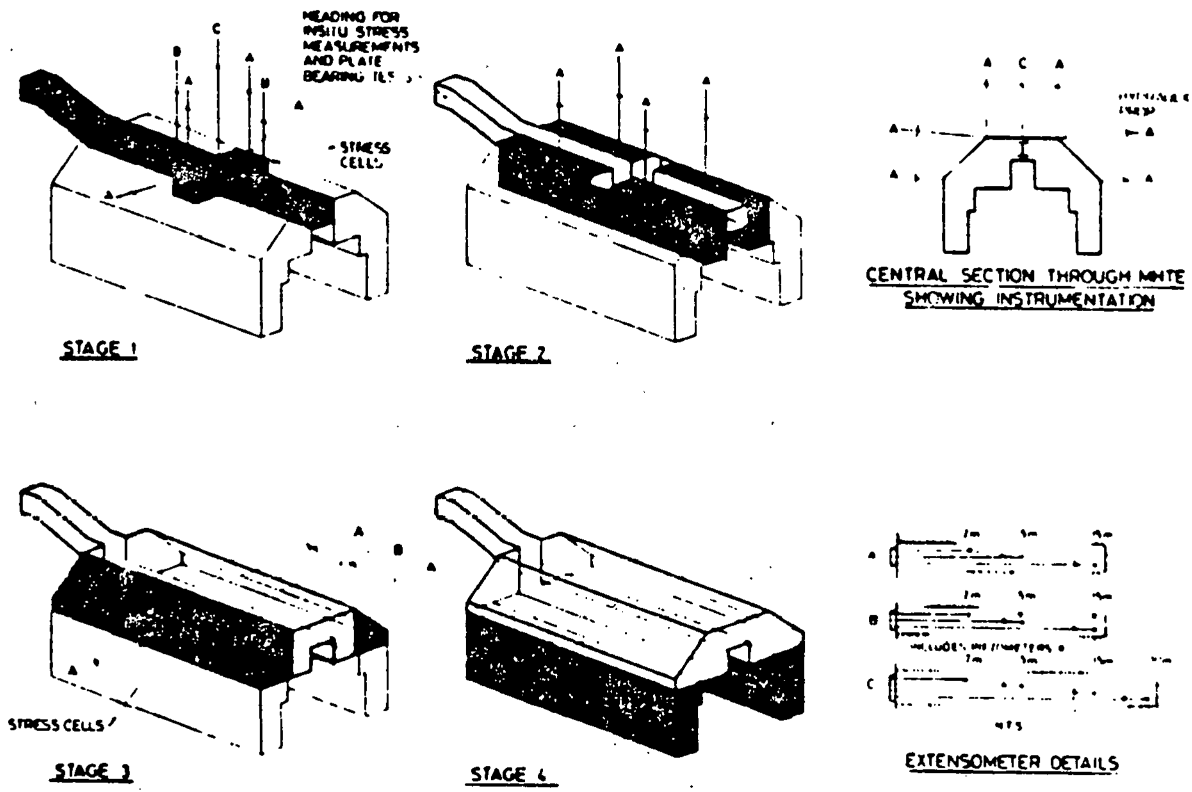
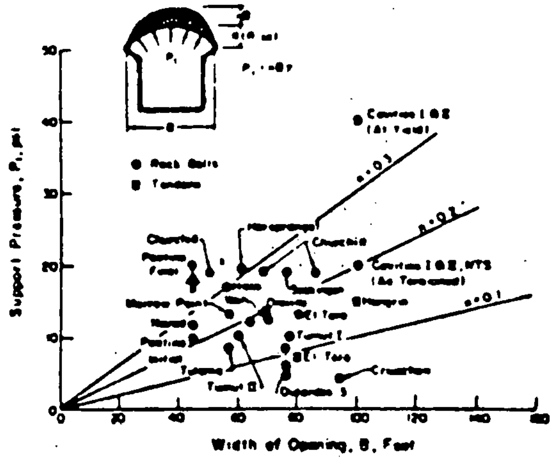
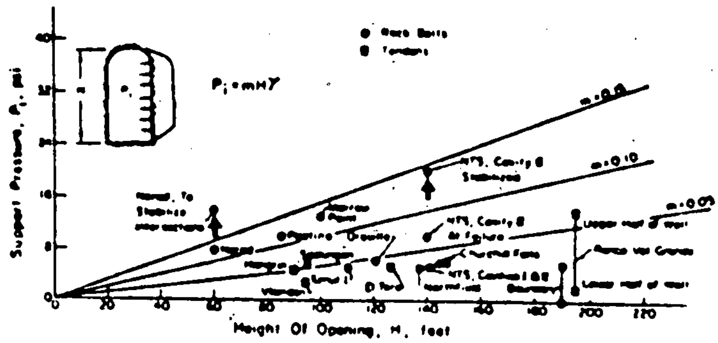


FIGURE C-3. Machine hall test enlargement: stage excavation
(Bowcock et al., 1976)



SUPPORT PRESSURES USED IN CROWN OF CAVERNS



SUPPORT PRESSURES USED ON CAVERN WALLS

FIGURE C-4

Rock Bolting for Support Pressures Underground Caverns (Cording et al, 1971)

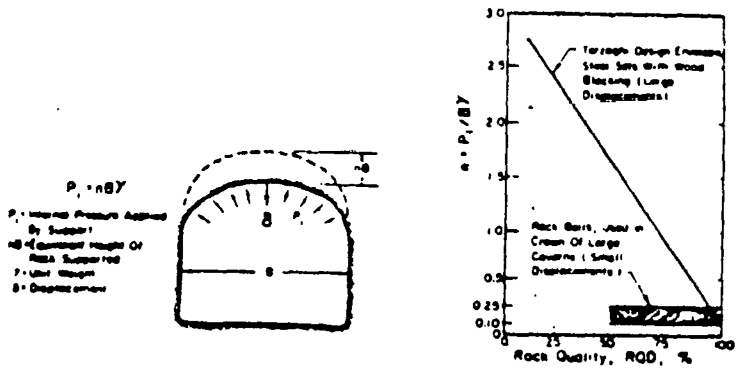


FIGURE C-5

Relation of Rock Quality and Displacement to Support of Opening (Cording et al, 1971) varying from 0.1 to 0.3 include most of the example quoted. For wall support, the pressure is plotted versus wall height H where:

$$P = m H$$

Values of n from zero to 0.15 bracket all the underground power stations included in Figure C-5.

Support pressures can be estimated by consideration of the likely block fallout estimated from the orientation of the room and the predominant joint directions. Sufficient support should be provided to carry the block assuming that the cohesion along the joints is zero. In estimating the maximum block size, joint spacings and joint continuity has to be considered. For irregular short joints, only partial roof fallout is likely, but for planer continuous joints, a large block spanning much of the room can significantly reduce the support pressures, Figure C-6. This support pressure can be supplied by bolts, cables, shotcrete, concrete, steel sets, etc. In bolt design, the bolt capacity and strength is selected to give ultimate average stress equal to the design pressure.

The support pressure estimation techniques developed for tunnels presented in the next section are, in general, applicable to large permanent openings. For large underground openings, the safety factor or degree of confidence should be higher than for most tunnels or underground mine openings and this is reflected both in the degree of geotechnical exploration and the quantity and quality of rock support.

5.0 STRESS AND STABILITY ANALYSIS

In the selection of rock support pressures, final opening location and opening shape, stress analysis using numerical models can be extremely useful. A result of stress analysis with respect to shape selection is shown in Figure C-7. Tensile stresses were eliminated by optimizing the excavation shape, John and Gallico (1976). Figure C-8 shows a finite element mesh, displacement and stress results for analysis associated with evaluating the effect of a major joint on room stability. Figure C-9 shows stress results for an investigation of the progressive relation and failure of rock around an underground power station.

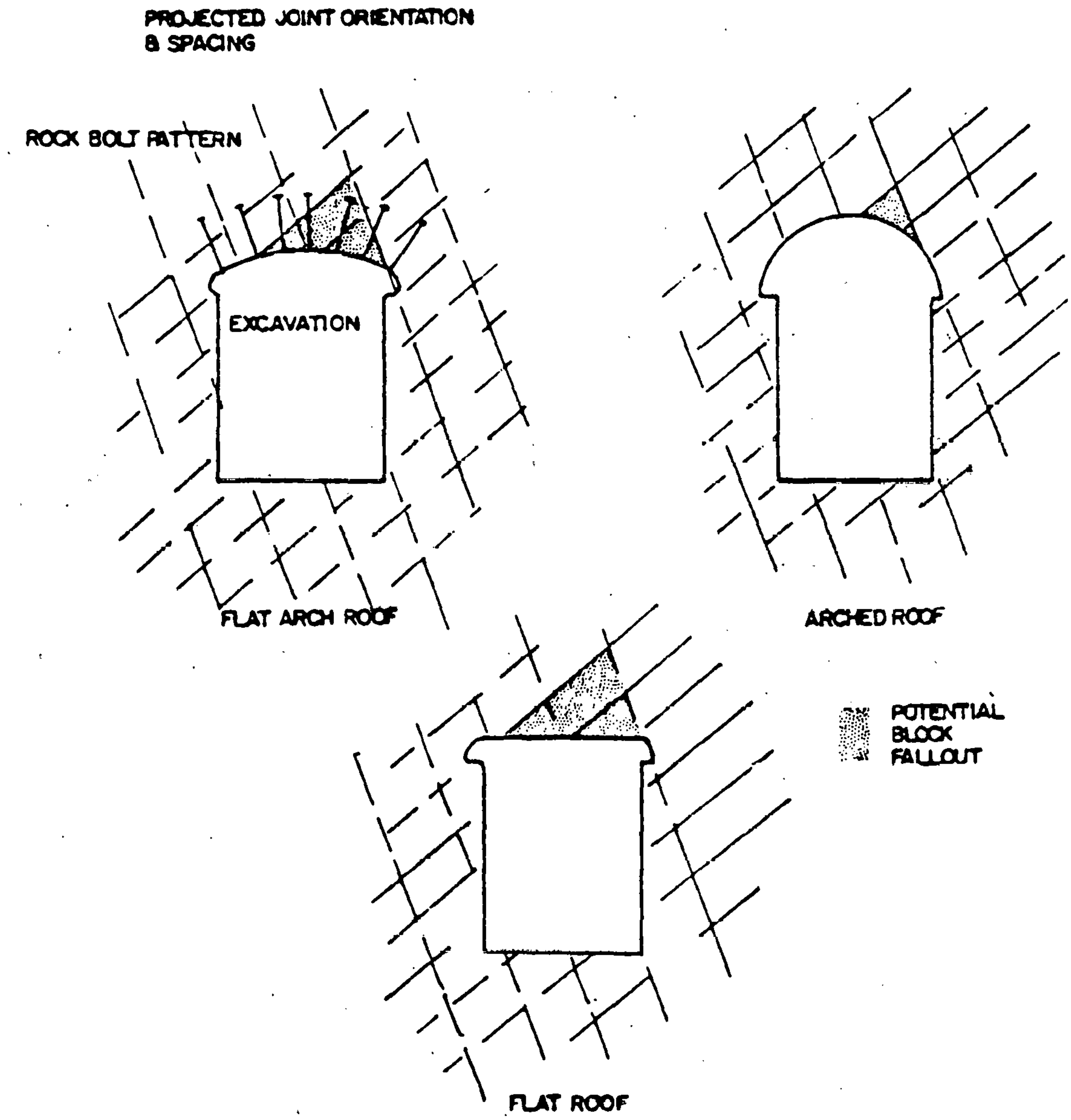


FIGURE C-6. Potential roof block fallout

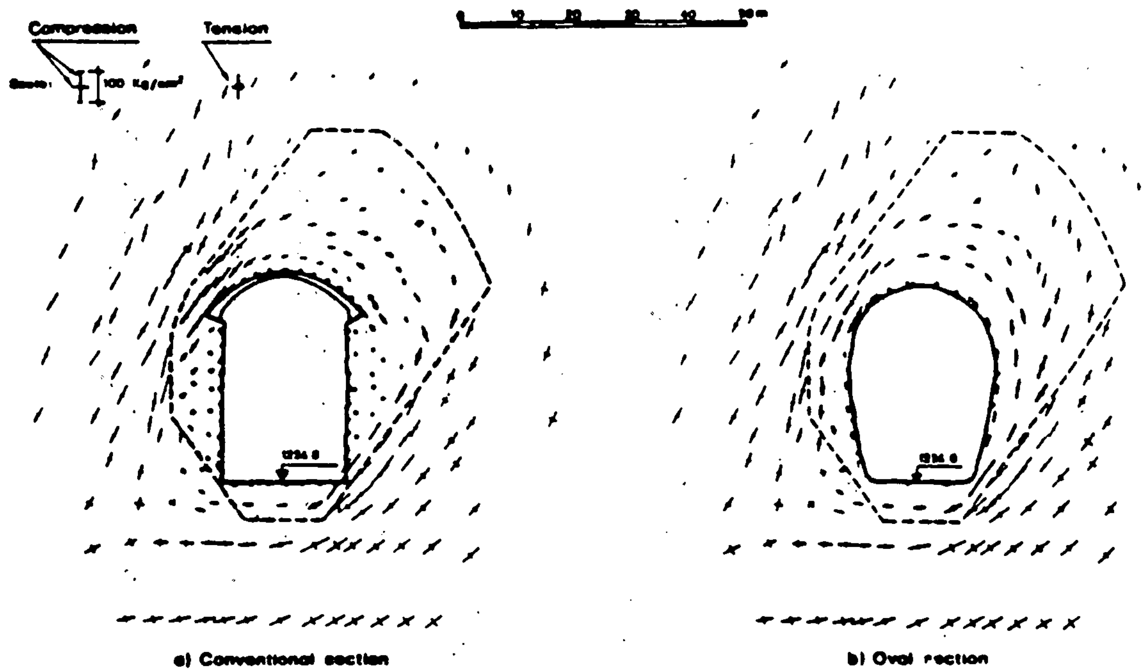
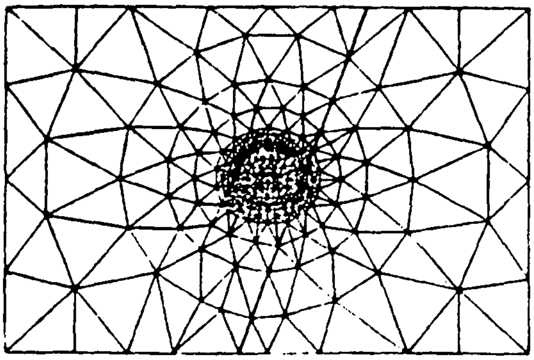
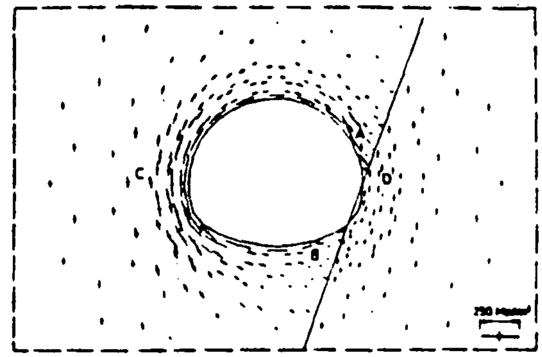


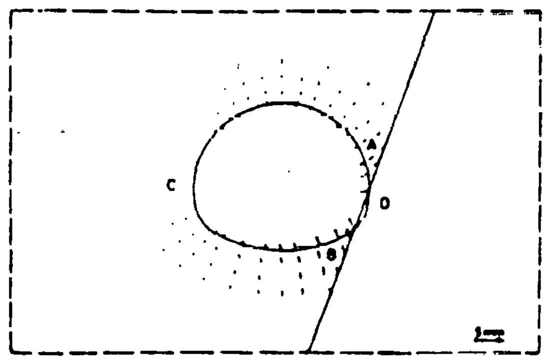
FIGURE C-7. Comparison of stress fields for two different cross-sections (John and Gallico, 1976)



a) Finite element mesh

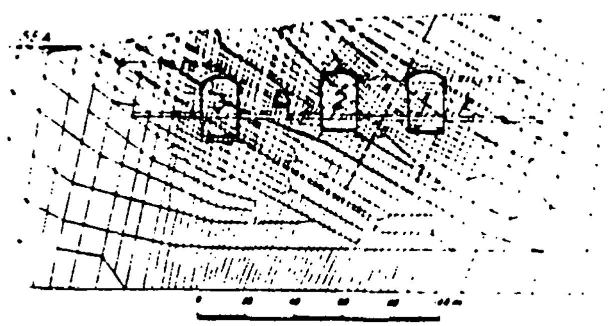


b) Displacements

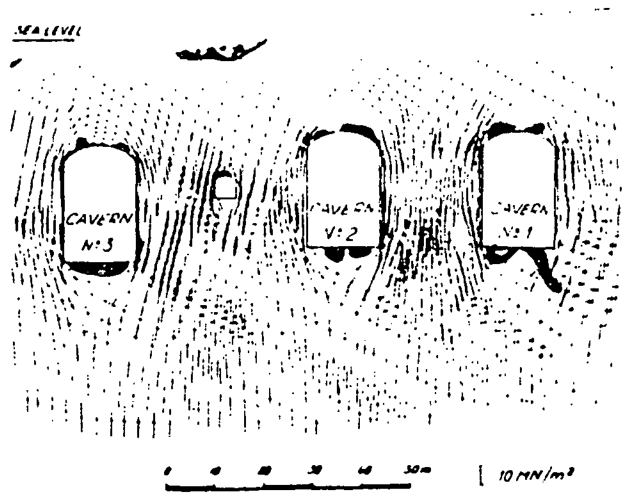


c) Principal stresses

FIGURE C-8. Finite element mesh and results for underground excavation design (Volstedt and Duddeck, 1977)



a) The element network simulating the structure of the rock



b) Results of the finite element calculations-no horizontal stress.

c) Results of the finite element calculations-horizontal stress 15 MN/m^2 present.

FIGURE C-9. Finite element mesh and results of underground excavations (Anttikoski and Aesaraste, 1977)

APPENDIX D

PROPERTIES OF DOME SALT

1.0 INTRODUCTION

This appendix presents the various rock mass properties of the Gulf Coast salt domes of Texas, Louisiana and Mississippi. The general characteristics of salt domes are much the same regardless of their location. Idealized sections are shown in Figure D-1. The real extent of the salt dome region is shown in Figure D-2 (Kupfer, 1963).

2.0 DESCRIPTION OF ROCK MASS

2.1 Lithology

There are more than 300 salt domes in the Gulf Coast Embayment, and more than 260 onshore domes in the Texas, Louisiana, Mississippi, and Alabama portion of the embayment. This description is confined to domes that are presently being mined by underground room-and-pillar methods.

In 1963, Kupfer listed ten operating or planned subsurface salt mines of the Gulf Coast. These are listed in Table D-1. The depths to salt in these domes range from 15 feet (Avery Island) to 1,880 feet (Bruinsburg) (Anderson et al., 1973). Depths to salt domes can be as much as 10,000 feet or more. The height of the domes above their base is extremely variable, depending on the amount of piercement into the overlying sediments. In domes that have risen to near the present land surface, it is of the order of 10,000 to 20,000 feet.

At the top of the near-surface salt domes is a caprock composed of anhydrite, gypsum and limestone. The limestone is generally at the top of the caprock, anhydrite at the base, and gypsum, anhydrite and calcite in the middle. Anhydrite is also draped down the sides like a hood. The caprock is normally 300 to 400 feet thick, but may be as much as 1,000 feet thick (Pierce and Rich, 1962) (Figure D-3). Two examples of salt domes will be detailed below.

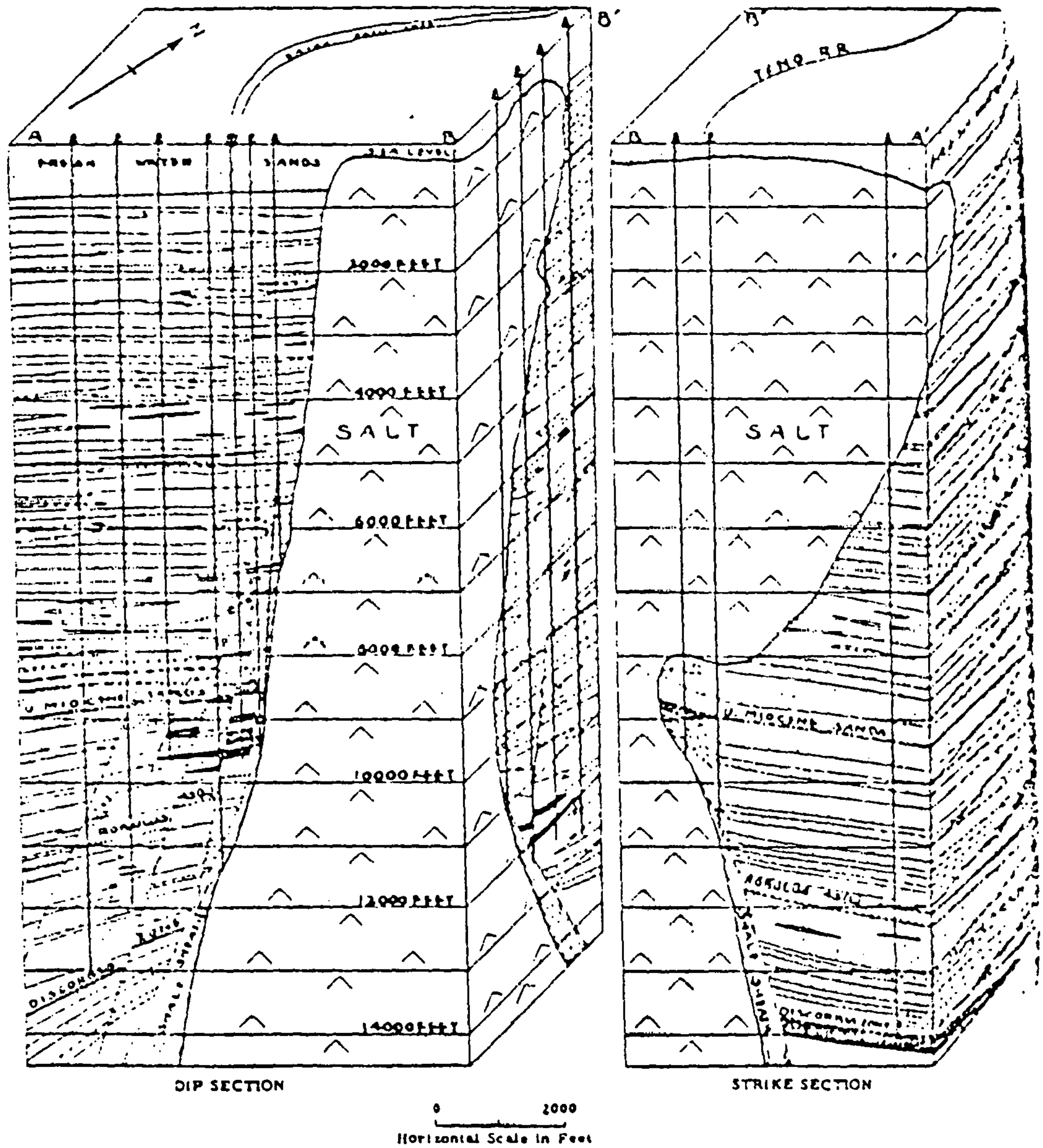


FIGURE D-1. Generalized Block Diagram of Avery Island Dome (Bates, et al, 1969)

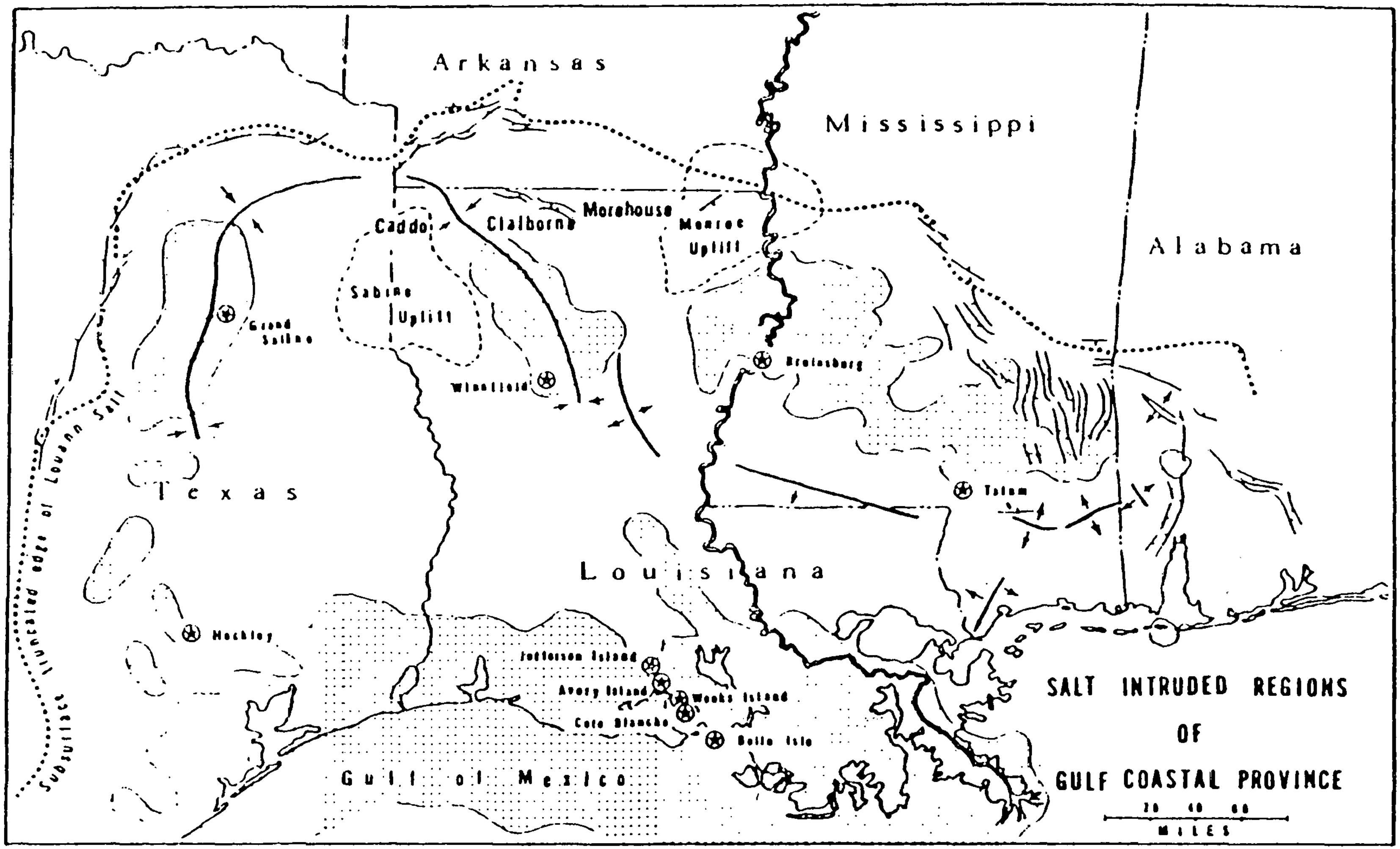


FIGURE D-2. Areas of intrusive salt (stippled) and location of underground salt mines (star) of the Gulf Coast region of the United States (Kupfer, 1963)

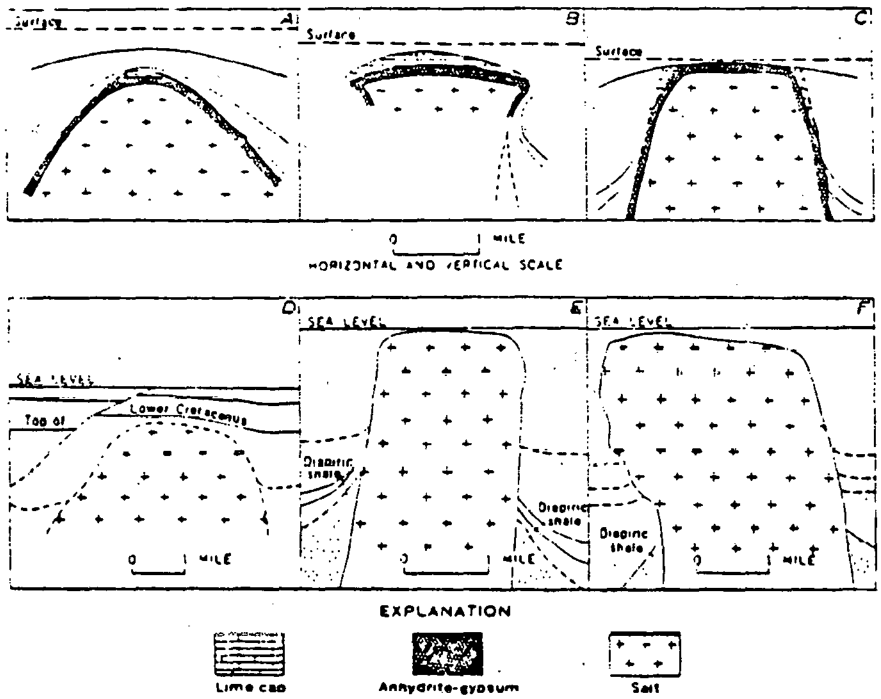


FIGURE D-3. Cross-section of salt domes
A-C: idealized sections;
D: La-Rue Salt Dome;
E: Weeks Island; and
F: Cote Blanche Island Salt Domes
(Pierce and Rich, 1962)

TABLE D-1*

STATUS OF GEOLOGIC MAPPING IN SUBSURFACE SALT MINES OF THE GULF COAST OF THE UNITED STATES

Name and Description	Mapped By	Comments
Grand Saline Dome Kleer Mine Morton Salt Co. Van Zandt Co., Tex.	Robert Balk AAPG, 1949	Classic paper Remapped by Muehlberger, Tex.Bur.Ec.Geol., 1959 Int. Geol. Cong., 1960
Jefferson Island Dome Jefferson Mine Diamond Salt Co. Iberia Parish, La.	Robert Balk AAPG, 1953 (Asstd. by G.T. Duvall)	Similar to Grand Saline; needs mapping in newer workings
Winnfield Dome Carey Mine Carey Salt Co. Winn Parish, La.	Hoy, Foose, and O'Neill AAPG, 1962	Stanford Research Institute
Weeks Island Dome Weeks Mine Morton Salt Co. Iberia Parish, La.	Donald Kupfer AAPG, 1962	Lower level mapped, upper level to be mapped
Avery Island Dome Avery Mine International Salt Co. Iberia Parish, La.	McMullen and Doxey (Unpublished)	Mapped summer 1961
Hockley Dome Hockley Mine United Salt Co. Harris Co., Tex.	Muehlberger and students (1961) (Inpublished)	Reconnaissance map, structure is very simple (personal communication, 1962)
Cote Blanche Dome Carey-Monsanto St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Belle Isle Dome Cargille Corp. St. Mary Parish, La.	Unmapped	Shaft sinking now in progress
Tatum Dome Lamar County, Miss.	?	Atomic Energy Commission
Bruinsburg International Salt Co. Claiborne Co., Miss.	Unmapped	Exploration drilling under lease and option

*Kupfer, 1963.

The Avery Island salt dome in Iberia Parish, Louisiana, is one of the Five Islands of the Louisiana Gulf Coast area. A generalized block diagram of the Avery Island Dome is shown in Figure D-1. The dome is circular in outline and the sediments dip steeply away from the dome. The country rock is the upper Miocene interval of soft, thick sand bodies and gravels with clay beds. The caprock is anhydrite, gypsum and calcite in ascending order and reaches a thickness in excess of 400 feet (Bates et al., 1969; Atwater, 1968).

Tatum Dome in Lamar County, Mississippi, is approximately 1,550 feet deep. The dome is nearly circular and nearly flat. The country rock is Miocene and Oligocene clays and sands and the contacts on the flanks are nearly vertical. The caprock ranges from 530 to 675 feet thick and consists of limestone, gypsum and anhydrite (Pierce and Rich, 1962).

2.2 Minerology

The salt dome deposits are almost pure sodium chloride except for the caprock. Anhydrite is the principal impurity and usually occurs as black bands in the salt. Bands of sandstone are known to exist as well as fragments of country rock (Pierce and Rich, 1962). Layering is the most distinctive physical feature. Most layers average 1 to 10 inches thick and consist of interbedded light and dark bands. The darker layers are anhydrite. Grain-size is coarse, distinctly crystalline, with prominent cubic cleavage. Most crystals range between 1/4 to 1/2 inch in diameter. Fine to very-fine-grained salt is rare. Pods of extremely coarse-grained salt occur with crystals 1 to 2 inches across.

2.3 Structure

Kupfer (1963, 1970, 1976) and Muehlberger (1959, 1968) have conducted or collected (from Balk and others) extensive studies of the structure of some existing underground salt mines (Grand Saline, Jefferson Island, Winnfield, Weeks Island, Avery Island and Hockey Domes).

The layers in the salt all stand essentially vertical and are isoclinally folded around vertical axes. The roof and floor of the working show transverse cross-sections of the folds which display varied pattern complications of the fold. The axial planes are vertical and parallel to the limbs of the folds. Detailed mapping shows micro-faults and complex folding. Typical attitudes of the features are shown in Table D-2. Closures are more common in the South Louisiana domes.

TABLE D-2*

TYPICAL ATTITUDES OF FEATURES IN THE SALT AT FIVE MINES

Salt Dome	Dip of Layering	Plunge of Lineations	Plunge of Folds
Grand Saline	51^o-90^o, Avge=80^o	53^o-90^o, Avge=75^o	78^o-80^o(two)
Jefferson	75^o-90^o, Avge=90^o	70^o-90^o, Avge=88^o	
Avery	66^o-87^o, Avge=77^o		
Weeks	78^o-90^o, Avge=86^o	(Ax. pl. of folds dip 80^o-90^o, Avge=85^o)	79^o-90^o, Avge=83^o
Winnfield	50^o-90^o, Avge=75^o	55^o-87^o, Avge=75^o	

*Kupfer, 1963

Fractures are uncommon, but natural exfoliation fractures develop as rooms remain open. Faulting is rare, and when found, is very minor. However, shear zones are very common on the periphery of the dome and smaller shear zones occur within the dome. The larger shear zones delineate the "spines" of the salt movement.

2.4 Rock Quality

The rock quality designation of domal salt can only be estimated. The bedding is essentially vertical, jointing rare to non-existent, and the rock salt 97 to 99 percent pure. These factors indicate that the RQD would be 90 percent or above (excellent).

3.0 PROPERTIES OF INDIVIDUAL DISCONTINUITIES

No testing of individual discontinuities of dome rock salt has been found in the literature. Iriaxial compression testing of salt rock cores (4-15/16 inch diameter) from Tatum Dome, Jackson, Mississippi, was conducted by the Division of Engineering Laboratories, Bureau of Reclamation. Shear strengths were determined during these tests, as well as stress-strain curves.

Hansen (1977b) conducted triaxial tests and obtained the failure envelope shown in Figure D-4. The average shear strength parameters in the normal stress range of 2,000 to 3,000 psi was a cohesion of 1,700 psi and a friction angle of 33 degrees.

4.0 PHYSICAL PROPERTIES FOR OVERALL ROCK MASS

Much of the data was obtained from Bradshaw et al., (1968), Deere and Miller (1966) and Project Dribble (1962). Project Dribble provided data for cohesion and friction angles and uniaxial compressive strength. Young's moduli were found in all of the above references. Bradshaw et al., (1968) obtained values of 0.5 x 106 psi for tangent moduli.

Rock salt is essentially isotropic, e.g., strength properties are similar when tested parallel or perpendicular to bedding.

Hansen (1977a) performed extensive tests on salt from Jefferson Island. Included in the tests are triaxial compression tests, triaxial creep tests and tensile strength tests. Indirect tensile strength tests averaged 220 psi. Average tangent modulus over a stress range of 2,000 to 3,000 psi was 10^6 psi.

In-situ elastic properties were determined by Christensen, utilizing a three-dimensional velocity log (Christensen, 1966). If a standard reduction factor of 0.4 (Deere and Miller, 1966) is used, the Young's Modulus would be on the order of 2×10^6 psi.

5.0 ENVIRONMENTAL FACTORS

5.1 Time (Creep)

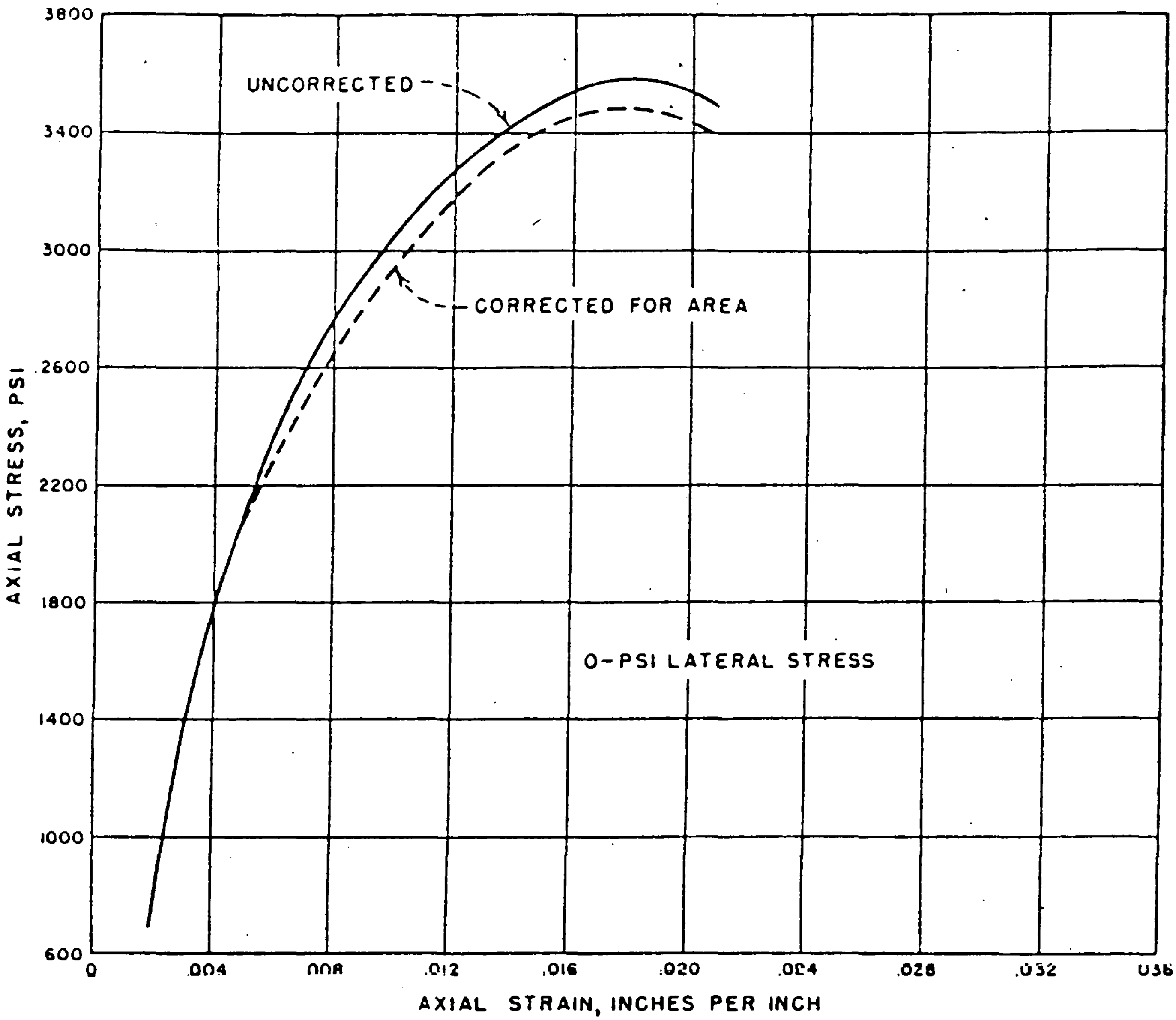


FIGURE D-4. Triaxial stress-strain curves
(Hansen, 1977b)

Some in-situ and laboratory testing of rock salt from domal salt mines has been conducted by various investigators. Laboratory studies included Project Dribble (1962) and Lomenick and Bradshaw (1969) and Thompson and Ripperger (1964).

Lomenick and Bradshaw conducted extensive tests of model pillars from bedded and domal salt. Included in these studies were rock salt from the Grand Saline and Cote Blanche Domes. Creep tests were conducted at varying temperatures and axial loads and with different pillar shapes. It was observed that there is an initially high rate of deformation that diminishes and becomes constant for the various rock salt types. An empirical relationship was developed from the tests for strain rate and cumulative deformation.

$$E^{o} = 0.39 \cdot 10^{-37}\, T^{9.5}\, \sigma^{3.0}\, t^{-3.0}$$

$$E = 1.30 \cdot 10^{-37}\, T^{9.5}\, \sigma^{3.0}\, t^{0.30}$$

Where:

E^{o} = strain rate (in/in/hr)

E = cumulative deformation (in/in)

T = absolute temperature (^{o}K)

σ = average pillar stress (psi)

t = time (hr)

This relationship appears to be the best creep law with respect to temperature. Most creep laws are a function of differential or axial stress and temperature. This shown by Thompson and Ripperberger in Figures D-5a and D-5b in tests on salt from Grand Saline Dome. The relationship derived was:

$$E^{o} = C \left(\frac{\sigma}{\sigma_o}\right)^{n}$$

Where:

E^{o} = strain rate (in/in/hr)

σ = axial or differential stress

σ_o = characteristic stress

C and n are constants

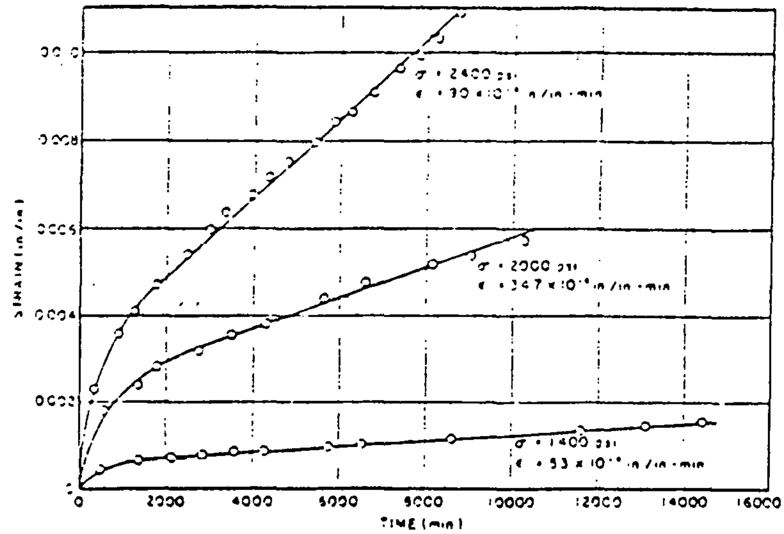


FIGURE D-5a. Creep curves for halite
(Thompson and Ripperger, 1964)

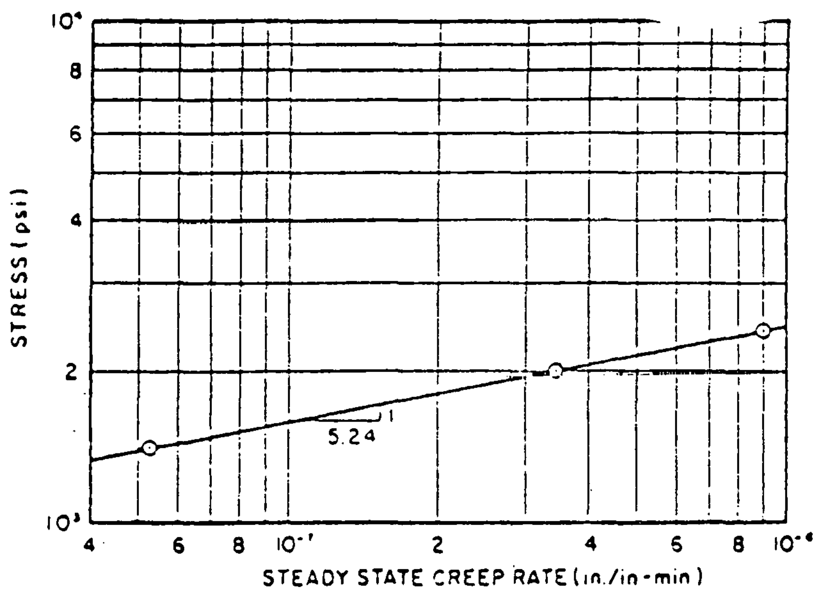


FIGURE D-5b. Stress creep rate curve for halite
(Thompson and Ripperger, 1964)

Project Dribble tests also exhibited creep under high axial and confining pressures. The axial strain of salt at 5,000 psi confining pressure is more than 10 times that with no confining pressure. Nair and Deere (1970) derived the equation:

$$E_c = A_\sigma^n t^m$$

Where:

A, n and m are constant

If temperature is considered,

$$E_c = A_\sigma^n t = B^m t$$

Where:

B is a function of temperature

Creep test performed by Hansen (1977a) yielded typical curves for on-stage and multi-stage creep. The curves fit the power law formulation ($e = K t^n$) with different K and n values depending on differential stress. Maximum creep strain was up to 11 percent.

Baar (1975) warns that theoretical calculations based on laboratory experiments must not be applied to in-situ conditions, because of lack of strain-hardening in actual pillars and stress adjustment.

Reynolds and Gloyna (1961) conducted in-situ creep measurements in the Grand Saline mine and found that the stress concentration of 4,000 psi on a room 66 feet in width and 23 feet in height at a depth of 700 feet was 0.001 in. per day. The time required for the deformation to be 95% complete was 4.7 years. The creep rate can be approximated by:

$$\frac{de}{dt} = 0.03\ e^{-0.635t}$$

Where:

$\frac{de}{dt}$ = creep rate

0.03 = A = constant

-0.635 = K = exponential constant

t = time

This is the decay formula.

5.2 Temperature

The physical behavior of domal rock salt is drastically affected by temperature. Thermal conductivity, thermal diffusivity and strength decrease sharply with increasing temperature and the deformation rate increases sharply. These tests were conducted in the laboratory by Lomenick and Bradshaw (1969). No in-situ tests have been found in the literature.

Laboratory testing by Lomenick and Bradshaw (1965) indicate that higher temperatures with constant stress increase the amount of strain by seven times. Increasing temperature after loading also accelerates strain.

Bradshaw et al., (1968) demonstrated that the compressive strength of dome salt from Grand Saline is reduced by approximately 33 percent when tested at 200°C.

5.3 Pressure

Increased pressure on model pillars causes increased strain. When compared to an increase in temperature, however, the changes are small. Long-term applied pressure can produce very large strains in the laboratory (Lomenick and Bradshaw, 1969). Baar (1975) predicts that this is also possible in-situ if measures are not taken to relieve the pressure

5.4 Water/Moisture

Domal salt has moisture trapped internally in vesicles. The porosity of dome salt is approximately 1.7 percent (Gloyna and Reynolds, 1961). Hansen found a water content of 0.02 percent in Jefferson Island salt (1977a). Seeps have been reported in several mines due to faulting and folding and some anhydrite bands are permeable. However, these seeps are not major.

The trapped brine can be released with considerable energy when the rock is heated. Salt from Winnfield, Grand Saline and Weeks Island Domes was tested by Bradshaw et al. (1968). The salt did not fracture at temperatures of up to 400°C.

6.0 NUMERICAL RESULTS OF LABORATORY TESTS

6.1 Thermal Properties

1. Conductivity - According to Bradshaw et al. (1968), we can use the values for single crystals (Figure D-6). NOTE: There is no mention anywhere of variation of K with pressure so presumably it is not significant.

2. Specific Heat - Sources agree that this changes very little with temperature or pressure.

3. Coefficient of Expansion - Varies from 2.0×10^{-5} to 2.2×10^{-5} in/in/^{o}F

4. Disintegration Temperature - Natural salt contains small brine inclusions which cause shattering at elevated temperatures. The main reference is Bradshaw et. al. (1968) where shattering temperatures are in the range 250-350^{o}C for bedded salt and 400^{o}C for dome salt.

6.2 Mechanical Properties

1. Elastic Constants

   a. Young's modulus: Serata has measured this and given a range from 0.8-2.3 x 10 psi.

   b. Bulk modulus: Serata gives 0.55-0.85 x 10 psi.

   c. Poisson's ratio: Serata says this can vary from 0-0.5 according to applied stress.

2. Yield and Failure - This is the point which is in dispute since it depends on rate of loading and instrument sensitivity. Baar (1977) thinks that the elastic limit of salt is reached at stress 100 psi. In contrast, Winkel (1972) and Hofer (1969) are producing yield points of the order of 1,000 psi or more. The curves presented by Heard suggest strongly that this discrepancy is a result of the short-time scale of lab tests.

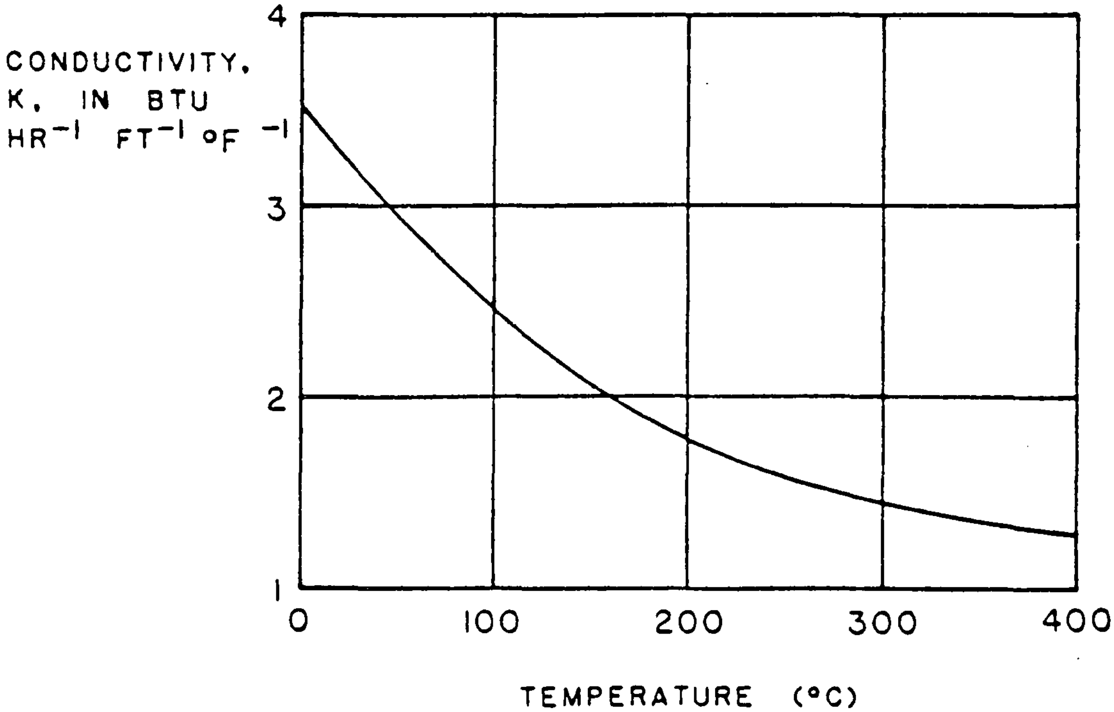


FIGURE D-6. Values of single crystals

3. Creep Behavior - Obviously, the form in which a creep law is framed depends strongly on the view taken in paragraph 2. The important references are Serata (1970) and Bradshaw et al. (1971) and Williams and Hocking (1979). Having chosen a law from laboratory tests, one must then be very careful about how to apply it to salt in bulk.

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APPENDIX E

STORAGE CAVERNS IN SALT

1.0 INTRODUCTION

This appendix describes the historical use of underground storage for various hydrocarbon and gases and chemicals in solution-mined caverns. Some of the economic, environmental, technical and safety factors associated with the construction of solution-mined storage facilities are also outlined.

From a technical standpoint, the impermeable nature of salt, as halite, permits containment of liquids and gases at low to high pressures. Since salt is easy to dissolve through well bores by water injection, large storage volumes can be economically constructed. Salt domes and bedded or layered salt beds are found to be favorably located in the United States with respect to possible use for storage near many refineries and areas of product demand.

2.0 EARLY HISTORY

Early in the 1920's, Holland began using salt cavities for the disposal of chemical and industrial waste materials. World War II spawned the idea of employing salt caverns for storage of gases and liquid hydrocarbons, and in 1948, propane was stored for the first time in the U.S. in cavities created in bedded salt deposits in Kansas. The use of such cavities for liquid propane and butane storage became extensive over the period 1948-1960.

By 1956, a summary of salt cavern storage statistics showed that construction costs for solution-mined LP storage were reasonable and the technical feasibility was well established. Possible contamination of LPG and other stored products through contact with the salt was considered to be negligible and only minor technical problems were encountered. As examples, supersaturation of the brine solution caused precipitation of salt within casings during cavity development and falling rock stringers sheared casing strings used for cavity development and recovery of products.

The storage of pressurized gases in salt cavities is a more recent development. For example, in the U.S., the first reported use of such storage facilities for natural gas was in 1961 when the Southeastern Michigan Gas Company leased a solution-mined cavern, near Marysville, Michigan, formed by routine brine production, from the Morton Salt Company and converted it for this purpose. The first cavern designed exclusively for natural gas storage was constructed by the Saskatchewan Power Company in Melville, Saskatchewan, in 1963. Here, a 290,000 barrel cavern was solution-mined in the Prairie Evaporite Salt at a depth of approximately 3,700 feet.

By 1970, total underground storage capacity reached about 160 million barrels. Transcontinental Gas Pipe Line Corporation constructed the first solution-mined salt cavern for gas storage in the United States in 1970. Here, twin caverns were completed in the Eminence Salt Dome in Covington County, Mississippi, over the depth interval 5,700 feet to 6,700 feet. Due to the depth of these caverns within the salt, giving rise to higher confining pressures and temperature, and the plastic nature of salt, a technical problem arose through cavity closure upon gas pressure reduction. This closure phenomenon has also been noted at other storage facilities in Europe.

At this point in time, underground storage of liquefied natural gas (LNG) in solution-mined caverns has not been attempted and proved. The technical aspects of storing LNG in salt have not been thoroughly researched; however, difficulties are to be anticipated. The extremely low temperature of LNG may break down the salt and disrupt the salt integrity required for containment. Secondly, boil-off, with the subsequent loss of a portion of the stored fluids, with time, will be severe. Due to the boil-off factor, some type of refrigeration will probably be required in connection with an LNG underground storage unit. Attempted construction of LNG storage caverns in salt, if needed in connection with peak shaving or base loads, will be preceded by a basic research program.

The common use of surface tanks for the storage of crude oil has reduced the need for construction of solution-mined caverns in the

United States. However, tactical or strategic storage of crude is extensively practiced in many European countries where geologic conditions permit. The need for such storage arises from the lack of readily available oil supplies through production, and a consequent dependence of maintaining a sufficient and protected supply on hand in the event foreign sources are interrupted. The possibility of constructing tactical or strategic storage in the United States is now being considered by various federal agencies.

3.0 TECHNICAL CONSIDERATIONS

Excellent trade journal articles date back to 1950 on the technical aspects of storage in solution-mined cavities. In the past, a proper heed to technical considerations has resulted in a minimum number of cavern construction problems giving rise to safety hazards. Although it appears advantageous for industries involved in storage to adopt guidelines or standards for the construction, development, and operation of solution-mined cavities, they have not been adopted to date. It may be important to the storage industry that such standards or guidelines are modified in the future for both geotechnical and environmental factors.

The characteristics of the liquid or gas to be stored with regard to temperature and pressure partially determine the suitability of a particular location for solution-mined storage. The geotechnical feasibility is partially based on the following factors:

- The physical properties of the rock overlying salt,
- The physical properties of the salt itself, such as impurities,
- The depth to the top of salt,
- The thickness of the salt,
- The availability of a water supply,
- The method of brine disposal.

In the absence of an industrial code for the design and construction of storage, and despite the fact that the criteria for storage in solution-mined caverns are fairly well-defined, investigation of geologic conditions prior to attempting solution cavern storage construction and development should be considered essential. An exception to the need for a geotechnical investigation occurs where past construction and operation of cavern storage at a particular location proivdes the necessary feasibility criteria. Where solution-mined storage is located in new areas, the following type of investigation may be considered applicable:

1. A core drilling program, consisting of one or more small diameter holes should be conducted. By core analysis, combined with laboratory testing and information from well logs, the physical and hydrologic characteristics of the rock and salt strata should be determined. Laboratory measurements to determine salt permeability affecting containment should be made and the amount of impurities that may affect cavern development techniques by washing should be determined.

2. Well logs should be interpreted and laboratory tests analyzed to determine the physical strength of the overlying rock strata. A rock mechanics program may be conducted on the basis of the well logs and lab data to determine safe operating pressures and plan maximum cavity development. This type of program is regarded as particularly applicable to multiple storage cavity development.

3. In addition to determining the suitability of the roof or caprock condition, the depth to the top of the salt and other characteristics of the salt strata that will affect the washing program should be determined in the feasibility study. The data from core drilling may also be used to establish setting depths for various casings and tubings used in well development and operation.

4. A feasibility study may also require identification of fresh water supply sources and methods for brine disposal.

For the type of storage and the volumes required in the past, few problems have arisen in the development and the operation of underground storage. Greater volumes of crude or product storage may be required in the future. If these volumes are to be located within a limited area, the data obtained during the feasibility study may be used in advanced methods of mathematical modeling to establish safety factors for maximum storage cavity diameters and well-to-well spacings.

The economics of storing hydrocarbons and chemicals as liquids or gases, in comparison with other forms of storage, are extremely favorable. The geologic conditions for practicing solution-mined storage have been proven through 25 years of cavity development and operation. Construction of solution-mined storage will continue in the future for LP gases and chemicals where appropriate geologic conditions and other factors related to distribution and demand are available. Requirements for methane (and low BTU gas) storage will be minimal, since more favorable storage options usually exist. The future of LNG storage is questionable and depends upon establishing feasibility by appropriate research and development. Future strategic storage requirements for large volumes of crude or LP gases is partially dependent upon passage of regulations or legislation. Appropriate investigations for the technical feasibility of constructing and developing solution-mined storage should be conducted.

4.0 UNDERGROUND GAS STORAGE PERFORMANCE AND SAFETY MONITORING

4.1 Cavern Collapse

The likelihood of a cavern collapsing has been evaluated as being a remote occurrence provided that contributory conditions are avoided or monitored. All four known instances of salt cavern collapse (Bayou Choctaw, Louisiana, 1954; Grand Saline, Texas, 1976; Belle Isle, Louisiana, 1973) occurred during brine solution mining and are believed to have resulted from uncontrolled or accidental leaching of the salt near the top of the dome, rather than from structural failure of the cavern roof. Thickness of the cavern roof in each of these occurrences was less than 300 feet.

4.2 Operational Performance

As noted by Katz and Couts (1978), even the most casual observer visiting a gas processing plant, a compressor station, or similar facility is impressed with the amount of instrumentation dedicated to the protection and control of equipment malfunction and system failures. Every aspect of the surface installation, even those in which the probability of failure is very slight, is constantly observed by human operators or automatic instrumentation and almost every conceivable malfunction is covered by a contingency plan for corrective action and damage control. This same philosophy of operational monitoring and contingency planning should be a major part of any subsurface storage design.

The materials of the subsurface environment, rock and its contained fluids, are not uniform and homogeneous to the degree that we are accustomed to find in manmade materials produced under modern levels of quality control. In designing a steel surface storage tank, we may call for materials meeting certain specificaions, observe and inspect the fabrication, and pressure-test the unit before use. In the design of underground storage, we may search for areas where the character and structure of the geological materials seem most favorable but otherwise we must accept them as they are and design accordingly. Even with the most extensive application of available geotechnical knowledge and instrumentation, we are never able to fully inspect, test, or understand all geological and hydrological characteristics of the storage enclosure. The possibility of an unidentified joint plane or fault or an unrecognized and unpredictable variation in lithology may exist. The problem may be more severe in aquifer or depleted field storage where the only access to subsurface knowledge is by indirect means such as seismic and gravity surveys and more direct but still very sparse information from rock samples, core analyses, and logs from widely spaced bore holes. It is also a problem in mined storage caverns where a seemingly innocuous minor fracture or joint in the cavern wall may represent a much larger fracture or other structural defect only a few inches or feet beyond the limits of the excavation. Even with the most careful exploration, design, and development, it is prudent to provide a means of recognizing the escape of the stored liquid or gas beyond its intended enclosure. Because of the otherwise desirable remoteness of underground storage from the surface environment, such leakage may continue for a very long time and involve very substantial quantities of gas before it is recognizable unless the initial design includes provision for early detection of such leakage.

Failure of natural occurring material or of a correct understanding of their characteristics is not the only hazard in underground storage. Access to, and use of, underground storage requires manmade installations and materials both underground and at the surface. Cement bonds between rock and casing may fail, casing or tubing may corrode, or a truck may back into a well head. The consequences of such events may range from small volume leakage around the well itself, to gas charging and pressurization of a shallow aquifer, to rapid venting of the storage reservoir. Any such event must be detected as soon as possible and then controlled effectively. If immediate control is not possible, such a detection must set in motion a contingency plan of emergency operations, remedial action, damage control and public protection.

Three distinguishable environments are involved in operational monitoring and safety considerations. Each has its own characteristics, potential problems and each requires specific monitoring and control functions.

4.2.1 The Deep Subsurface Environment.

The deep subsurface environment is that immediately surrounding the storage reservoir or cavern, normally consisting of consolidated rock. In this environment, the major potential problem is leakage from the storage reservoir or cavern itself because of structural lithologic inadequacies. Each installation requires its own specific design, but presently, the most common method of monitoring the deep environment is through observation wells situated above and peripheral to the storage reservoir. Gas escaping into adjacent fluid-filled, porous, stratigraphic units, particularly those of restricted communication, increases the fluid pressure in these units; this may be observed by monitoring the height of the fluid level in observation holes. Further, with increasingly sensitive analytical instrumentation, it is now possible to detect dissolved gas in formation waters at a level of only a few parts per million. Thus, by observing variations in water level and analyzing for trace quantities of gas in water samples, it is possible to detect the migration of gas from adjacent formations. Lateral gas migration can be detected by similar methods or by peripheral observation wells completed in the aquifer outside the intended limit of stored gas. Obviously the number and location of observation wells and the zones in which they are completed are dependent upon the geology of the specific storage area.

4.2.2 The Near Surface Environment

The near surface environment includes the unconsolidated overburden together with shallow consolidated rock formations. This environment is that which is freuently entered in the course of normal surface utilization and includes "shallow" aquifers contributing to a groundwater supply, quarriable resources, and the materials penetrated by footings and pilings of surface structures. Ideally, escaping gas would be detected and controlled before reaching this shallow environment. However, it is in this environment that unanticipated gas accumulations may pose the greatest threat because of its accessibility and frequent penetration. Gas detection and monitoring techniques for this environment are similar to those recommended for the deeper environment; however, their location and design depends not only upon the geology and hydrology of the area, but upon the character of surface utilization. This level of monitoring must be reviewed and amended periodically as surface use changes.

4.2.3 The Surface Environment

Significant occurrences of stored gas in the surface environment should only occur in the case of severe mechanical failure. Even major leaks from the storage reservoir or cavern will be attenuated by the long and constricted flow path through the overlying rock and normally would be recognized and controlled long before venting to the surface.

The most probable cause of gas release into the surface environment will be directly or indirectly associated with the mechanical installations of wells, shafts, or pipelines. All have occurred. Direct venting occurs when a well head or shaft seal fails or is ruptured by accident and the gas flows directly into the atmosphere. Such events are normally unpredictable with little or no opportunity for detection in advance. Indirect failures due to casing or tubing corrosion or cement bond failure often develop more slowly and, depending upon the nature and location of the defect, may be detected in either the deep or shallow subsurface monitoring systems or by direct observation of the installation itself by such means as the observation of the level and pressure of annular fluids, bond logs, and repetitive radioactive surveys. When such mechanical leakage goes undetected, it may result in the injection of gas into and pressurizing of shallow formations which may subsequently blow out. In the case of pipelines, failure is more commonly due to defects in materials or corrosion.

While the probability of direct gas venting to the atmosphere is small, should it occur, it is likely to be sudden, of considerable volume, and not subject to immediate control. Particularly in the case of LPG, which, being heavier than air, disperses at near ground level, a significant hazard could exist over a broad area. Where it is even remotely possible that such an event could pose a hazard to property and human life, a contingency plan should be prepared including notification of public safety officials, and optional evacuation plans as well as damage control measures.

5.0 LEGISLATION AND ENVIRONMENTAL IMPACT OF UNDERGROUND GAS STORAGE

5.1 The Environment

The impact by human actions upon the environment is an undeniable result of man's very existence on this planet. It is only recently that governments have assumed the responsibility of assessing the magnitude of man's impact on the environment and deciding whether this magnitude of change endangers the safety of animals, plants and man, and whether the benefits are lesser than, equal to, or greater than the importance of the change.

The underground storage of gas has an impact upon the environment, like any change. Storage fields affect, to varying degrees, the groundwater of the area, land use, acoustical levels, and depending on the area, man and other biota.

5.2 Federal Legislation

The objectives of a successful environmental impact report (EIR) are simple: all evidence collected must demonstrate that the impacts predicted are not of a magnitude to adversely affect the safety of the public and/or dangerously affect the ecosystems. The underground storage of gas will require an EIR, if federal approval is necessary, or if state laws require such analysis. The Natural Gas Act was passed providing the Federal Power Commission (FPC) with the authority to issue certificates to qualified applicants who are willing to conform to the provisions of the act and the requirements, rules and regulations of the Commission. The National Environmental Policy Act (NEPA) was passed in 1969 to provide a mandate for protecting the environment, and this act is applicable to those projects subject to federal jurisdiction.

The Bureau of Natural Gas of the Federal Power Commission is charged with releasing a final environmental impact statement (EIS) after all evidence is presented before the staff. All departments of the Federal government are also requested by the FPC to review the evidence presented by the Gas Company (applicant) before the final EIS is published. This report is directed to be an unbiased, comprehensive document that weighs the pros and cons of the project and that complies with the established legislative requirements.

Early in the application of the "new" environmental laws, several environmental statements presented by the FPC were contested by intervenors declaring that the FPC staff had not taken an objective approach to the project.

5.3 Court Hearings

In the case of Greene County Planning Board vs. FPC, 1972, the courts criticized the FPC for "abdicating a significant part of its responsibility" and being "content to collate the comments of other Federal agencies, its own staff and the intervenors and once again to act as an umpire. The danger of this procedure and one obvious shortcoming is the potential, if not likelihood, that the applicant's statement will be based upon self-serving assumptions" (footnotes ommitted).

The intervenors, in a recent FPC hearing, charged that the FPC staff made statements that relied too much upon evidence, facts, illustrations, and tables submitted by the applicant and that the staff's final statement in the EIS virtually paraphrased the evidence submitted by the applicant.

In this recent FPC hearing pertinent to the environmental impact of a gas storage field, it was decided that the applicant should retain a mutually agreed upon third-party for technical review of the geologic data in order to substantiate or disprove the methods and conclusions presented by the applicant. This data included the results of a subsurface geological exploratory program, caprock analyses, pump tests, and geophysical logs of boreholes. Selection of the third-party was made from qualified geological and environmental consultants who could provide a broad base or scope to the review.

5.4 Advantages of Third-Party Evaluations

The advantages of this form of review were considered to be basically three-fold: 1) An independent and critical review of data ia provided; 2) Creditable witnesses are made available by the consultant for testimony and examination at forthcoming hearings; they are charged to present and defend their results to people other than the applicant's management or the FPC staff; 3) The third-party is mutually agreed upon before the review so that their results and conclusions should be respected by both the applicant and intervenors.

The environmental reviewer will recognize that such storage fields cannot be sited at random and they depend on certain crucial geological factors in the subsurface which are somewhat rare. Therefore, unless the environmental impacts are extremely damaging and in the absence of suitable alternatives, or a favorable alternate action cannot be undertaken, it would be difficult to disallow such storage. The cost-benefit ratios will normally support the approval of a technically sound gas storage field.

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APPENDIX F

CONSTRUCTION OF THE HUNTORF FACILITY

1.0 GEOLOGICAL CONSIDERATIONS

The stresses to which the salt caverns would be subjected, in particular high rates of de-pressurization, ideally require a regular cavern configuration which should be a cylinder with a more or less half-sphere-shaped vault on the top. Obviously, such ideal shapes are not normally obtained, since this would require an absolutely homogeneous structure of the salt dome, i.e., uniform chemical composition and physical behavior of the salt throughout the geological formation. Nonetheless, a critical need is finding cavern locations with conditions as close to ideal as possible.

The search for two suitable locations for the Huntorf Storage Caverns started in November 1974 and ended in June 1975 with five exploration boreholes, each about 850m deep, two of which found salt formations of suitable quality for the purpose. After core samples had been taken, the exploration boreholes were filled and cemented.

The general geological structure of the Huntorf area was found to be the following:

0 m to appr. 5 m	peat, marshy
to between 30-35 m	alluvial sands, clay, gravel
to between 260-350 m	tertiary
to between 400-420 m	transgression, tier below chalk: upper and lower cretaceous
to about 490 m	transgression, tier below caprock: anhydrite

Tier below the borehole end: Zechstein rock salt.

In the locations judged suitable, the salt was found to contain small amounts of impurities, composed of fine-grained anhydrite deposited in the boundaries of fine-to-medium-sized salt crystals. The impurity content was estimated to be between 1 and 7 percent. Excessive impurity levels, salt contamination and structural deformation justified rejection of the remaining sites.

Expert opinoins invited from German and foreign petromechanical institutes indicated that the cavern design dimensions were within acceptable limits. They were described as:

salt cover on top of the cavern	150 m
top of cavern at depth	650 m
sump of cavern at depth	800 m
average cavern diameter not to exceed	55 m
maximum permissible ovality	1 :2
cavern well distance	200 m

The cavern's production boreholes were to be drilled at a distance of about 22m from the respective exploration holes.

2.0 PRODUCTION WELLS

Principally, the air flow velocities in the compressed air pipes should be kept low in order to minimize frictional pressure losses. Production pipe diameters inside the well were therefore not to be less than 20 inches. As a result, the well dimensions that were to be adopted exceeded the borehole dimensions commonly applied in the oil or natural gas technology. Hence, new methods and/or new combinations of methods had to be developed and applied when drilling and fitting these wells. This work began in February 1975 and ended in November the same year.

3.0 SOLUTION-MINING

For the purpose of the solution-mining of the caverns, the wells were fitted with a 7-inch diameter and a 10-3/4-inch diameter casing, concentrically suspended from a well head manifold which had specifically been provided for solution-mining. A program has been devised according to which mining of the cavern would proceed in three steps, with echometric soundings to be taken between each and after the last step. Estimated time for mining of one cavern was about eight months.

Solution-mining of the two caverns was basically carried on simultaneously. Pipeline and pumping installations were provided to take fresh water from the small Hunte River, approximately 1 kilometer from the plant area and discharge the brine at a rate of up to $600m^3/h$ into the brackish waters of the Weser estuary, about 15 km from the station.

Towards the end of the first phase of leaching of cavern NK 1 (mining of the cavern sump), and after the first echometric sounding, a substantial rise of potassium and magnesium contents was observed in the brine. The echometric measurement had, however, revealed that these impurities were not deposited in separate seams, but intermingled with sodium chloride. It was, therefore, decided to continue solution-mining at a reduced flow rate and to shorten the intervals between soundings to a maximum of six weeks. Consequently, time needed for mining of the cavern, including breaks for six echometric measurements (instead of three), was roughly one year instead of the eight months originally planned.

In cavern NK 2, however, conditions were sufficiently close to the geological expectations to permit the actual mining process to adhere to the original schedule. The leaching operation started September 1975 and was completely finished by January 1977.

Figure 3-11 shows typical sections of both caverns as actually obtained and as measured by the echometric sounding gear. Apart from the irregularities in the cavern NK 1, which occurred due to the less favorable salt conditions, a certain deviation of the roof shape in both caverns from the ideal may be noted. This has most probably been caused by inhomogenities and tectonic disturbances in the top formations of the salt dome.

The irregularities found were judged minor and had no effect on the suitability of the caverns for the intended purpose. Consequently, the next steps were taken, i.e., removal of the last brine.

4.0 REMOVAL OF LAST BRINE

The brine, after leaching was finished, was removed by a submersible pump. The pump was of a special type (bottom intake model), manufactured by Byron Jackson, Centrilift Division, makers of oil bore pumps, and one of only two models built in the world. The unit has 93 stages, is 180mm in diameter, and 43m long and it has to be crane-assembled above the borehole. Three 3 kV submersible electric motors, mounted in tandem with a total power of 370 kW, powered the pump with a lifting capacity of 80-100m^3/h of brine against a head of 116 bar.

Unfortunately, the pump failed and had to be repaired and modified repeatedly during its commissioning phase. Eventually, to empty cavern NK 1, a 60% capacity pump, substituted by the manufacturer, was used. The bottom intake unit was, after repairs, successfully used in cavern NK 2. This caused about a two-month delay in the original completion of the caverns. The emptying operation started in December 1976 and was finished in July 1977.

5.0 COMPLETION OF WELLS

Among the different arrangement possibilities, a free suspension of the inner casing was adopted to allow unobstructed thermal expansion of the production casing. This may be as much as 400mm for the 24-1/2-inch well casing shoe at a depth of 600m. A welded production pipe of 21" in the upper and 20" diameter in the lower part was suspended from a casing hanger, borne by the 24-1/2-inch well head bottom flange. It is hanging free with the casing shoe at a depth of 670m in cavern NK 1 and 685m in cavern NK 2, i.d., between 25m and 35m below the cavern roof. The casing shoe of the production pipe has been laid so deep into the cavern in order to maintain a reasonable distance between the air extraction point and the cavern walls.

The annular space between the well casing and the air production casing will, during air injection, conduct a small by-pass flow of air into which some ammonia is injected. It is expected that this measure will protect the well casing against corrosion. A number of samples have been inserted into the annulus in order to verify the justification of this measure.

Both wells can be isolated by means of two 20" ball valves. The first one is installed on the top of the well flange. It has been provided with a pneumatic valve actuator and will act as a safety closing valve for the protection of the cavern against undue unloading. The second valve, located on the top of the first one, is actuated by an electric drive, integrated into the power plant's control system, and will serve as an isolating valve for normal operation.

Installation of production casing and well head required about two weeks' time per cavern.

APPENDIX G

THE HUNTORF EXPERIENCE

(From a paper presented by Z. Stanley Stys at the EFDA/EPRI Workshop in Airlie, Virginia, December 1975)

1.0 AIR STORAGE SYSTEM ENERGY TRANSFER (ASSET) PLANTS

The idea of the compressed air storage energy transfer plants is basically not a new one. Brown Boveri made several studies on this subject by the 1950's. However, not until March 1974, after almost two years of discussions, has a German utility ordered the world's first plant of this type, which is going to be located at Huntorf, near Bremen, and will go into operation by the middle of 1977. The following shall describe briefly the Huntorf plant and the experience gained so far in designing and building it.

The 60-cycle power unit, whose design is based on this experience and is able to handle air storage pressures suitable for aquifers up to ultra high pressures necessary to make manmade caverns economical, will also be discussed.

2.0 HUNTORF PLANT

The Huntorf plant is located in North Germany between the cities of Bremen and Oldenburg (Figure G-1). The Huntorf ASSET plant cycle is as follows (Figure G-2). Air is taken into the axial flow compressor which constitutes the first stage of compression. This compressor is basically the same design as a standard gas turbine compressor. An intercooler follows this compression stage before the air is lead to a centrifugal high speed blower to be finally compressed to 1,000 psi. In this compression stage, the air is twice intercooled and subsequently aftercooled before it is stored in an air storage facility. The intercooling is necessary to approach the isothermic or ideal line of compression. The aftercooling is for two reasons: firstly, to lower the volume of the cavity, and, secondly, to avoid possible heat effect of the cycling of the walls of the cavern. Since thecavern is leached out of a salt dome, all precautions have been taken to avoid any possible problems with heat cycling phenomenon.

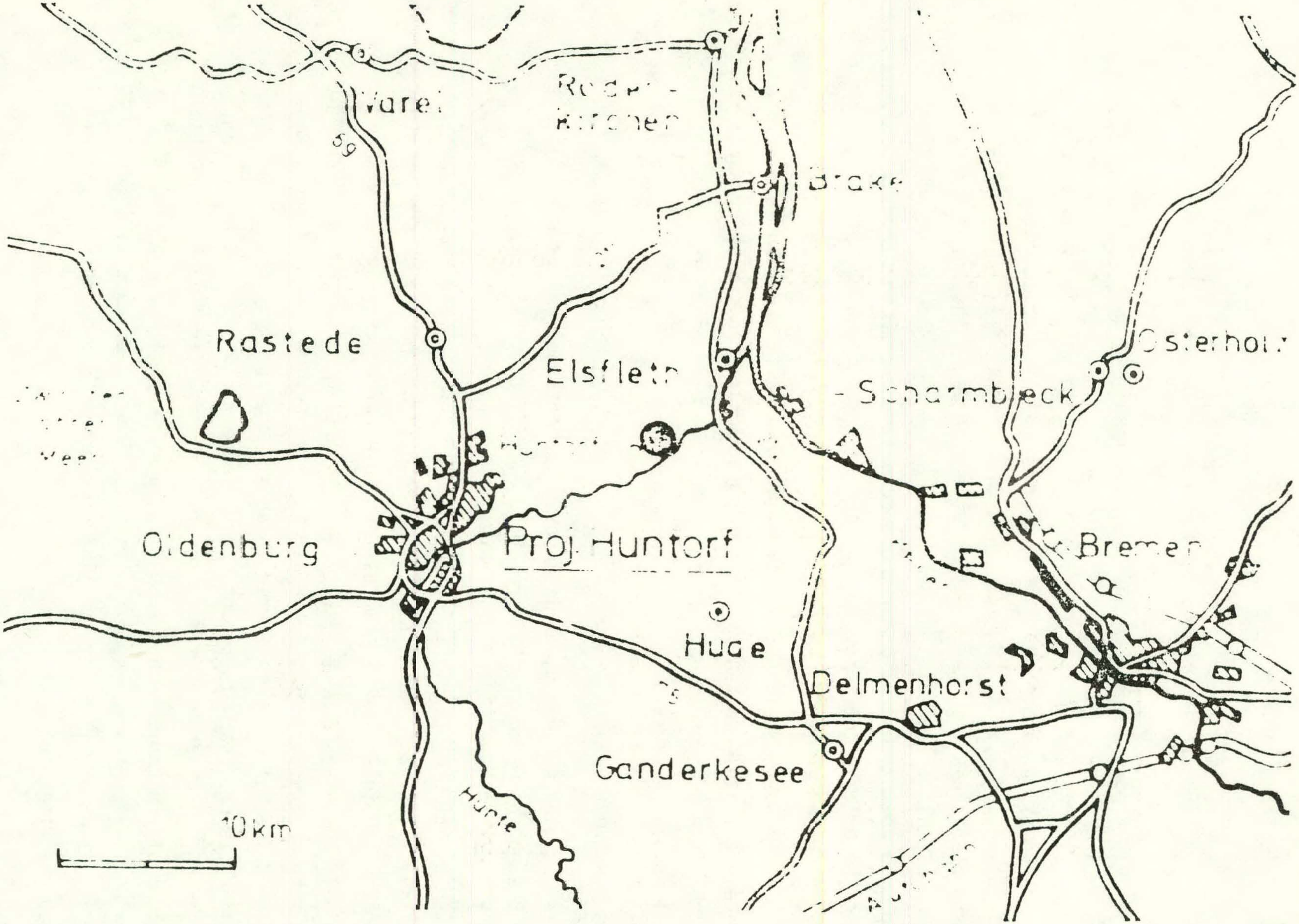
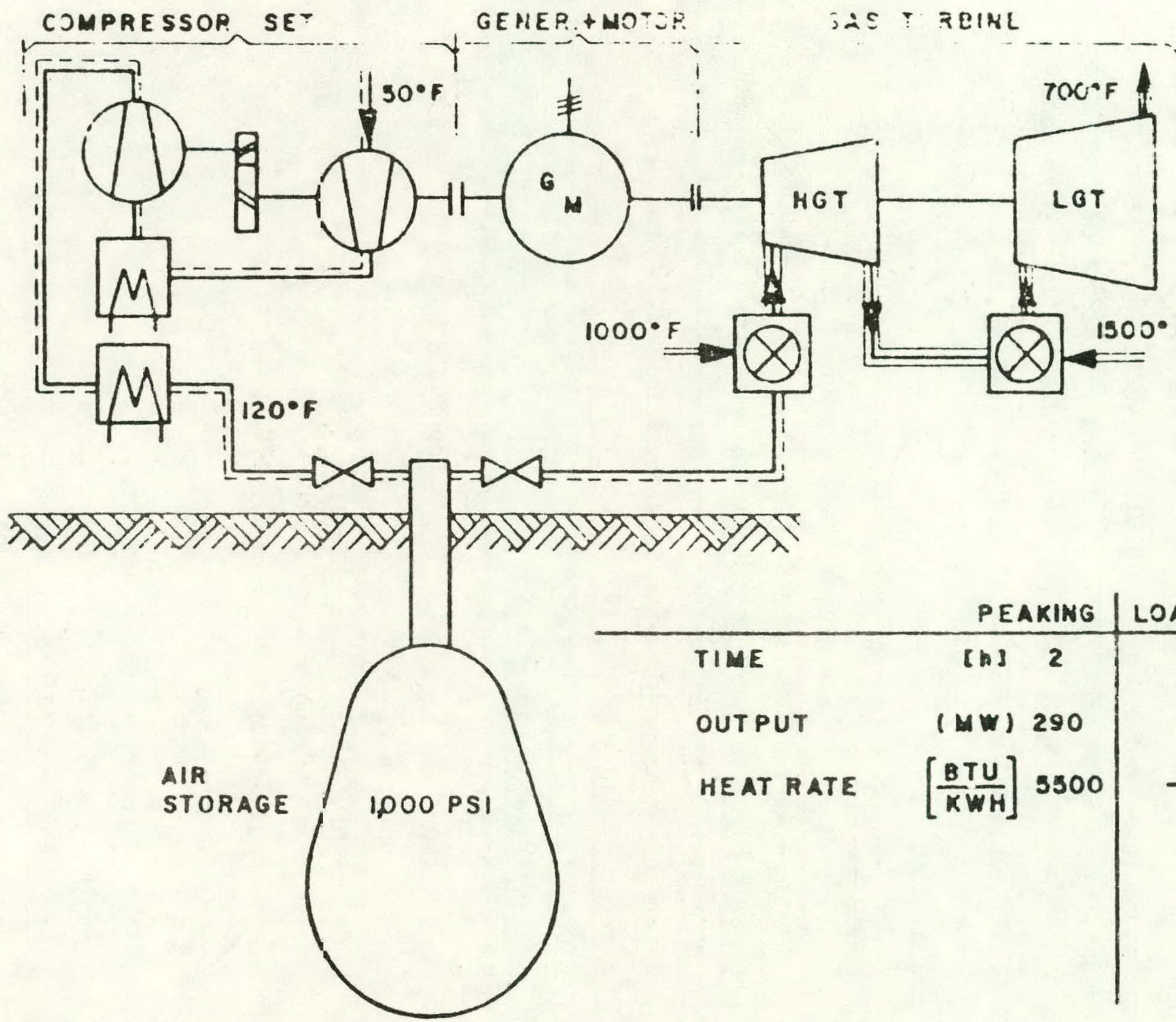


FIGURE G-1. Huntorf location



		PEAKING	LOADING
TIME	[h]	2	8
OUTPUT	(MW)	290	58
HEAT RATE	[BTU/KWH]	5500	—

FIGURE G-2. Huntorf plant cycle

The cycle on the TS diagram (Figure G-3) pictures clearly the compression stages and subsequent intercooling and the heating in the two combustion chambers with an intermediate expansion. The heat contained in the exhaust gases could have been utilized in preheating of the incoming air to the first combustion chamber. In this way, the heat consumption could be reduced by about 30%. Nevertheless, the customer has foregone this improvement in trying to lower the cost of the plant, having as a first goal to prove the concept's feasibility rather than strive to deliver the ultimate economy and efficiency.

2.1 Plant Data

Installation - HUNTORF 290 MW Air Storage Peaking Plant, near Bremen, West Germany

Owner - Nordwestdeutsche Kraftwerke AG. (NWK) Hamburg

Power Plant Design & Equipment - Brown Boveri & Cie, AG (BBC), Mannheim

Cavern - Kavernen Bau-und Betriebs-Gmbh (KBB), Hanover

Order Placed - March, 1974

Operation Date - June, 1977

Plant Main Characteristics -

Output:	290 ME (futinh 2 hours)
Input:	58 MW (during 8 hours)
Fnergy Produced:	580,000 kwh/day
Energy Input:	468,000 kwh/day
Ratio EP/EI:	1,24
Heat Consumption:	5,500 BTU/kwh

2.2 Cavern

Size of Cavern - 10 million cft.

Depth - 2,000 ft. (top of the cavern)

Air Inlet Temperature to Cavern - 120 degrees F.

Operating Pressure - 1,000 psi - 650 psi

The air storage facility was created by the solution-mining technique, leaching in a salt dome two underground cylinders with a

Temperature/entropy diagram of air-storage process

a Charging
b Discharging

1 Compression stages
2 Intercooler
3 Aftercooler
4 Expansion in h.p. turbine
5 Expansion in l.p. turbine
6 Temperature rise in h.p. combustion chamber
7 Temperature rise in l.p. combustion chamber
8 Storage pressure at end of charging
9 Storage pressure at start of discharging

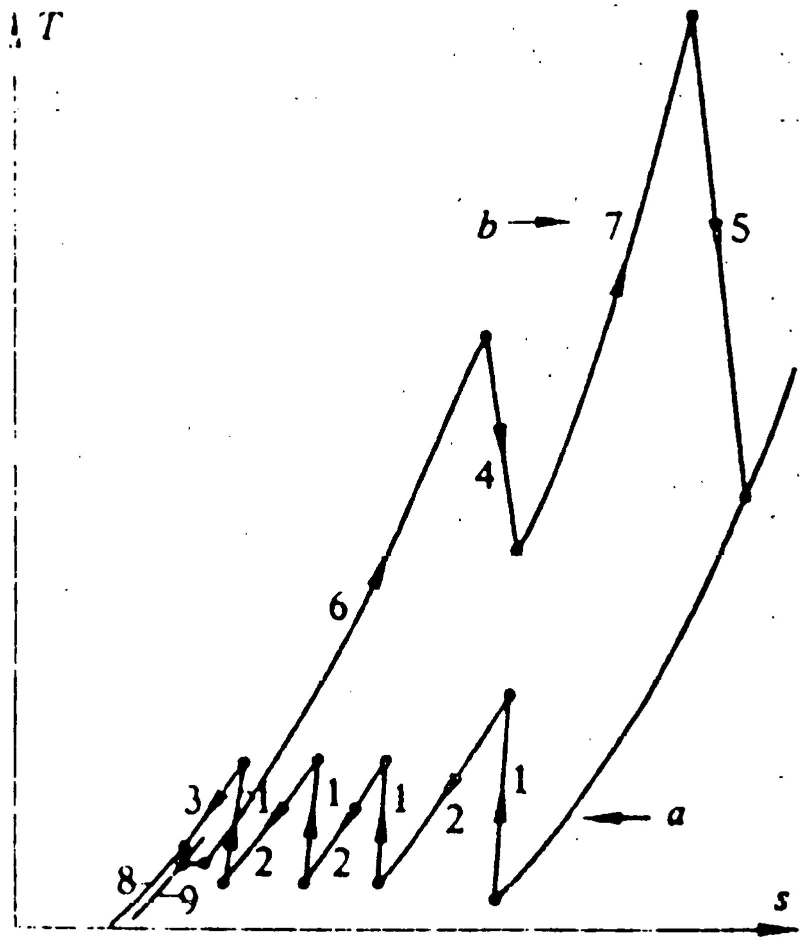


FIGURE G-3. Plant cycle on TS diagram

diameter of 100 ft. and height of 600 ft. with the top located 2,000 ft. below the earth surface (Figure G-4).

Salt being plastic material tends to close such a cavity. Since there is some pressure cycling through charging and discharging modes, the mathematical model shows that the Huntorf cavern will close to one-half size in some 460 years and close completely in about one million years. The customer, nevertheless, is going to go ahead with this plant. These calculations are now being double-checked by Dames and Moore's London organization. On the other hand, salt under the influence of moisture tends to heal its own cracks should any develop. By changing the pressure level, a certain amount of water will precipitate on the walls of the cavern and subsequently accumulate in a sump at the bottom of the cavern. This water will have to be pumped out every five years or so in order not to reduce markedly the volume of the cavern.

2.3 Gas Turbine

Type - L-GT-12/10
Fuel - Natural gas, No. 2 oil, low BTU gas
Heat Consumption - 5,500 BTU/kwh
HP Inlet Pressure - 650 psi
HP Inlet Temperature - 1,000 degrees F.
LP Inlet Temperature - 1,500 degrees F.
Mass Flow - 934 lbs/s
Speed - 3,000 rpm

2.4 Generator

Rating - 341 MVA
Voltage - 21 KV
50 Hz
3-Phase

2.5 Clutches

Type - (SSS) Synchro Self Shifting

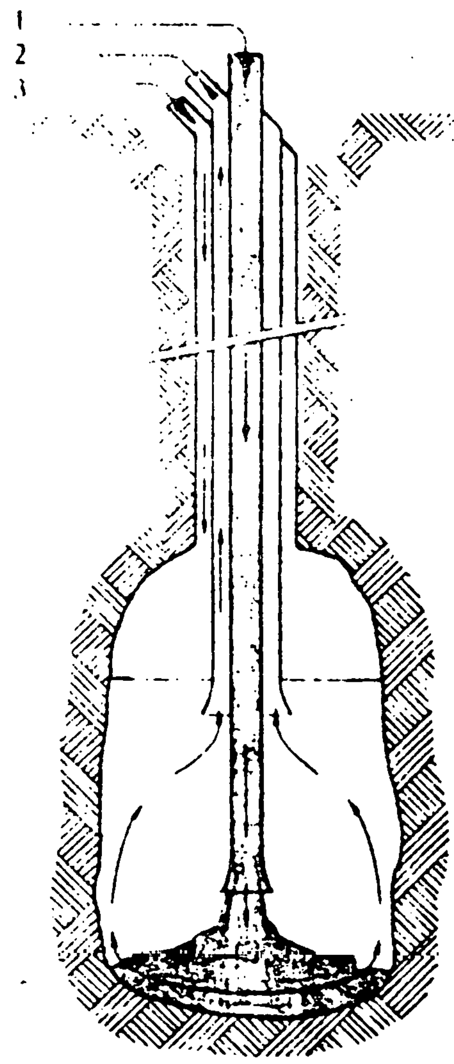


FIGURE G-4. Solution-mining principle

Manufacture - Rank, Augsburg, West Germany

The clutches at both ends of the generator are made by the Rink Company on the license of SSS Gear Works of London, England. Although ingenious, since they can in-clutch and de-clutch in operation, they do not present anything new since over 200 of this type of clutch are in operation all over the world, most of them on CODAG Patrol Boats of the NATO Navy. The largest clutch of 340,000 hp is going to be installed at a hydro pump storage plant in Germany.

2.6 Compressors

LP - Compressor - Axial
Type - A.90
Speed - 3,000 rpm

HP - Compressor - Centrifugal
Type - RZ 71
Speed - 7,600 rpm
Input (rated point) at 1,000 psi - 58 MW
Mass Flow - 230 lbs/s

The compressors are of more or less standard design with subdivisions of compression trains to produce the most efficient cycle.

3.0 PROBLEMS AND SOLUTIONS

There would be no progress made if new areas of technology were not explored with courage and perseverance and problems encountered solved. Designing and building Huntorf station gave a chance to exercise this claim.

3.1 Salt Carry-Over

Although operation of a gas turbine in a salty atmosphere is known to the industry through the experience of maritime installations or those near the sea site, operation however identical to Huntorf is not known so far. BBC was ready to implement any precautions derived from previous similar experience; however, only tests could prove if any or to what extent such were necessary. The customer himself contacted the largest outfit in mining in Germany to conduct these tests.

The first series of tests, although proved negative, were not conclusive enough to dispare thoughts of possible problems. Thus, a second series of tests were done to satisfy the customer and BBC. Five of these tests were conducted in which moist atmosphere in rock salt base was driven into apparatus which measured salt content. Finally, a model cavern in salt was built simulating depressurization conditions prevailing in operation and the air velocities were changed as one of the parameters. Again, all tests were negative.

Only if velocities are so high that salt water droplets from the sump are torn from the water surface and carried all the way to the turbine blading is corrosion possible. Such high velocities, however, are not to be expected in the normal operation of the plant. It is understood that similar experience was made in the United States in connection with natural gas storage in the caverns leached in the salt domes.

3.2 Combustion Under High Pressure

BBC two-shaft gas turbine has combustion at the level of 300 psi. The 650 psi combustion in a combustion chamber was not experienced so far. Although theoretical calculations show that a successful extrapolation to this pressure level is possible, a scaled-down version of such high pressure combustion chamber is being built to be tested. Governing system of the two combustion chambers working at different pressure levels is known from the operation of some two dozen two-shaft gas turbine sets.

3.3 Temperature Cycling Effect

Since an aftercooler is provided, temperature will remain practically constant during charging period. However, during the discharging period, temperature of the stored air and the walls of the reservoir is a function of pressure and time. As can be seen from

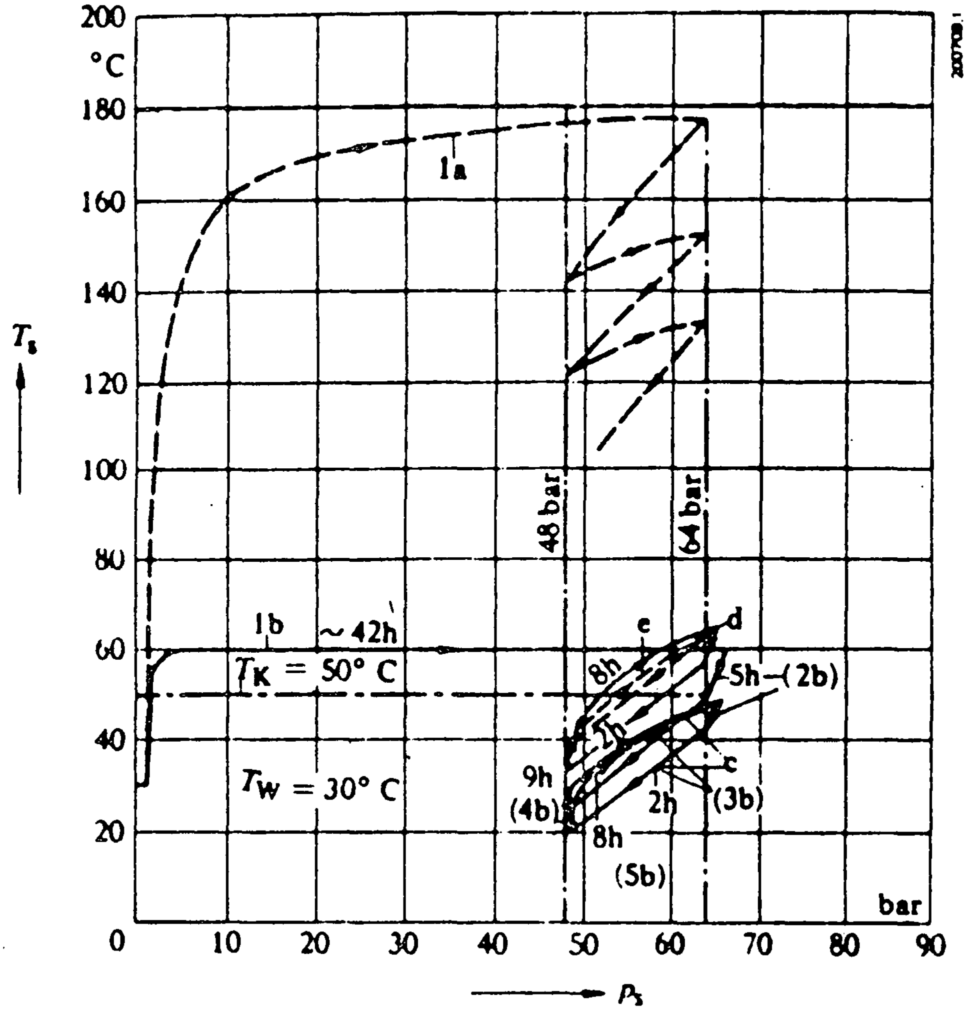
Figure G-5, the first charge of the reservoir will be almost isothermal. The subsequent discharges and recharges present small variation of the wall temperature.

4.0 CREATION OF A 45:1 PRESSURE RATIO GAS TURBINE

4.1 Basic Philosophy

The basic economic foundation of the ASSET plant was the applicability of the high pressure ratio gas turbine. The standard open cycle gas turbine operating with a pressure ratio of 1:10 was too low to make the air storage facility economical. The raising of this storage pressure to 1,000 psi proportionately reduced the necessary volume of such cavity. In order not to take the excessively high pressure drop from the storage to expansion, several rows of blading were added in the front of gas turbine blading based on experience with a standard steam turbine design. The parameters of the gas entering the first stage of this expender are 650 psi and 1,000 degrees F, i.e., parameters of an old-fashioned steam turbine. The metallurgy of the blades and the height of the blading was adjusted to the corresponding quality and quantity of the gases. After the first stage of expansion, the gases are reheated to the level of 1,500 degrees F and are of the pressure 165 psi, i.e., a nominal entry parameter of a standard and quite conservative gas turbine.

In spite of the fact that the new gas turbine of 45:1 pressure ratio was created, no special new addition to the art of engineering was made in designing Huntorf plant. The expansion turbine and axial flow compressors are standard gas turbine components. The generator has a hydrogen-cooled rotor and water-cooled stator. Excitation is fully static with a bank of thyristors containing certain redundance so individual units can be changed in operation without the necessity of shutting down the whole plant. As mentioned, the SS cluthces are not a new application. The high-speed, high input presents a modification of the clutches in operation. However, the stresses in this clutch are lower than in those already in operation.



Reservoir conditions

T_s = Air temperature in reservoir
T_w = Reservoir wall temperature
p_s = Pressure in reservoir
T_k = Air temperature at reservoir inlet
– – – – = Adiabatic reservoir wall (a)
——— = Actual reservoir wall (b)

1a, 1b = Charging the empty reservoir
2b = 5 h pause between end of charging and start of discharging
3b = Discharge in 2 h
4b = 9 h pause between end of discharge and start of charge
5b = Charging in 8 h
c = Steady-state temperature cycle for actual wall and T_w = 30 °C = const.
d = Steady-state temperature cycle for actual wall if T_w has risen to 50 °C = T_k
e Steady-state temperature cycle with adiabatic walls

FIGURE G-5. Temperature-pressure variation in the cavern

The axial flow compressor is followed by a high-speed centrifugal blower. The centrifugal blower is a standard industrial machine which was used in several chemical processes. The gear between the main shaft and the centrifugal blower is also of a standard design. The reason that it was possible for Brown Boveri to create in such a short time an expander with a 45:1 pressure ratio was the fact the Brown Boveri technologies of steam and gas turbines are compatible. Both steam and gas turbine rotors namely are built up from sections and welded together by a well-proven welding technique used for 40 years. The process goes as follows:

The machined discs are positioned one on top of each other and welded in the vertical position. The shaft is subsequently turned 90^{o} when the first layer of welds are proven to be flawless and the weld spaces are then filled with the material, when in the horizontal position, on the machines especially designed for this purpose. Subsequently, the rotors go to the annealing furnace to assure uniformity of the crystalline structure of the material (Figure G-6).

Only after this operation is the rotor machined and the grooves are cut, i.e., the standard procedure of creating a turbine rotor is followed.

Since both steam and gas turbine rotors are built in exactly the same way, it is obviously possible to weld them together, i.e., weld a part of the steam turbine blading carrying sections to the gas turbine blading carrying discs. Thus, a machine was created which can utilize in the front parameters of the steam turbine design (650 psi - 1,000^{o}F) and in the middle section, after reheating, parameters of a standard gas turbine (165 psi - 1,500^{o}F) (Figure G-7).

4.2 <u>60-Cycle Unit</u>

In order to create a most reliable unit from the start, standard modules of proven machines only are going to be used in designing a 60-cycle unit for the U.S. market. The back end of the machine is the determining factor of its size, since the rotor of the largest 60-cycle machine constitutes its most important part. BBC's largest 60-cycle

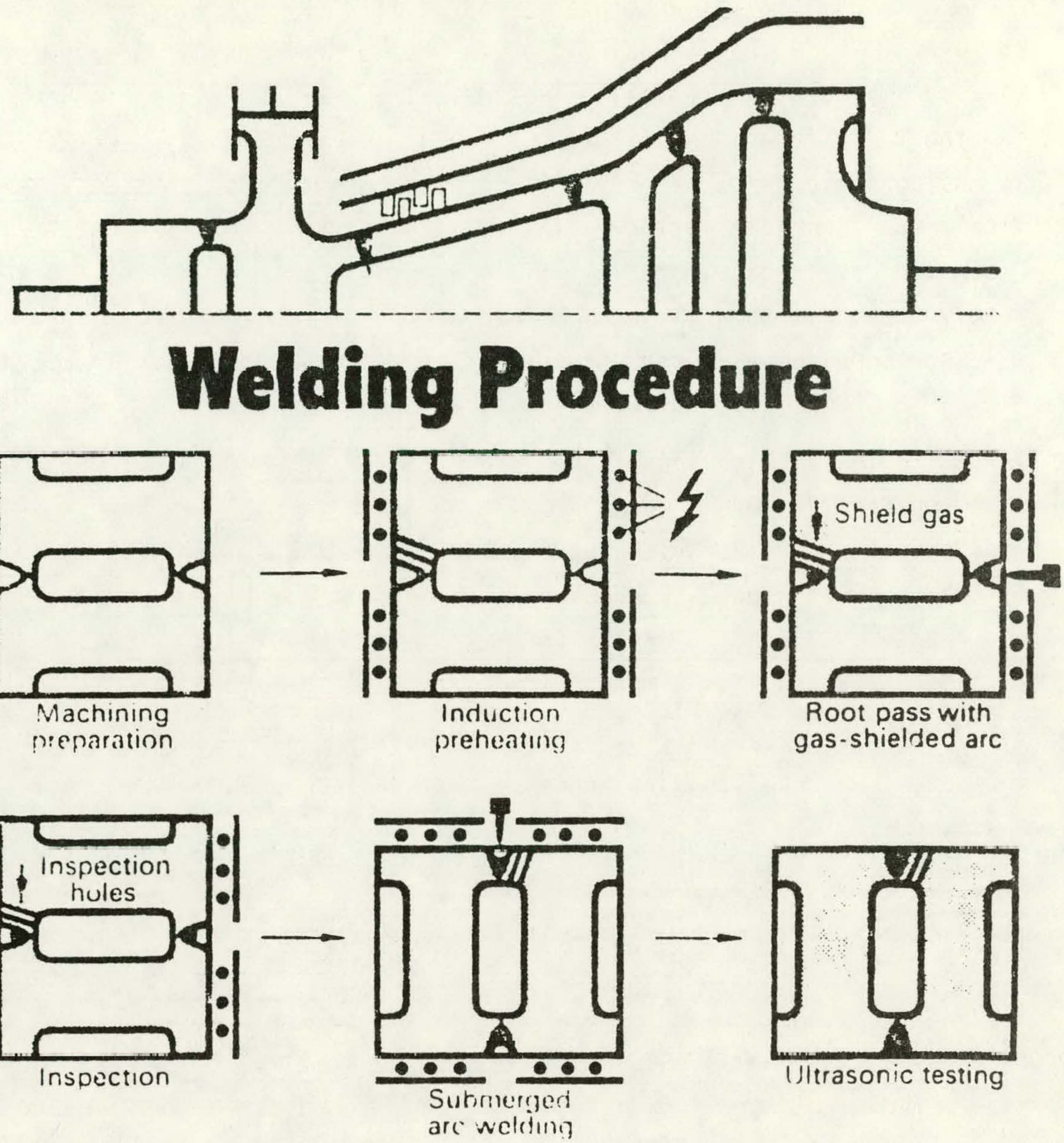


FIGURE G-6. BBC welding technique

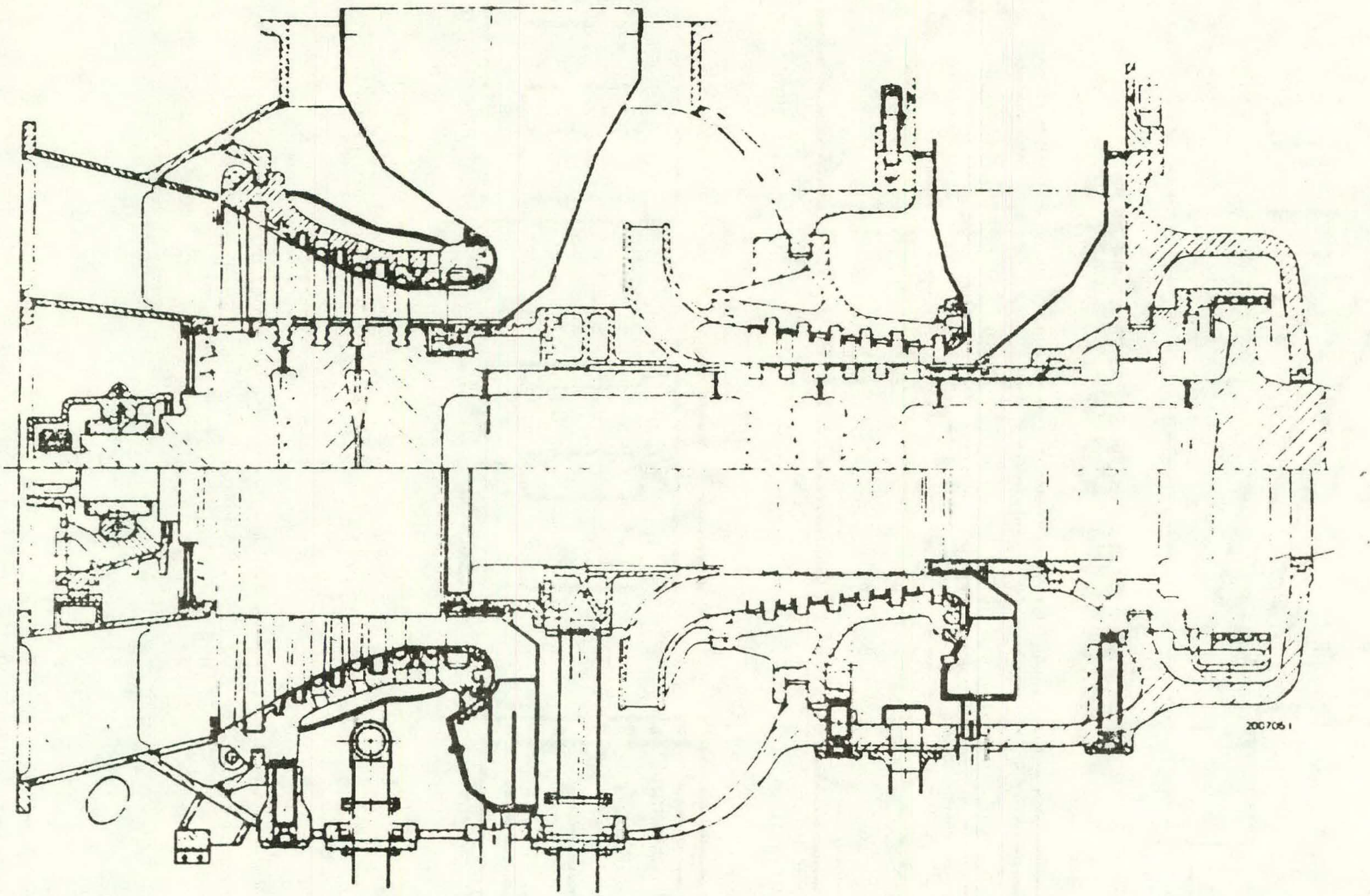


FIGURE G-7. Cross-section expension turbine machine is the type 11D2, which is produced by Turbodyne in the United States. The expander portion of this machine can produce 170 MW. By welding a steam turbine section to this rotor, a unit of 210 MW can be created.

The Huntorf unit has a gas turbine rotor of size 13 gas turbine, the largest 50-cycle machine, and a steam turbine in the front giving total output of 290 MW. In order to insure that Huntorf experience is transferable to the 60-cycle area, all the parameters of the 60-cycle unit, which are not relevant to speed, are being kept the same, i.e., pressure levels, temperatures, basic configuration, governing system, etc.

The advantage of the ASSET unit is its basic flexibility as far as the fitness into the operation system of a utility. Huntorf plant was designed to fit into the grid of NKW with flat power valley at night (58 MW) and sharp peak during the day time (290 MW). There is no reason that peaks of longer duration like f.k., 8 to 10 hours, or even longer cannot be covered. Obviously, a proper energy balance has to be established and a suitable energy storage provided to assure such an energy transfer. Figure G-8 shows how volume of the storage can be calculated, once pressure level of the storage is established.

It has to be mentioned at this point that the original calculations of Huntorf plant were based on a lower, than finally chosen, storage pressure of 1,000 psi. The cost of piping, valves and the facility itself was prohibitive at low storage pressures.

Most of the U.S. utilities have peaks ranging from 6 to 12 hours daily. However, the valleys at night are deep enough to take advantage of the full generator output, working in the compression cycle as a motor. Even when shorter than 12 hours, compressioncycle is only available by providing larger than for peaking needed generator, suitable energy transfer can be accomplished, i.e., provided such energy is available during the off-peak time. There is no problem in optimizing the compression cycle by choosing suitable axial and centrifugal compressors since a large range of proven-in-operation machines is available.

– Exergy (availability) of stored air (p_R = constant)

Air temperature in reservoir = 50 °C
Ambient conditions are 1·0 bar and 15 °C

p_p = Storage pressure
E_x/V_s = Exergy per m³

The curve shows the theoretical maximum electrical energy which can be produced during no-loss transformation per m³ of storage capacity by discharging the reservoir without supplying supplementary energy to the combustion chambers.

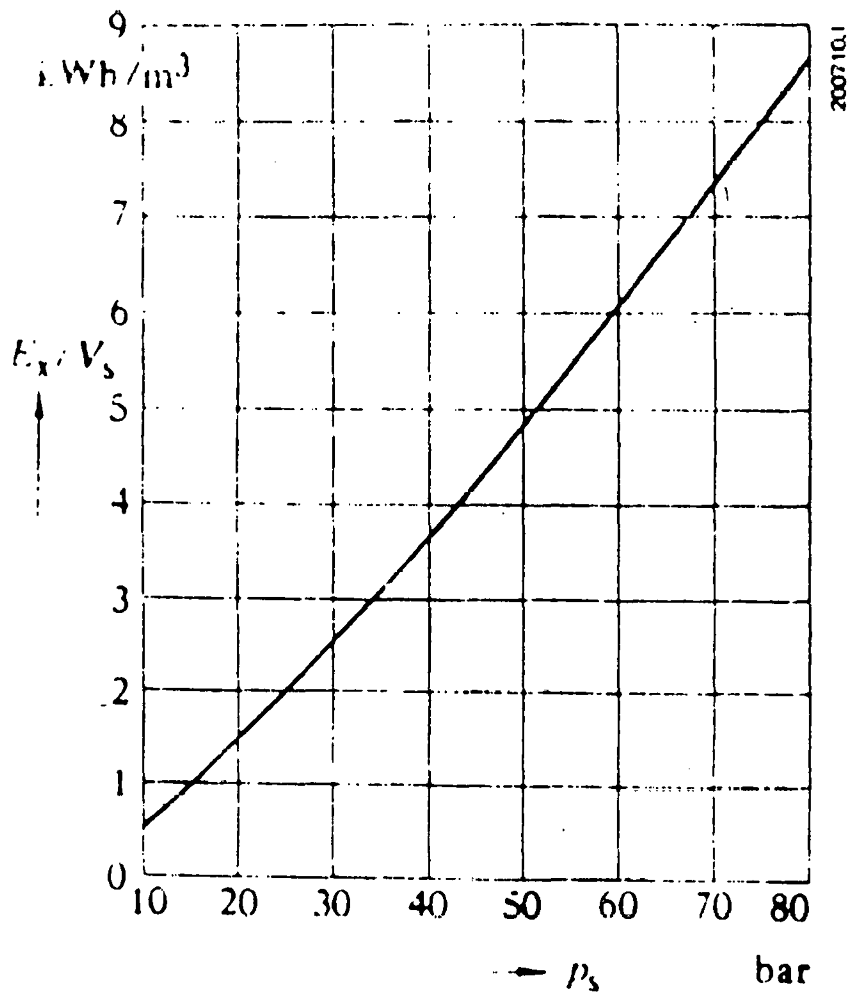


FIGURE G-8. Energy storage vs. pressure

Intercoolers and exhaust regenerators are also basically standard and proven-in-operation equipment.

5.0 COMBUSTION CHAMBER

Brown Boveri gas turbines have a single combustion chamber. The 6 ft. diameter, 15 ft. high cylindrical structure is constructed with metal tiles forming concentrical rings, where the combustion takes place. The burner design is such that even very low BTU fuels can be burnt in it (80-90 BTU's per cf). These standard combustion chambers have been adopted to the ASSET plants.

6.0 PLANT LAYOUT

Basically, the whole installation is a very simple one (Figure G-9). The building has a crane which can service the heaviest piece with exception of generator stator. The whole plant is 120 x 60 ft. with a stack 100 ft. high. The installation is totally remote controlled and is going to be dispatched from 100 miles distant point. There will be no personnel in the plant.

7.0 PERFORMANCE

7.1 Partial Load Heat Rate

The heat rate at partial loads of an ASSET plant is much better than the partial load heat rate of a standard gas turbine. This is due to the fact that in connection with an ASSET plant there is a possibility of mass flow control, whereas a standard gas turbine not having such provision is circulating the same amount of air at all times. The only possibility to vary the load is to vary the heat drop by changing the temperature of the gases, which is quite an efficient way to control the output (Figure G-10).

8.0 STORAGE PRESSURE

8.1 Standard Unit

The BBC standard unit will be able to handle pressures of about 650 psi at the inlet of the first turbine. The constant volume storage

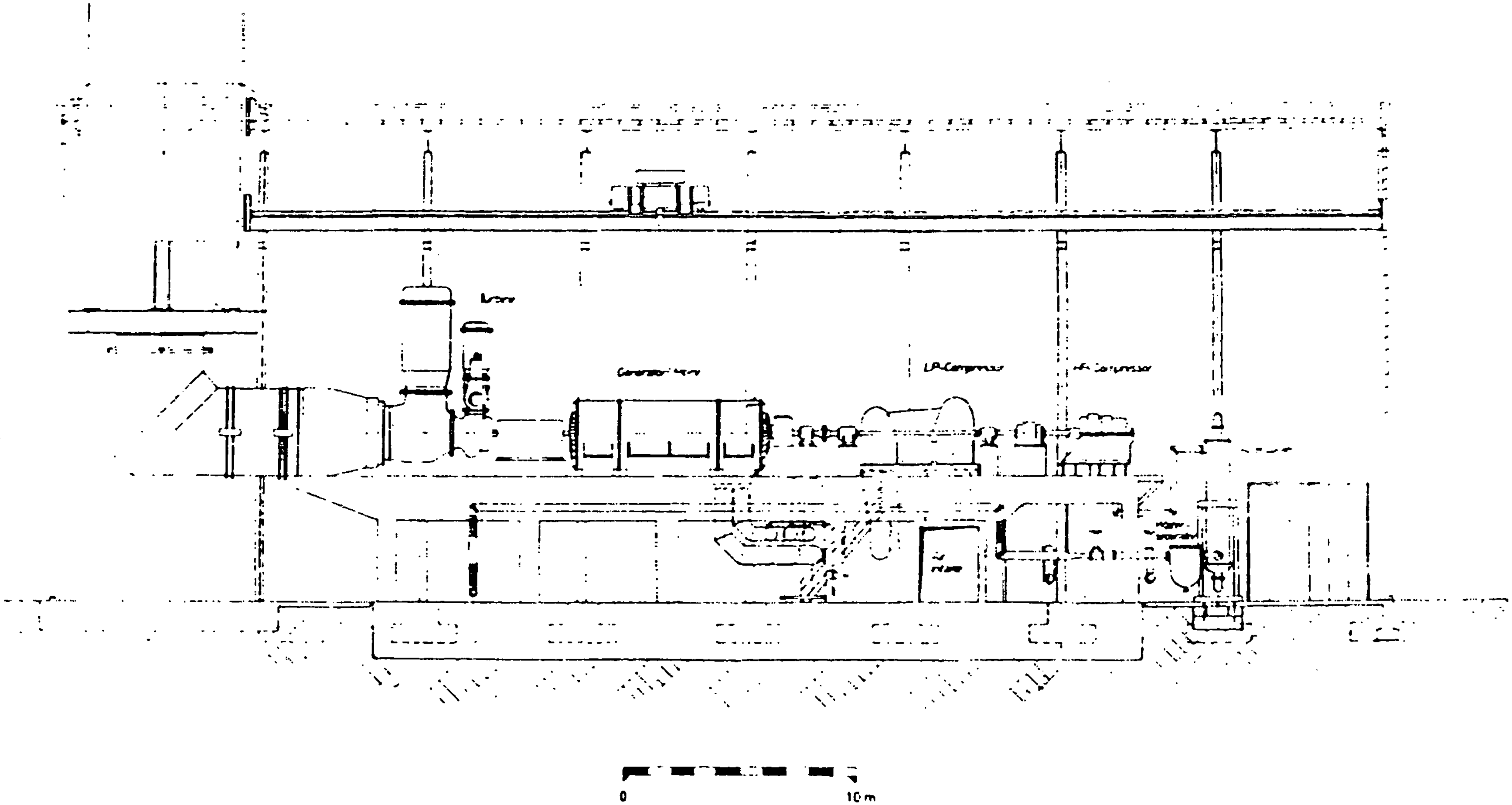
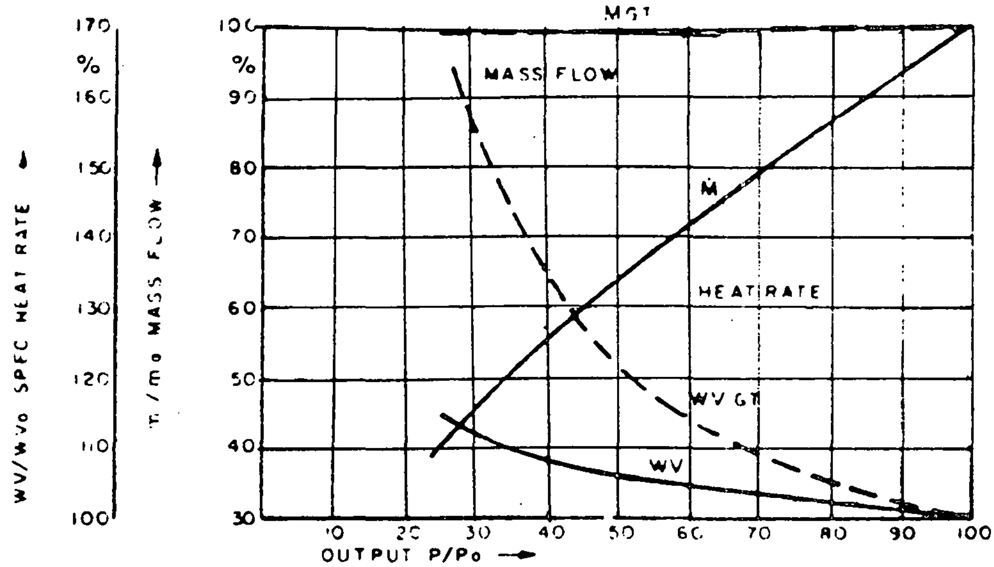


FIGURE G-9. Plant layout



PARTIAL LOAD OF THE AIR STORAGE GAS TURBINE AND OPEN CYCLE GAS TURBINE.

FIGURE G-10. Partial load curve

pressures of 1,000 psi should be possible. Such pressure ranges are suitable for salt domes, leached cavities, lower strata aquifers, or hydrostatically balanced (constant pressure) mined caverns.

8.2 Low Pressure

Some aquifer stratas allow pressures lower than 650 psi, i.e., f.i., in the range of 400-500 psi. Such pressures can be handled by a standard unit by omitting several initial rows of blades in the front part of the high pressure section of the turbine. The output will, of course, diminish correspondingly.

8.3 High Pressure

In order to lower the size of the cavern in case of a mined cavity, it is probably cheaper to go deeper and use higher pressure of the storage system. Such pressures, i.e., 3,000 psi, can be handled by a standard unit with a topping unit in the front of it. This unit will have a separate generator. The air will be preheated by the exhaust gases before entry to the topping turbine to avoid complication of the third combustion chamber. After expansion, the air with 650 psi will be lead to the first combustion chamber of the standard unit and then follow its basic cycle.

8.4 Future Improvements

There is a large amount of heat carried away by water during the compression cycle. Utilization of this heat in a production or porcess steam or refrigeration would further improve cycle efficiency. This procedure was accomplished with a chemical company trying to utilize this heat source and it was shown that the savings achieved could be quite substantial.

9.0 CONCLUSIONS

Several projects have been studied for Germany, Luxembourg, France and Denmark. Some of these projects would have been already realized if not for the economic slow-down which was also prevailing in Europe.

One of the most active ones is a project in Germany. A mined cavern, with a hydrostatic pressure equalizing reservoir (Figure G-9), built by standard tunnel drilling machines, is being considered.

The fact that there was a Huntorf plant being built that was commissioned by the middle of 1977 resurrected a great interest among utilities and architect engineers also in the United States. With the availability of salt domes in the Gulf area, aquifers in the Midwest, depleated oil and gas wells in Texas and California, defunct salt, potash, iron and other mines in other parts of the country, there is a natural potential to build such plants all over the country. Even a manmade cavern, especially excavated for air storage, is not too exorbitantly high in cost, compared with today's extra addition to fossil and nuclear plants, to comply with environmental and safety requirements only.

The basic idea to be able to transfer off-peak power to the peaking period, to have a better load factor on the base load machines, or even defer new capacity investments, is appealing more and more to many utilities. Building an energy storage facility similar to pumped hydro storage in a flat country certainly presents a definite advantage from an environmental standpoint of view. Thus, it is hoped that the Huntorf plant fulfills industry expectations and its example will be followed by other utilities in this country.

REFERENCE.

"Huntorf - The World's First 290 MW Gas Turbine Peaking Plant," Mattick, Haddenhorst, Weber, Stys - American Power Conference 1975. Air Storage Power Generating Plants, Zaugg, BBC Review 7/8. New Energy Storage System Sold, Stys, Electrical World, June 15.

APPENDIX H

AQUIFER AND CAPROCK PROPERTIES

1.0 INTRODUCTION

The underground storage container in most natural gas storage fields is the pores of rocks such as in sandstones or porous carbonates. Since the air is stored in the pores and a cavern does not have to be encountered, the important properties in aquifer storage are the porosity and the permeability. The strength of the rock in being able to support an excavated cavern is unimportant.

2.0 PERMEABILITY (Katz & Lady, 1976)

Permeability is the character which describes the flow of fluid through the rock. A unit of millidarcy or one-thousandth of a darcy is used in oil and gas production technology as well as storage. The darcy represents a flow rate of one cubic centimeter per second through opposite faces of a cube one square centimeter in cross section at a flow rate of one cubic centimeter per second when the fluid has a unit viscosity of one centipoise such as water. Thus, water would flow from face to face through a one centimeter cube of 1 millidarcy (md) sand at a rate of 0.001 cc/sec. when it has a pressure drop of 14.7 psi. Rock permeabilities vary tremendously, but those used for gas storage might have a value which lies between 10 and 3,000 millidarcies. For compressed air storage, there is a special premium for high permeability because of the daily turn around and one hundred to two hundred millidarcies is likely to be a lower limit.

2.1 Threshold Pressure

Cotton fabric is permeable. Air passes through it with relative ease. But every Boy Scout learns that he can make a pair of emergency water wings by knotting the ends of his pant legs and using them to entrap a sufficient quantity of air to provide a modest level of buoyancy. The trouser fabric which is permeable in an absolute sense becomes relatively impermeable under certain conditions. Specifically, it becomes impermeable to air when the apertures in the fabric mesh are filled with water retained there by capillary action. The Boy Scout learns by experience what we would predict through a knowledge of capillary behavior: that this condition of relative impermeability exists only while the differential in air pressure across the fabric is less than the capillary pressure retaining the water between the threads. If the emergency water wings are immersed too deeply, this limiting pressure is exceeded and air escapes. He might also learn, as we would predict, that he can entrap less air in a coarsely woven sweater than he can in a finely woven shirt. The limiting pressure is inversely proportional to the diameter of the apertures in the fabric.

Talking in the language of capillary behavior -- the pressure at which a non-wetting phase (air) is first able to displace a wetting phase (water) from a porous media is termed the "threshold displacement pressure" or simply "threshold pressure." It is the capillary saturation in a sedimentary caprock which gives rise to the condition of "relative" impermeability, and it is the threshold pressure which defines the limit under which the condition of relative impermeability exists. This threshold pressure, in turn, is determined by the diameter of the capillary apertures. Finally, we should note that relative impermeability exists only in the presence of two immiscible phases, one of which preferentially wets the porous medium. Fortunately, this latter condition will almost invariably be met since almost all pore space in rock below the water table is water-saturated and since most rock-forming minerals are hydrophyllic: preferentially water-wet.

2.2 Permeability and Porosity

Permeability is a measure of the ease with which a fluid may move through a porous material. When dealing with particulate matter, it is the summation of the flow capacity of all channels within the porous network. Porosity is the proportion of pore space or void within a material expressed as a percentage of its bulk volume. Particularly when dealing with fine-grained, relatively impermeable materials, it is necessary to make further distinctions. Total porosity is a measure of all pore space within the material. Effective porosity is that pore space which is interconnected by permeable flow paths. It is entirely possible to have a material of high total porosity with virtually no effective porosity. Volcanic pumice is such a material. When the diameter of the apertures between pore spaces becomes very small, as they commonly do in caprock materials, it is necessary to recognize relatively effective porosity, pore spaces which are only slightly interconnected and will act as effective pore space in the long-term but as ineffective pore space in the short-term (Figure H-1, a-f).

Both permeability and porosity are commonly defined and measured in terms of saturation by a single phase. Their treatment becomes further complicated in the presence of two immiscible phases such as air and water. Some flow paths may be occluded by capillary water or by bubbles of air, thus reducing the effective permeability. Cul-de-sac pore space, blind alleys in the pore network, may be permanently water-filled and thus become ineffective to air, or vice versa, thus reducing the effective porosity relative to one phase or the other. Small volumes of water held by capillarity in the critical apertures may entrap air in some pore spaces, greatly reducing effective porosity even though the total air saturation may be relatively large. This condition is quite common, for example, in connection with the entrapment of hydrocarbons in those dolomites which are commonly described as "chalky."

3.0 CAPROCK INTEGRITY

One of the most critical elements of a compressed air energy storage (CAES) system is its integrity, its ability to retain the compressed air within the intended storage reservoir. The integrity in turn is primarily a function of the permeability of the confining rock unit, or caprock, with respect to air. Although they are not directly related to the ultimate sealing mechanisms of most sedimentary caprocks. porosity and permeability are significant in that they control the reserve or safety factor of a caprock. If, for a brief period of time, the threshold pressure is exceeded, the non-wetting phase, gas or air, will begin to invade the caprock. The rate of penetration is a function

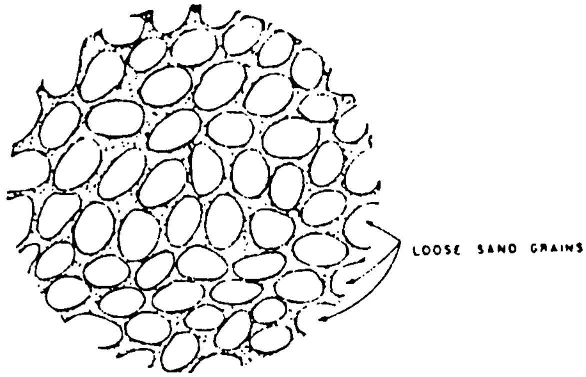


Figure a. Effective Pore Space

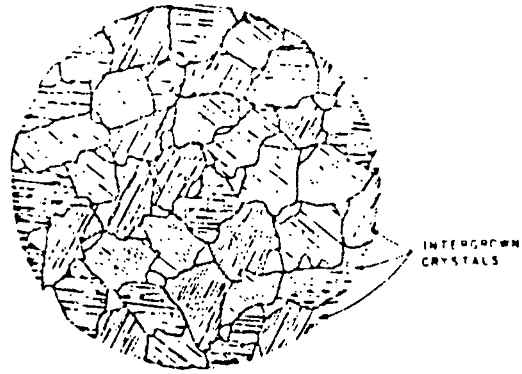


Figure b. Ineffective Pore Space

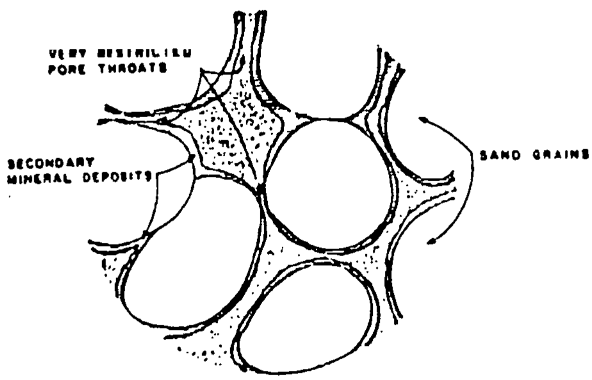


Figure c. Relatively Effective Pore Space

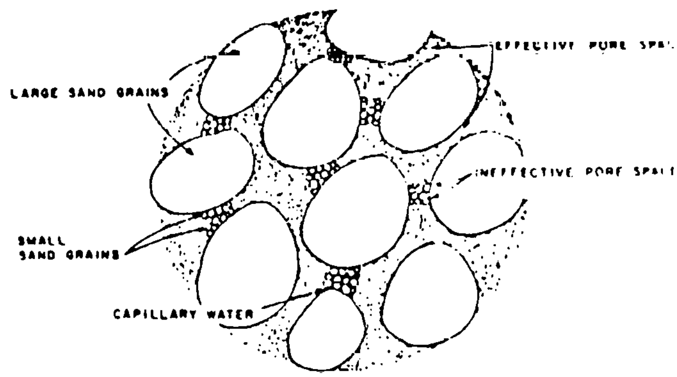


Figure d. Pore Space Rendered Ineffective by Occlusion

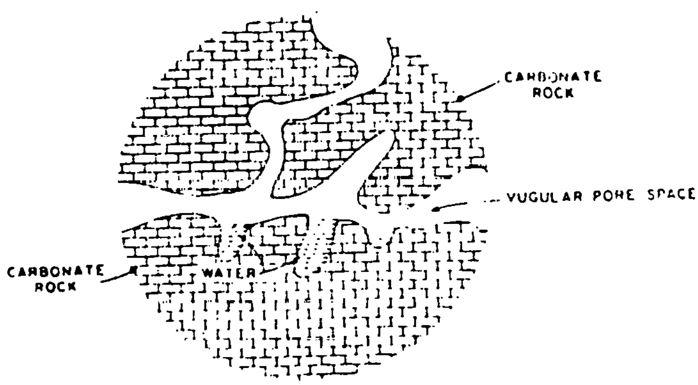


Figure e. Pore Space Rendered Ineffective by Water Content

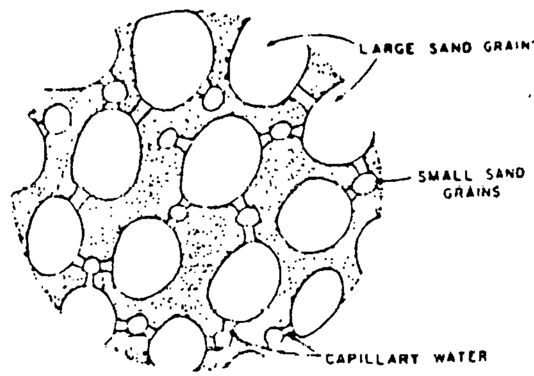


Figure f. Permeability Reduced By Partial Water Saturation

FIGURE H-1. Various configurations of pore space, both effective and ineffective of the caprock's permeability, both to gas and to water. Because fine-grained materials typically exhibit much lower permeability to water than to gases and because of the greater viscosity of water, it is the strata's permeability to water which will exert dominant control on the rate of gas invasion. As gas invades the caprock, it displaces water from some of the pore space, and the extent of gas invasion is therefore in part determined by the amount of pore space available. If pressure and permeability are constant, gas will penetrate more deeply into a dense caprock in a given period of time than it will into a porous caprock. Once the threshold pressure is exceeded for any reason, low permeabilities and moderate porosities provide a safety factor which retards and contains gas migrating upward from the reservoir.

3.1 Caprock Lithologies

The ideal caprock material would be non-porous and absolutely impermeable. An additional desirable characteristic would be deformability, permitting the caprock to maintain its seal across such common mechanical discontinuities in rock as joints, fractures, or faults. Salt is one rock type which approaches these ideal requirements very closely. The mineral halite, common salt, has the property of deforming with relative ease under moderate pressure. Because of this "creep" behavior and due to its mode of deposition, bedded salt has extremely low porosity and is usually impermeable within the limits of measurement. Where salt overlies a potential storage reservoir, it approaches the ideal caprock. Unfortunately, salt and its similar but less deformable sister evaporite, anhydrite, have only limited geographic and stratigraphic occurrence.

3.2 Shale

Shale consists of very fine particles of minor detritus, largely of the plate silicates called clay minerals, which were deposited as watery muds and were gradually compacted and de-watered through the weight of overlying sediments and in some cases, by tectonic forces. As water is removed, the sediment becomes progressively stiffer, turning to clay and ultimately, with an ill-defined distinction, to shale.

Because of the very small particle size of the shale-forming detritus and because of the deformability of many of the shale-forming minerals themselves, the permeable channels within a shale may be expected to be of very small diameter. This results in very high threshold pressures. Further, until the water content is very greatly reduced, most shales exhibit deformability through pseudo-plastic flow. A pure shale, that is to say one made up almost exclusively of clay minerals such as illite, may therefore closely approximate the ideal requirements for a caprock, being relatively impermeable within rather broad limits and also deformable.

However, pure shales, like pure sandstones and pure carbonates, are relatively rare. These three primary sedimentary rock types are simply end-points of a lithologic continuum which includes all degrees of intermixing. Thus, most shales are either calcereous, containing some proportion of carbonate, or areanaceous, containing some proportion of sand, or they may contain a proportion of both. Relatively small proportions of either sand or carbonate can very substantially alter the mechanical and fluid mechanical properties of shale. In general, increasing carbonate content decreases deformability and, consequently, increases the material's ability to maintain an open fracture. A modest sand (or silt) content may result in increased pore size with increasing permeability and decreasing threshold pressure. Not only do carbonates and sands intermix within shales, but also they very frequently intergrade vertically, and thus, they produce sections in which beds that are dominantly shale are interbedded with beds that are dominantly sandstone or carbonate.

3.3 Carbonates

The major rock-forming carbonates are limestone and dolomite. Most carbonates originate in the precipitation of carbonate crystals at the sea floor. As the crystals grow, they interlock and form a dense mass, frequently with porosities of as little as 2 percent or less. If unbroken by joints, fractures, or similar mechanical discontinuities, such carbonates may be absolutely impermeable, or at the very least, relatively impermeable to very large threshold pressure limits. However, carbonates are not always impermeable. Some are formed by the accumulation of fossil fragments or round accretions of carbonate called oolites. Such rocks commonly have substantial inter-fragmental or inter-oolitic porosity and permeability.

Even those limestones which were dense and impervious at deposition may develop secondary porosity through the effects of percolating water which, on the one hand, may remove material by solution or, alternatively, may deposit additional carbonate, further reducing porosity. Water movement may also result in mineralogical change, notably by replacing some of the calcium in limestone with magnesium to form dolomite. Such dolomitization results in a reduction of the mineral volume with a consequent increase in pore space. The principal disadvantages of carbonate caprocks are (a) their lack of deformability and thus their susceptibility to leakage through joints and fractures, and (b) their frequent heterogeneity. Carbonates which appear extremely dense and impermeable in one location may exhibit extensive solution porosity and permeability at another joint only a few tens of feet distant.

Those carbonate caprocks which have proven effective in practice have, for the most part, been shaley limestone, or limestone with rather abundant shale interbeds. Several workers are of the opinion that, even though shale is the subordinant lithology, it may constitute the effective caprock in such instances.

4.0 METHODS OF CAPROCK EVALUATION

There are two generally accepted methods for the evaluation of caprock. Each has its advantages and disadvantages, and although separately presented herein, the two methods, pump testing and core analysis, should be viewed as complimentary rather than mutually exclusive.

4.1 Pump Testing

Pump testing involves the reduction of pressure beneath the caprock by pumping water from one well while simultaneously observing pressure response, usually in terms of height of water column, that occurs in observation wells completed above the caprock. Pump tests are particularly useful for the determination of gross caprock permeability and the recognition of major features such as faults. Under ideal conditions, such a test may contribute to the evaluation of several hundreds or even thousands of acres.

Since pump tests involve only single phase flow, the flow of water through the caprock, they are a test of permeability, not the threshold pressure. Nor does the pump test permit identification of those portions of a lithologically and stratigraphically complex caprock which are most effective. Finally, a pump test requires the completion of a pumping well and several observation wells, and therefore implies a fairly advanced stage of site development.

Pump tests are not always applicable. In order to be responsive under practical pumping rates, both the reservoir and observation zones must be of somewhat restricted permeability. In the reservoir, it must be possible to achieve a significantly lower pressure over a reasonably broad area. In the observation zone, the rate of recharge from overlying and laterally contiguous sources must be sufficiently low that the pressure can be reduced by the limited volume of water drawn downward through the caprock.

4.2 Core Analysis

Caprock evaluation through the analysis of core samples provides direct physical measurements of caprock parameters. Customarily, this includes determination of permeability, porosity, and threshold pressure. The radius of investigation of core analysis is limited to the diameter of the core or the borehole from which it is recovered, and the validity of core analysis data depends in part upon the degree to which it is extrapolated. Normally, it will be necessary to core and analyze the caprock in a number of wells in order to reach reasonable confidence that the data is applicable throughout the storage field. On the other hand, core analysis does permit the measurement of threshold pressure, the most critical parameter, and can provide very detailed data on a foot-by-foot basis, permitting identification of the critical zones within the gross caprock section. Finally, evaluation of caprock through core analysis can, and generally does, begin in the early stages of site selection or development with the drilling of the first well.

As caprock evaluation has been developed by the natural gas storage industry, both techniques are used: core analysis to obtain detailed data on all caprock parameters on a foot-by-foot basis; and pump testing to provide a general evaluation which is sensitive to caprock inadequacies which might not be identified in the coring program such as faults, joints, or fractures, localized non-deposition or erosion of caprock, or localized changes in faces.

4.3 Other Methods

Two other methods of caprock evaluation should be mentioned briefly: "experience" and "pilot testing." Experience says that a "A" shale formation has proven to be a satisfactory caprock at the "X" and the "Y" fields; therefore, it can be assumed that the "A" shale will be effective at the "Z" storage field. Certainly, it is reassuring that the caprock in a proposed storage field has been successfully employed in other, nearby fields. This is particularly true if the caprock in the new field can be shown to be lithologically identical with that in the proven fields, and if the general stratigraphic and structural relationships appear to be similar. But the geological environment is infinitely variable. No one rock sample is exactly like another, nor are the stratigraphic sequences from which the samples are obtained. One structure may include caprock which is folded without disruption, while another, apparently similar folded structure may contain faults and fractures. Natural gas storage experience is replete with examples of apparently similar structures in which one field was successful while another was not. Experience may provide a basis for cautious optimism, but it does not constitute an adequate caprock evaluation.

The application of pilot testing is self-evident. A limited quantity of gas is injected into the reservoir and is monitored, either by observing reservoir pressure or by observing pressure in formations above the caprock, or both, until it is evident that the caprock is not leaking. It is, in effect, a limited state of full-scale operational testing. It, therefore, requires an advanced stage of field development. Further, since caprock leakage almost invariably proceeds at a slow rate, a truly rigorous pilot test would require a period of observation extending over many months or years. Finally, again recalling the conditional or relative impermeability imposed by the threshold pressure, a pilot test can never be considered conclusive until the maximum operational pressure differential is brought to bear against the caprock overlying the full areas of the storage reservoir. Pilot tests may be useful to confirm or disprove the existence of suspected gross caprock deficiencies, but they cannot in themselves be considered as ultimate proof of reservoir integrity.

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APPENDIX I

AQUIFER GAS STORAGE EXPERIENCE

(Neil Rudd)

1.0 STORAGE EXPERIENCE

1.1 Principles

Compressed Air Energy Storage in aquifer reservoirs is directly comparable to the well established technology for the storage of natural gas. Aquifer storage of gas was first investigated during the 1930's and, since the late 1940's, has become a well-developed and widely adopted practice. The 1977 statistical report of the Committee on Underground Storage of the American Gas Association lists 57 aquifer storage operations in 10 states operated by 24 different companies. At least three additional aquifer storage projects are being developed at the present time.

In principle, aquifer storage simply recreates the conditions under which natural gas is entrapped in nature. Gas partially displaces the native water within a porous reservoir, usually sandstone, and is confined in that reservoir by a combination of geological and hydrological characteristics. Most commonly, upward and lateral migration of the gas is controlled by the use of domal or anticlinal geological structures in which shale or some other relatively impermeable lithology overlies the porous reservoir. The buoyancy of the gas with respect to water prevents downward migration. Stratigraphic traps, fault traps, and isolated porous bodies such as reefs and bars have been developed for aquifer storage.

The obvious dissimilarities between CAES and conventional gas storage are in cycle frequency (daily as opposed to yearly) and in the character of the materials stored. Daily cycling raises some concern for two reasons. The first is the "pumping effect." Some workers believe that repeated cycling of some reservoirs literally pumps the gas outward. During the withdrawal cycle, the gas is primarily removed from near the center of the field leaving significant quantities around the periphery.

During each successive injection cycle, this "edge gas" may be displaced a little further outward. If this pumping effect is noticeable after four to six annual cycles, how significant may it be with hundreds of daily cycles? The major concern arising from the storage of air as opposed to gas is the presence of oxygen. The possibility of mineralogical alteration by direct contact with oxygen or through the working of aerobic bacteria needs to be considered. Probably this is more a question of field efficiency than it is insurable risk.

1.2 Leakage

Gas storage companies are understandably reluctant to discuss leakage. With the promise of absolute confidentiality, data on approximately thirty aquifer fields, including three which have been abandoned because of excessive gas leakage have been obtained by Dames & Moore. This data does not include those aquifer storage projects which were abandoned prior to being put on line because the possibility of leakage was recognized.

Present methods of gas inventory determination are not precise. Gas losses of 2 percent per year, perhaps as much as 5 percent in some cases, may exist without being recognized unless they are detected by observation wells at or near the surface. Recognized gas leakage has occurred in approximately 25 percent of the fields studied. It is suspected in another 10 percent. In approximately 12 percent of the fields studies, leakage has been so severe as to result in abandonment. In one field, severe gas losses from the primary reservoir are recaptured in an overlying reservoir and recycled.

It will be recognized from the above statistics that not all leakage necessarily results in abandonment. Under some circumstances, even severe leakage can be controlled as in the case of Natural Gas Pipeline Corporation's Hersher Field, cited above, where leaking gas is recycled. Smaller volumes of gas leaking from the primary reservoir may go into solution in the water saturating overlying formations, may be entrapped as isolated bubbles in porous rock, or may accumulate under relatively impermeable strata in the overlying geologic section. The seriousness of a leak depends not only upon its magnitude, but also upon the specific geologic environment of the storage project and the utilization of the surface area above and around the storage project.

1.2.1 Origin of Leaks

In many cases, it is not possible to specifically identify the mechanism of leakage. Some cases of leakage have clearly been avoidable and simply reflect inadequate or incorrect evaluation of geological conditions as the following brief "case histories" will indicate:

1. Storage was attempted in an inferred area of closure along the crest of a plunging anticlinal trend. Closure was considered "proven" on the basis of a few widely scattered exploratory wells. Only after gas had been injected and leakage suspected were additional wells drilled in the areas of critical updip closure which showed that little if any structural closure existed in fact.

2. Structural exploration revealed two areas of domal closure connected by a shallow saddle. One dome was developed for storage after extensive caprock evaluation. Based on success of first stage of development, it was subsequently decided to increase thickness of gas column and incorporate the second dome within the storage areas. Caprock testing was omitted in the second stage of development. Leakage became evident. Later investigation of caprock over the second dome indicated existence of a subtle facies change resulting in higher permeability to gas over the second dome than over the first.

3. Storage was developed in a carbonate reef containing both large, vugular porosity and finely disseminated dolomitic porosity in approximately equal proportions. Reservoir volume was calculated on the basis of geophysical logs which could not discriminate between modes of porosity and non-displaceable water, and a value appropriate to large vugs was used, approximately 6 Bef of gas was injected. It was subsequently

discovered that due to high residual water saturation in dolomite porosity, the reservoir volume was only adequate to contain 3.5 Bef, the remaining 2.5 Bef having been displaced beyond the limits of entrapment.

Other cases of leakage have been less readily avoidable. There have been several cases of high angle faults of small displacement which were not detected during the exploration phase either by drilling or by other studies. Very localized lithologic changes or erosional truncation of caprock are suspected in some instances. The majority of instances of gas leakage appear to be of a geological origin; however, some relate to the development and operation of the field itself. While it is typically minor in degree, gas leakage associated with the wells themselves is not uncommon. This may arise from improper cementing of casing, from subsequent failure of the cement bond, from casing corrosion, and a large variety of other essentially mechanical defects. Such leakage can, on the other hand, have very serious consequences as in one case in which gas from a deep storage reservoir operated at 3,500 psi leaked into a pressurized and shallow sandstone aquifer only a few hundred feet below the surface. Eventually, the shallow sandstone blew out rather catastrophically creating a crater around the well head which then failed, allowing the well to blow.

Another form of leakage resulting from operation is due to the so-called "umbrella effect." When the vertical permeability of a reservoir is significantly lower than the horizontal permeability, as when shale partings or interbeds are present, the gas bubble may not develop its intended thickness but flow out in a thin zone immediately beneath the caprock with the result that gas escapes from within the areas of closure. When recognized, this can often be controlled with proper injection techniques.

1.3 Effects of Leakage

The flammability of natural gas creates some hazards which will not be associated with CAES. However, many of the more serious consequences of leakage in gas storage have nothing to do with its flammability. A case in point is the overpressurization due to leakage of a shallow sandstone aquifer described above. Perhaps the most common consequence of leakage is disruption of near-surface hydrology with consequent impacts upon water supply. Even slight pressurization of shallow aquifers can cause artesian flow in water wells, the appearance of new springs, etc. This has been observed on several occasions in connection with the repressurization of oil reservoirs. Even without pressurization, the accumulation of gas or air in shallow aquifers can cause some wells to go dry, pumps to lose their prime, the entrapment of gas and water in water supply, etc.

2.0 ADDITIONAL COMMENTS

2.1 Variations in Risk with Time

At first glance, it would appear that the most serious risk of CAES failure would be in the first weeks or months of operation. It would appear that gas storage experience does not support this conclusion. The Ravensworth Cavern where leakage became apparent only in the eleventh year has been mentioned. Second-hand information about other cavern failures indicates that most of them also occurred after the cavern had been in use for some time. This is certainly the case in the instance where pillar collapse has been suggested as the cause of failure.

Similarly delayed failures are not uncommon in aquifer storage. In one case, a field operated successfully for twelve years but withdrawal in the thirteenth year showed that most of the gas had suddenly escaped. A similar sudden but delayed gas loss was noted in another field after eight years of operation. It is suspected that at least one of these cases is related to the "pumping effect" and "umbrella effect" discussed above. One hypothesis is that due to the pumping effect combined with the umbrella effect, a high gas saturation was eventually developed in a portion of the reservoir extending to beyond the spillpoint. Once this condition had developed, injected gas could more readily follow this avenue of movement and it could displace water to fill the closed reservoir and accordingly most of the injected gas subsequently escaped.

Also mentioned above, fatigue failure, the caprock by thermo-mechanical and moisture content changes. If this actually occurs, it becomes more probable with the passage of time. Of course the same is also true for cement and casing failure and other mechanical aspects of the subsurface installation.

2.2 Variations in Risk with Geologic Province

To evaluate the incidence of known and suspected leakage in terms of geologic environment is difficult but some obvious conclusions have been reached for the gas storage reservoirs considered. Since 85 percent of the operating storage fields are located in the relatively flat lying paleozoic sedimenta of the Upper Midwest, the statistics are severely biased. While one might intuitively expect a higher frequency of leakage in areas of greater structural complexity, the present available data is insufficient to support this opinion. There may be a greater incidence of serious (sufficient to cause abandonment) leakage in the more strongly folded areas, but the data is not really sufficient to support that case either.

2.3 Variations in Risk with Competency

This is a very subjective comment, based primarily upon experience and the present data conclusion is that storage fields operated by companies who operate many fields are less likely to allow leakage than those operated by companies whose storage experience is more limited. Statistically, the risk of a company's first storage operation leaking seems very high. There may be some geographic bias in this conclusion since the majority of gas storage is operated by gas utilities and is therefore located within their service areas. A company whose geographic service area includes Central Illinois operates in a much more favorable environment than does one whose service area includes Northern Indiana. There may also be a bias in corporate management philosophy, some companies being willing to invest more heavily in pre-operational testing and evaluation and others being more willing to accept the risk attendant upon a lower exploration and testing budget. Generally speaking, the more experienced a company is, the more heavily it invests in careful exploration and testing.

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APPENDIX J

INDUCED SEISMICITY

1.0 INTRODUCTION

Induced seismicity is the change in seismic activity induced by some activity. The seismicity of a region refers to the frequency and magnitude of earthquakes or earth vibrations caused by blasting or meteorite impact or any sudden loading. Induced seismicity is of importance in CAES design because the frequency and magnitude of earthquakes could change because of groundwater pressure and/or stress changes resulting from the presence of the CAES.

This appendix discusses known examples of induced seismicity and its impact on CAES design. No alternatives are suggested but the need for further research and quantification of this important variable is highlighted for future consideration.

2.0 BACKGROUND EXAMPLES OF INDUCED SEISMICITY

Induced seismicity can be attributed to two main sources: stress change or pore-water pressure changes. The filling of dams can induce seismic events by both sources whereas mining activities generally induce seismic events because of stress changes alone.

2.1 Pore-Water Pressure Changes

Two classical demonstrations of the influence of varying the pre-water pressure on earthquake activity are available; at Denver and at Rangely. At Denver, liquid waste products were disposed of by injection into formations at about 3,600 meters in depth. Within a few weeks of the beginning of fluid injection, April 1962, a swarm of tremors, including some strong earthquakes, occurred with epicenters near the well. Injection was terminated in February, 1966, because of a suggested causal relationship between fluid injection and the Denver earthquakes. Figure 1 shows a plot of earthquake number, injection pressure and volume of injection fluid with time, Handin and Raleigh (1972).

At Rangely, oil production had decreased the fluid pressure rapidly until 1957 when water injection was initiated for secondary recovery. A seismic station located 65 km away from Rangely in 1962 recorded several small earthquakes in the vicinity of the Rangely Oil Field. Subsequent seismological stations were installed and a correlation between the annual number of earthquakes and the volume of fluid injected per year noticed. Subsequently, further stations located the source of the events to near the injection wells and stress measurements have confirmed a possible mechanism. Raleigh, et al. (1972) and Haimson (1972) suggest that the stresses in the Weber sandstone are such that the injection of pore fluid and reduction in effective stress was sufficient to cause failure or slip along a fault in the sandstone; see Figure 2. By varying the injection rate, earthquakes can be triggered or controlled.

2.2 Dam Filling

The construction and filling of dams has been recognized as a cause of increased seismic activity in over thirty cases. Gupta and Rastogi (1976) undertook a comprehensive review of many of these cases and leave in no doubt the correlation between induced seismicity with dam loading. Figure 3 shows the epicenter location relative to Boulder Dam and Lake Mead, and Figure 4, the relation between water level and local seismicity.

Up until the early sixties, no major earthquakes had occurred as a result of dam filling although the correlation had been noticed. However, during the 1960's, damaging earthquakes occurred near large reservoirs in Kariba in the Zambia-Rhodesia border region, at Kneriasta in Greece and at Koyra in India. These earthquakes, of magnitude greater than six, claimed many human lives and caused significant damage. Now seismic monitoring before construction, during construction and filling is routine. It is believed that most of the induced seismic activity is associated with reactivated pre-existing faults.

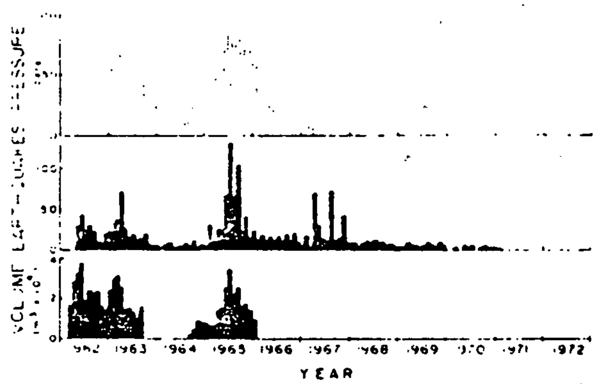
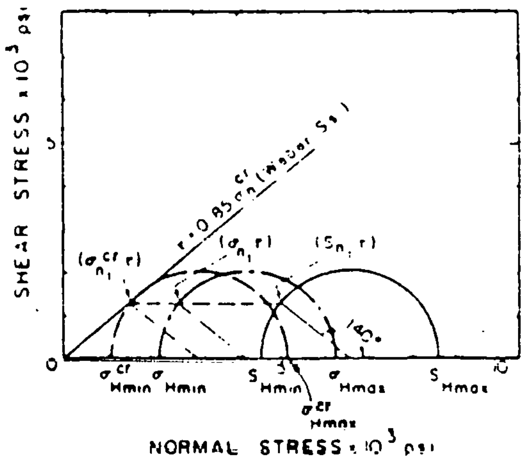
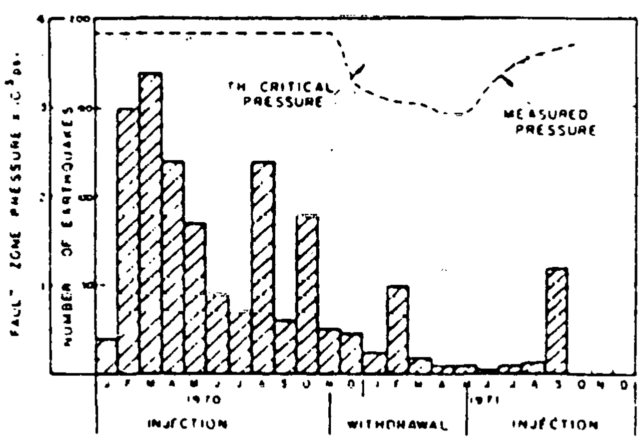


Figure 1 Monthly number of earthquakes in the Denver area, monthly volume of injected water and wellhead pressure in the disposal well (Handin and Raleigh, 1972)



a) Stresses acting on the fault



b) Frequency of earthquakes at Rangely

Figure 2 Stresses and frequency of earthquakes at Rangely Oil Field (Haimson, 1972)

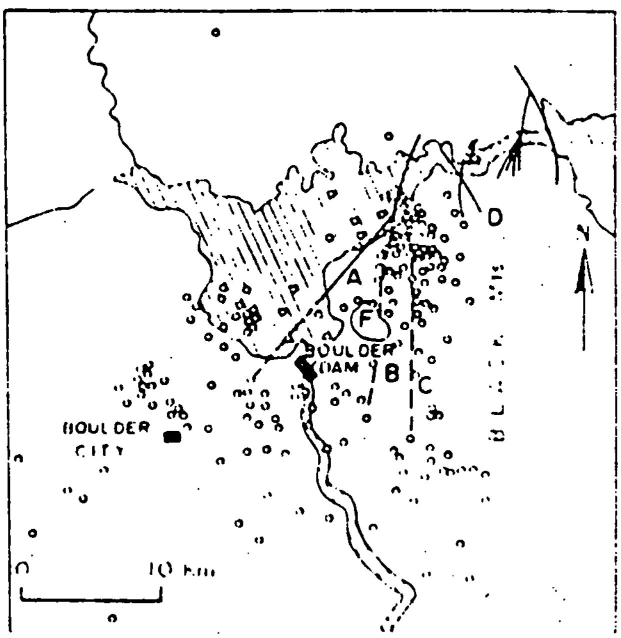


Figure 3 Epicenter locations in the Lake Mead area from June, 1942 to December, 1944. A, B, C and D are the faults (Carder, 1945)

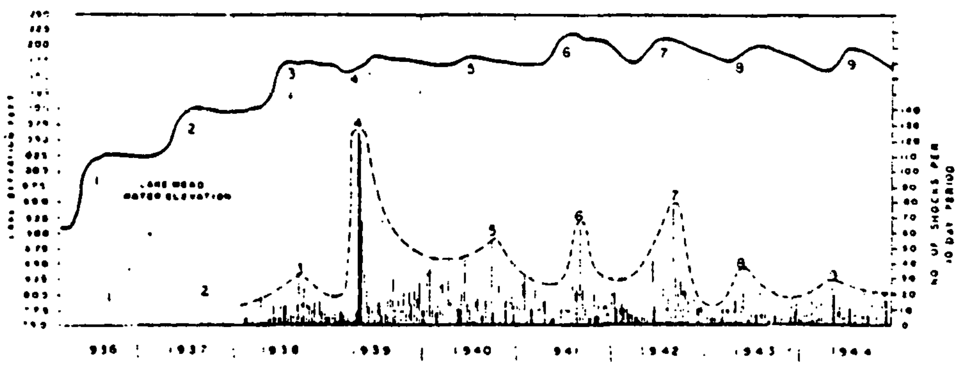


Figure 4 Lake Mead water levels and the local seismicity for 1936 and 1937 (Carder, 1945)

In many dams, however, including some very big areas, no seismic activity has been observed. Gupta and Rastogi observe "it is believed, therefore, that special geological and hydrological conditions are required for the triggering of earthquakes of engineering importance."

The Koyra earthquake of 1967 was one of the most significant to date having claimed over 200 lives, injuring 1,500 and rendering thousands homeless. The dam and associated Shirazi Sagar Lake were situated in the peninsular shield of India in a region believed to be aseismic. However, soon after the impounding of the reservoir in 1962, reports of earth tremors near the dam site became prevalent. The frequency of these tremors increased considerably from 1963 onwards. In 1967, five earthquakes of sufficient magnitude to be recorded on Indian seismological observatories preceded an event of magnitude 5.5 on September 13, 1967. The major event occurred on December 10, 1967, and was estimated by various agencies to be between 6 and 6.5; the Indian Meteorological Department estimated its magnitude at 7.5. The focal depth was defined to be between 8 and 30 km below the surface.

2.3 Mining Induced Seismicity

Mining induced seismicity is well-documented in association with surface mining (Pomeroy, et al., 1974) and underground mines (Osterwald, et al., 1955, Smith, et al., 1974, Cook, et al., 1966, Blake, 1972). Pomeroy, et al., discuss induced seismicity associated with surface quarrying and deduce that the change in stress required to cause seismic activity at that location was less than 1 MPa; this is significantly less than the failure strength of the rock. They conclude that the area must have been in a condition close to failure before mining began.

The seismic activity associated with underground mining in eastern Utah, reported by Osterwald, et al., and Smith, et al., 1974, has been the subject of extensive study by the U.S.G.S. Surprisingly, the seismic events are located up to 1,000 m below the mine level. The authors suggest that there is a strong spatial correlation of earthquakes and active mining and hence, "The unloading and redistribution of the overburden stresses are thus suspected as the trigger of the deeper seismicity." The minor impact mining has on stress redistribution at significant depth below the mine indicates that the rock at that depth must be near failure before mining.

Rock bursts are sudden failures of rock in a mining area and these can cause seismic waves to propagate similarly to earthquake induced waves. Some types of rock bursts are similar to earthquakes because the source mechanism is a slip along a joint or fault. In other instances, the rock burst results from compressive rock failure in a pillar or roof strata. The South African Gold Mines have had some of the world's largest rock bursts with equivalent earthquake magnitude of up to 5. These result primarily from high compressive stresses around openings or remnant mine pillars. However, some rock bursts in South Africa are the result of slip along faults away from the mining area.

It is interesting to speculate on the impact of stress changes on the seismic frequency magnitude relationship for a region. The examples quoted above suggest a significant change in the frequency magnitude curve for only a small change in stress or pore-water fluid for the regions. Obviously, there must be other regions where stress and pore-water pressure changes would produce only minor changes in the frequency magnitude curves. In areas where the stress changes induce near-instantaneous increase in seismic activity, one can conclude that rock failure is involved or the safety factor against sliding for a pre-existing joint or fault is locally 1.0 or less.

3.0 STRESS CHANGES AROUND A CAES

Induced seismicity has been attributed either to stress changes or pore-water pressure changes. The construction of underground caverns for CAES will alter the stress field and could give rise to increased seismicity similar to that experienced in mining operations. However, the site selection procedure will ensure that areas of high tectonic stress and regions that might be close to failure are avoided.

In aquifer storage, the air pressure must exceed the pore-water pressure to create the storage "bubble." The pore-water pressure will therefore be increased and the effective stress reduced. The potential for induced seismicity will therefore be present. In balanced systems, the pressure in the underground reservoir will be hydrostatic and may or may not exceed the existing pore-water pressure and increased seismicity activity may or may not occur.

The effect of CAES on the seismicity of a region is difficult to quantify since the relationship between stress change and frequency of earthquakes is not known. To evaluate this relationship, the mechanisms of earthquakes must be understood and many questions in this area still remain unanswered.

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APPENDIX K

HAZARD INDEX ANALYSIS

A methodology for comparative evaluation of CAES and UPH schemes, on the basis of a weighted score of all potential modes of failure, has been developed. The weighted scoring produces an ordinal ranking which designates undesirable outcomes with correspondingly low values. With appropriate coefficients, the algorithm may be used to generate a multiplier (greater than or equal to one) for adjusting the rates in Section 5.3 according to the Hazard Indexed risk rating for any particular site.

The methodology is based on the assumption that the level of long-term risk of CAES and UPH schemes can be analyzed as a function of the expected or predictable consequences of a set of potential modes of failure. The consequences of these potential modes of failure can be valued, for comparison purposes, in several different ways. The most useful scale for measuring relative performance is an ordinal scale. Such a ranking describes quantities in terms of "greater" or "smaller" but does not imply cardinally valued distances between values. However, quantification of pertinent variables will be used to define the appropriate position along the ordinal scale for a particular item.

The hazard index is defined as a function of the likelihood of failure, the expected magnitude of failure, and the consequences of failure.

Individual hazard index $I_i = f(L,M,C) = (L_i)\ (M_i)\ (C_i)$ where

L_i = Likelihood of Occurrence

M_i = Magnitude of Failure

C_i = Consequences of Failure

The components of this model are described individually in the following sections.

<u>Likelihood of Failure</u> (L_i)

The likelihood of failure, L_i, is a function of design, engineering, material, site, climate, maintenance, and monitoring characteristics of a CAES or UPH plant.

occurrence can be fairly well defined in quantitative terms using available statistical data.

On the other hand, phenomena such as roof collapse, creep closure, air leakage, etc., depend on factors whose effects are not readily quantified, such as rock degradation with time. The determination of a probability of failure is then, to a large extent, a matter of subjective judgment. The numerical connotations of the term "probability" may be misleading, so the term "likelihood" is used instead.

The likelihoods-of-occurrence of the sudden events listed above may be defined once a particular site is chosen. However, if a quantitative value is to be used, then the interval values that may be assigned should reflect the confidence with which the likelihood can be determined. It is intended at this time to describe likelihood on the basis of a scale ranging from 0 to 10, with 0 representing a probability of occurrence of 0 and 10 representing a probability of occurrence of 1.

In accordance with the subjectiveness involved in assigning many probabilities, it is intended to use only the numbers 0, 1, 3, 5, 7, 9 and 10. This implies that the confidence interval corresponds to a probability of 20 percent. The selection of that interval represents the confidence coefficients for these probability assignments.

Expected Magnitude of Failure (M_i)

This value quantifies the magnitude of a particular failure mode. The likelihood (L_i) of a particular failure of magnitude (M_i) is a function of M_i. A discrete number of failure magnitudes are considered. Values for magnitude-of-failure are assigned for each potential mode of failure on a scale of 0 to 10, with 10 representing an incidence of the highest magnitude and 0 representing no damage. In the case of air leakage, a value of 0 would correspond to no pressure loss while a value of 10 would correspond to total pressure loss. The assignment of this value is a subjective application of engineering judgment, presumably based upon an understanding of rock behavior. So as not to imply a confidence level of greater accuracy than exists, only values of 0, 1, 3, 5, 7, 9 and 10 should be assigned.

Consequences of Failure Mode (C_i)

The consequence of a failure mode, C_i, is a weighting factor which represents the extent of the hazard posed by a particular failure mode.

Because the consequences of air loss are different for different potential modes of failure, they imply different kinds of hazards, levels of hazard, and different control problems. These represent parameters in the development of a consequence of failure factor.

The subparts of the consequence-of-failure function are

1) severity of potential failure (S_i),
2) response to and ease of maintenance (R_i), and
3) ease of monitoring (E_i).

Evaluation of the C_i component is the most subjective of the three, because it msut be applicable to a wide variety of conditons, many of which cannot be defined in absolute or demonstrable terms. Although it may be possible to assign a numerical value to these factors, determination of a C_i value will depend on subjective weightings and assembly method for the composite.

As an example, a casing failure may result in the loss of a large volume of air that was costly to inject. The control problems created, however, may be of greater or lesser dimensions. Every Failure Mode implies a unique level of concern, in terms of design expertise or costs required for its anticipation, prevention, or remedy. The air loss mentioned may be relatively cheap to stop, and monitoring and maintenance devices could be readily available to designers. The consequences of such a failure would have an accordingly low (C_i) value.

At the other end, a seepage failure may result in a large air leak that is difficult to detect. In addition, maintenance and remedal measures may require sophisticated technicians and be costly to implement. A resulting consequence of failure value, C_i, will be high.

The subparts of the consequence-of-failure function are

1) severity of potential failure (S_i),
2) response to and ease of maintenance (R_i), and
3) ease of monitoring (E_i).

Evaluation of the C_i component is the most subjective of the three, because it must be applicable to a wide variety of conditions, many of which cannot be defined in absolute or demonstrable terms. Although it may be possible to assign a numerical value to these factors, determination of a composite C_i value will depend on subjective weightings and the method of computation.

Total Hazard Index

The individual hazard index I_i for each individual failure mode, the total hazard index potential for a given storage scheme, can be computed as shown:

$$H_j = \sum_{i=1}^{n} [I_{ij} = (L_{ij}) (M_{ij}) (C_{ij})]$$

It may be desirable to compute the Total Hazard Indices for various time spans (j) since the probability of occurrence of various failure modes will usually change with different time periods. Summing over the desired values of H_j for a given time period provides a measure of the total hazard within that period. This will supply a knowledge of the different Index values at various stages in the life of a facility. A design life of 30 years for CAES schemes implies that a risk assessment for time periods much more than 30 years would be of little interest. Evaluations for time periods in accordance with current actuarial practice, but no greater than the expected facility life, would be adequate to describe the risks associated with short- and long-term time periods. To evaluate the potential risks of alternate sites where the conditions will vary somewhat, an assessor may compute new hazard indices, with the overall lowest index representing the least risky site.

It should be emphasized that the "Hazard Index" is, in essence, a tool for distinguishing individual sites. An index value is entirely dependent upon the geologic, tectonic, and hydrologic conditions of any particular site. As such, a "representative" hazard index for all CAES caverns has little or no meaning. The hazard index methodology outlined above can be applied, however, to any CAES scheme where the basic conditions are known. Base case hazard conditions for the CAES/UPH Failure Modes are outlined in Section 4.6.

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