MASTER

A FEASIBILITY STUDY OF UNDERGROUND ENERGY STORAGE USING HIGH-PRESSURE, HIGH-TEMPERATURE WATER

Final Report

JAMES L. DOOLEY
GERALD P. FROST
LINN A. GORE
R. PHILIP HAMMOND
DONALD L. RAWSON
STUART L. RIDGWAY

Prepared by

R & D ASSOCIATES
Post Office Box 9695
Marina del Rey,
California 90291

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ABSTRACT

A technical, operational and economic feasibility study on the storage of energy as heated high pressure water in underground cavities that utilize the rock overburden for containment is presented. Handling peak load requirements of electric utility power networks is examined in some detail. The cavity is charged by heating water with surplus steaming capacity during periods of low power requirement. Later this hot water supplies steam to peaking turbines when high load demands must be met. This system can be applied to either new or existing power plants of nuclear or fossil fuel type. The "round trip" efficiency (into storage and back) is higher than any other system--over 90%. Capital costs are competitive and the environmental impact is quite benign.

Detail installation and design problems are studied and costs are estimated. The continental United States is examined for the most applicable geology. Formations favorable for these large cavities exist in widespread areas.

Schematic of Underground Thermal Energy
Storage System

PREFACE

This report presents the results of a three-month initial study of a new approach to storage of off-peak energy by electric utilities to handle the peak loads on the network. The technical feasibility and economic viability are assessed for storage of pressurized hot water in specially prepared deep rock cavities. The cavity water is heated to boiler temperature by the main steam generator during low-load periods. By lowering the pressure, steam is supplied to drive a conventional turbine alternator set as a peaking unit.

Feasibility of the large cavities has been explored, including mining techniques, stability under lithostatic, hydrostatic, and thermal stresses, and lining techniques. In addition to feasibility and costs, a preliminary survey of geological regions within the United States likely to have suitable sites for such cavities was made.

The work was done for ERDA by R & D Associates, Marina del Rey, California. The company has considerable background in the technology of deep underground structures from previous work on Project PACER (Contract AT 292-3324), the ARPA study on Payette (20), a long experience with underground nuclear testing, and from work on "hardening" of military installations. Other work includes special studies on in situ stress related to block motions. Portions of the background information and skills used are proprietary.

SUMMARY

The concept of storing energy in hot pressurized water underground as a means of meeting electric utility demand peaks on conventional, nuclear or solar generating plants has been found to be technically feasible and economically viable in this study. The use of deeply buried rock cavities as pressure vessels is commonly practiced for natural gas storage, but has not been applied to holding water or steam to date. In the past few years, however, intensive study of such applications has been pursued, and recent advances in rock mechanics analysis and earth science now permit such cavities to be designed with some confidence. Adequate technology is on hand for the construction of these cavities, the only limit in demonstrated practice being the width of the largest unsupported span. By using multiple smaller spheres or an ellipsoid-shaped chamber instead of a large single sphere, one could keep the spans within current experience at a slightly higher cost.

Since the remainder of the storage system consists of conventional steam power equipment used in familiar ways, a carefully planned demonstration program of cavity construction and testing would permit early realization of this highly attractive and widely applicable power storage option. Data assembled from several sources confirm that costs, environmental effects, and safety are all favorable compared to other storage options when the cavity itself can be demonstrated satisfactorily.

In this preliminary study it has been assumed that a steel liner would be necessary to maintain the purity of the stored water for turbine and boiler use. Detailed study of whether

a liner is needed and of the best methods of installation and attachment would be part of the preparation for a demonstration program.

Underground thermal energy storage systems generally would be sited near a new or existing power plant and be charged directly from the boiler or reactor. As shown in the accompanying technical and cost summaries, the system exhibits pronounced economies of scale, but is most attractive over a range of 1/2 to 2 million kWh of stored electric output. Power output rates of 200 to 1000 MW were examined in the study, and the effects of boiler pressure were considered over a range typical of both nuclear and fossil fueled plants. A preliminary survey of geologically suitable United States sites has been made, with indications that a majority of large U.S. utilities could expect to find suitable underlying rock formations somewhere within their system. The following tables include data on the system related to the power output, the amount of storage and a capital cost recap of TESS for both nuclear and fossil fueled main plants. Specific capital costs per kW of output and per kWh of storage are also included.

I. Power Related Data

PLANT TYPE	NUCLEAR FUEL	FOSSIL FUEL
STORAGE PRESSURE CHARGED, psi	1080	1860
STORAGE PRESSURE DISCHARGED, psi	575	1080
STORAGE TEMPERATURE CHARGED, °F	550	625
STORAGE TEMPERATURE DISCHARGED, °F	480	554
FRACTION WATER FLASHED TO STEAM, PERCENT	11.7	14.9
STORAGE ENERGY DENSITY, kWh _e /ft ³ AT 85 PERCENT TURBINE EFFICIENCY	0.54	0.63
INPUT-OUTPUT EFFICIENCY OF STORAGE SYSTEM, PERCENT	93-95	90-93
STEAM FLOW UP PIPE, lb/hr/kW; PIPE AREA, in ² /MW APPROPRIATE	1.0-1.25	0.5-0.7
CAVITY DEPTH AT TOP, ft	1225	2450
SHAFT DEPTH, ft	1700	2800
SHAFT SIZE, ft IN DIAMETER*	15-20	15-20
TUNNEL LENGTH, ft	1000-2000	1000-2000
ROCK REMOVED FROM SHAFT AND TUNNELS, T	61,000	91,000

* Shaft diameter depends on cavity size and excavation rate.

II. Storage Related Data

SPHERICAL CAVITY DIAMETER, ft	125	200	275	325
CAVITY VOLUME, $\text{ft}^3 \times 10^6$	1.02	4.18	10.86	17.93
ROCK REMOVED, T $\times 10^3$	80	325	850	1400
SURFACE, INTERNAL, $\text{ft}^2 \times 10^4$	5.0	12.6	23.7	33.2
STEEL LINER THICKNESS, inches	3/8	3/8	1/2	1/2
LINER WEIGHT, T	390	975	2450	3425
ENERGY STORAGE, $\text{kWh}_e \times 10^6$				
NUCLEAR LOW PRESSURE	0.52	2.13	5.55	9.14
FOSSIL FUEL OR HIGH PRESSURE	0.60	2.46	6.45	10.68

III. Complete Peaking Plant Costs

ALL COSTS ARE IN 1976 DOLLARS ($\times 10^6$) AND INCLUDE 20 PERCENT MINIMUM FOR UNCERTAINTIES, 25 PERCENT FOR ADMINISTRATION PLUS 20 PERCENT ON ALL COSTS FOR FINANCE CHARGES. COST RANGE SHOWN.

CAVITIES ARE SIZED FOR 10 hr OF PEAKING OUTPUT IN THESE EXAMPLES.

A. LOW PRESSURE PEAKING POWER SYSTEM (1000 lb/in.²)

PEAKING OUTPUT (MW)	200	500	1000
CAVITY SPHERE DIAMETER (ft)	192	260	325
- GENERATING PLANT COMPLETE (\$)	46-55	83-92	139-145
- COOLING TOWER (\$)	3-3	6-6	13-13
- UNDERGROUND SHAFT COSTS AND PIPING (EXCEPT CAVITY) (\$)	12-21	16-25	20-31
TOTAL POWER RELATED COSTS (\$)	61-79	105-123	172-189
TOTAL CAVITY COST RANGE (\$)	25-31	54-62	81-99
COMPLETE PEAKING PLANT COST RANGE (\$)	86-110	158-185	253-288

B. HIGH PRESSURE PEAKING POWER SYSTEM (2000 lb/in.²)

PEAKING OUTPUT (MW)	200	500	1000
CAVITY SPHERE DIAMETER (ft)	181	248	310
- GENERATING PLANT COMPLETE RANGE (\$)	46-55	84-93	141-145
- COOLING TOWER (\$)	2-3	5-6	11-13
- UNDERGROUND SHAFT COST AND PIPING RANGE (EXCEPT CAVITY) (\$)	16-29	20-34	29-43
TOTAL POWER RELATED COSTS (\$)	64-87	109-133	181-202
TOTAL CAVITY COST RANGE (\$)	22-29	47-56	77-94
COMPLETE PEAKING PLANT COST RANGE (\$)	86-115	156-189	258-296

C. COMPARISON OF STEAM SOURCES CAPITAL COST--A TESS CAVITY VS A NEW COAL FIRED STEAM PLANT.

Since the peaking turbine-alternator and its associated equipment is almost the same regardless of the steam source, a direct comparison can be made between a TESS cavity source and a new coal fired steam generator. The TESS cavity must include its liner, shaft and piping while the coal fired steam generator includes coal handling and pulverizing, air preheaters, environmental cleanup, feedwater pumps, preheaters, etc. Based on a high pressure system and a 10 hour duty cycle as stated above, the capital cost comparison is:

POWER OUTPUT MW _e	200	500	1000
SPHERICAL CAVITY DIAMETER (FT)	181	248	310
COST OF SHAFT, PIPING & LINED CAVITY COMPLETE (\$)	38-57	67-90	106-137
COST OF AN EQUIVALENT SEPARATE NEW STEAM GENERATING UNIT COMPLETE (\$)	60-80	125-175	235-335

This does not compare operating costs or operational characteristics.

D. COMPARISON OF A COMPLETE TESS WITH SURFACE PUMPED HYDRO.

The lower initial capital cost of a pumped hydro peaking system is more than offset by its higher fuel cost when compared to a TESS peaking plant. This is due to its lower "round trip" efficiency--into storage and back to the wire. In the table below a 20 year life and 10% interest rate is used to get the present value of the incremental fuel costs over a "no storage" plant. 1000 MW delivery for 10 hours.

TYPE OF STORAGE SYSTEM	CAPITAL COST OF PLANT \$ x 10 ⁶	ENERGY RECOVERY FACTOR %	CAPITAL COST PLUS PRESENT VALUE OF EXTRA FUEL USED
PEAKING SURFACE PUMPED HYDRO PLANT (\$)	140-260	67	291-411
PEAKING TESS PLANT COMPLETE (\$)	258-296	89	296-339

IV. Summary of Specific Costs*

PEAKING POWER-RELATED CAPITAL COSTS	LOW PRESSURE	HIGH PRESSURE
SURFACE GENERATING EQUIPMENT (\$/kW)		
200 MW	231-276	231-275
500 MW	166-184	168-189
1000 MW	139-145	141-145
HYPERBOLIC COOLING TOWER (OPTIONAL) (\$/kW) ADDITIONAL	12-13	11-12
UNDERGROUND TESS COSTS (\$/kW) (EXCEPT CAVITY PROPER)		
200 MW	61-106	78-143
500 MW	31-49	41-68
1000 MW	20-31	29-43

Storage Related Capital Costs				
CAVITY SIZE--SPHERICAL DIAMETER (ft)	125	200	275	325
UNIT COST--CAVITY COST COMPLETE (\$/ft ³)	9.96	7.33	5.59	4.50
UNIT COST--CAVITY COST COMPLETE (\$/kwh STORED)				
LOW PRESSURE	16-25	12-14	10-12	8-11
HIGH PRESSURE	14-22	10-12	9-11	7-9

* COSTS INCLUDE 20 PERCENT OR MORE OF DIRECT COST FOR UNCERTAINTIES, 25 PERCENT FOR ENGINEERING AND ADMINISTRATION AND 20 PERCENT ADDITIONAL FOR FINANCING COSTS DURING CONSTRUCTION IN 1976 DOLLARS.

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SECTION 1. INTRODUCTION

1.1 NEED FOR ENERGY STORAGE

Almost every power company is faced with the problem of supplying its users' power demands under peak load conditions, and yet these utilities have long part-load periods when the extremely high cost capital equipment is not fully utilized. This makes the cost of electric energy vary with the time at which it is delivered. For many years the utilities have sought ways to alleviate the staggering heavy investment to handle peak loads with an inefficient, low average load condition. The demand load variation in many areas is ± 20 percent from the mean. A typical weekly power demand profile is shown in Figure 1-1. It is not within the scope of this study to establish exact load variations since this has been done by many others [1]. R & D Associates has studied several sizes of Thermal Energy Storage Systems (TESS) that hopefully bracket a utility's requirement in order to learn the influence of size on the viability of this storage system.

The current United States total of 8100 MW of operational peaking output is expected to grow to about 40,000 MW by 1995. Clearly there is a need for better energy storage systems [1].

1.2 METHODS GIVEN CONSIDERATION

Described below are some of the methods considered for storing energy in the large quantities needed by the utilities where immediate retrieval during peak load or emergency conditions is required [1,2].

Figure 1-1. Typical Weekly Power Demand Profile for Utility Showing the Availability of Less Expensive Power for Storage System

1. Water stored at an elevation. Water is pumped to an upper level reservoir during periods of light load and used through a water turbine alternator for power when needed. Unfortunately, geographic limitations and environmental restrictions limit application of this system. Considerations are being given to underground cavities for the lower reservoir. This equipment need not be located at or near the main electric power plant.
2. Compressed air storage in underground cavities. This system is associated with a special gas turbine-alternator set so the alternator drives the compressor for charging the reservoir and the high pressure air can be heated in the turbine combustors by burning fuel in it before expanding through the turbine when power is to be delivered. To date only natural cavities and abandoned mines have been considered for this purpose. The power output is limited by the gas turbine size (<250 MW) so multiple units must be used.

Storage of the uncooled compressed air stored hot in rock chambers has recently been considered. The air is then used in the turbine expander without heating.

3. Electrochemical energy storage methods are well known in smaller sizes. Larger installations are being studied. None are presently in operation.
4. Kinetic energy storage has been used since the invention of the wheel. Flywheels up to 50 T have been used in some mine hoists and larger, more highly stressed (rims) units are under study and development.
5. Heated oils and salts that can be stored at low pressure and high temperature have been used for

peak load steam generation and are currently under study for both peak loads and solar power plants. The working medium and the required heat exchangers are costly. The oils are temperature-limited because of thermal deterioration.

6. Steam and hot water have been stored in surface pressure vessels for applications requiring relatively small capacities. The cost and fabrication limitations have restricted the size of the installations in the past; however, new developments in steel-wire wrapped, segmented cast iron pressure vessels have renewed interest in this system.
7. Heated high pressure water stored in underground cavities where the rock overburden acts as both the containment vessel and the insulation. This cavity would be charged with the excess steaming capacity of the main steam generating units during off-peak periods. This energy can be used for conventional feed water heating to eliminate turbine bleed steam or it can be used as steam directly in peaking turbines. This report restricts itself to the latter application.

When stored thermal energy is to be recovered for power generation, the hot water in the cavity is allowed to flash to steam as the pressure is slowly dropped. The turbine-alternator set used for peaking power may be similar to the base-load machines except that it normally operates at lower pressures and with little or no super-heat. This report includes description, analysis of some critical problem areas, and cost estimates for such a system which we will refer to as TESS.

1.3 ADVANTAGES OF TESS

Some of the advantages of this underground system of energy storage with saturated water compared to pumped hydro-storage are as follows [3]:

1. Location - The cavity would be in proximity to the power plant, which can be located near or even within the metropolitan areas that are the heavy users of electrical power at peak conditions. This would depend upon the geology beneath the particular area. There is no hazard involved, so the surface area above the cavity can be put to almost any nonresidential use as shown in the frontispiece. In contrast, the pumped water storage system generally requires two large reservoirs and terrain suitable to obtain the elevation difference.
2. Efficiency - Since the energy goes directly into the cavity from the Steam Generating Unit (SGU) during off-peak periods and through the steam turbine-alternator only once when it is finally used, the overall input/output efficiency is higher than in the pumped water storage system where the energy passes through the steam turbine-alternator once, and the motor-pump/turbine-alternator unit twice with attendant inefficiencies each way. Overall efficiency is shown in Section 6.3. The capitalized value of this fuel saving may overshadow the storage capital cost.
3. Cost - As shown in detail later, the cost of larger size cavities and attendant equipment is competitive

with any presently available storage system. Utilities currently pay from \$115 to \$215 per kilowatt of output and \$3 to \$15 per kilowatt hour of capacity for a pumped hydro-storage system. Other systems are generally even more costly.

4. Energy Density - The energy stored per unit of water volume is about 60 times higher than pumped water systems.
5. Size - There is no upper limitation on either power output or storage capacity with this system except for those of the power plant into which it is tied. The largest turbo alternators available can be used and supplied with steam from multiple large cavities if necessary. Sizes below about 200 MW and 500,000 kwh storage are relatively costly on a specific energy basis because excavation costs associated with the shaft and tunnel are not reduced appreciably with smaller cavities.
6. Redundancy - With the saturated hot water storage system, the steam turbines and alternators may be similar to those used in the power station for the base load. In a new plant they may be less costly with this standardization. In case there is trouble with the base load turbines or alternators, the peaking unit may be used as a substitute.
7. Short Time for Start-Up - Steam in large quantities is available from the hot water storage cavity at any time, except when fully discharged. The delay time to bring power "on line" is determined by turbo-alternator warm-up--usually about 30 min.

8. Dead System Restart - Steam is always available from the cavity for the restart of auxiliary and mainline equipment, even if an entire network is down.
9. Environmental Impact and Safety - TESS presents a benign set of conditions on the environment and no real safety hazard even in the unlikely event of an uncontrolled blowdown.
10. Esthetics - Because most of the required equipment is underground where it presents no eyesore to the public, it should be more acceptable than alternative systems with respect to concerns of this nature.

1.4 DISADVANTAGES OR PROBLEM AREAS

1. The system requires suitable underground rock to accommodate large cavity spans. The rock also must not degrade seriously with the thermally induced stresses developed during operation.
2. Some areas may have underlying geological formations that are completely unsuitable for UTESS cavities or they may only be made suitable at an unacceptable cost penalty.
3. For the first installation, it is felt that some developmental testing in the potential problem areas must be done prior to building the first demonstration cavity. This includes work on liner strengths at temperature and on internal equipment to insure very high boiling and condensing rates.

Reduction of these uncertainties, however, may actually reduce the elapsed time to the first operational system.

4. Except for salt cavities, current demonstrated practice extends to rock spans smaller than the more economical TESS cavity sizes. While current technology exists for the safe design and construction of large cavities, it has not been demonstrated. For this reason, some utilities may prefer to use smaller cavities in multiple at a slight cost penalty.
5. The TESS unit is expected to be operational for an extended period--over 25 years. Should some unanticipated event occur that required repair involving the main cavity or liner, the cost would be high and the downtime long compared to some other alternatives.

SECTION 2. CAVITY CONSIDERATIONS

2.1 CAVITY DEPTH SELECTION

Factors which can influence the selection of the cavity depth below the surface are as follows:

- System operation pressures
- Subterranean geology
- Rock quality and homogeneity
- Location--activities at surface
- Factor of safety--desired or required
- Cavity liner type
- Cost--mainly shaft and steam line costs
- Political influences
- Environmental impact influences
- Psychological attitudes

For purposes of illustration and estimation in this study, a depth has been used that provides 1.33 times the maximum operating internal pressure in the outside lithostatic pressure with an average overburden density of 2.5 (Figure 2-1). This is conservative and a good argument can be made for a cavity where internal pressure equals lithostatic pressure. It would cost less and may be better design for the liner stress in actual operation. A ratio of 1.0 saves about 7 percent on the power-related underground costs.

2.2 CAVITY WALL STRESSES

If the in situ horizontal compressive stress is small relative to the vertical compressive overburden stress, tensile stresses will appear in the upper and lower surfaces of deep tunnels and spherical cavities as the excavation proceeds.

Figure 2-1. Cavity Depth and Diameter

2.2.1 Cavity Inner Wall Stresses

It is beyond the scope of this study to characterize the stress conditions in the cavity wall under the combined and transient conditions from in situ rock prestress through the many stress readjustments induced by the excavation process, internal pressurization and inner wall temperature rise during the charging process. The stress analysis is complex, even for ideal elastic, homogeneous rock. None of these conditions exist in nature and any analysis must be site-specific.

The following simplified stress situations will illustrate conditions caused by instantaneously creating a spherical cavity in idealized rock. The examples serve to show the importance of having adequate in situ lateral stress distributed equally around the equator of the sphere and of using high-temperature, high-strength concrete in the thin liner behind the steel sealing shell

where $S = \rho gh$

S = rock stress

ρ = rock density

h = burial depth.

In Figure 2-2a the vertical stress S exists, but the lithostatic overburden pressure (ρgh) is vertical only. There are no horizontal pressure forces. In this case the rock inner wall at the top and bottom of the sphere is in tension. If $S = \rho gh$ = overburden stress. The inner wall compressive stress at the equator is about $2S$.

In Figure 2-2b the same vertical stress S exists, but there is also lateral compressive stress around the equator section. If the rock had undergone low yield plastic flow, this lateral stress would be the same as the vertical stress for that depth.

LITHOSTATIC OVERBURDEN PRESSURE ONLY

$$S = \rho g h$$

ρ = DENSITY
 h = DEPTH

LITHOSTATIC OVERBURDEN WITH LATERAL COMPRESSION

Figure 2-2. Theoretical Spherical Cavity Stresses

However, this is not always the case. In nature this lateral stress can vary in magnitude and azimuthal uniformity. If it is greater than $S/2$ the undesirable tension at the top is reduced to zero. If it is too great, the equatorial area inner wall stress can go into tension.

Desirable conditions imply a uniform lateral stress greater than $S/2$ and less than $2S$ although this is not mandatory for a successful cavity excavation.

Figure 2-3a illustrates the conditions that occur in the cavity rock wall when internal pressure is applied. In an infinite expanse of ideal elastic material the inner wall tension due to this pressure P is $P/2$ and the growth due to pressure is

$$\Delta r = \frac{Pr}{E} \frac{1 + \nu}{2}$$

where r = cavity radius, 100 ft (30.5 m)

P = internal pressure, 2000 psi (138 bars)

E = modulus = 1×10^6 lb/in.² for fractured rock

ν = Poisson's ratio = 0.28 for solid granite (zero for heavily fractured rock)

$\Delta r \approx 1.5$ inches (3.9 cm)

Figure 2-3b indicates the condition that exists when the inner rock wall is heated 500° F above rock ambient. If the rock is very competent (unfractured), the modulus could be high, $\sim 7 \times 10^6$ lb/in.², but generally is lower because of rock anomalies. The compressive stress on the inner surface of a sphere due to thermal expansion is

$$S_c = \frac{\alpha E T_i}{1 - \nu}$$

$$S_c = \frac{0.36 \times 10^{-5} \times 3.5 \times 10^6 \times 500}{1 - 0.28}$$

$$S_c = 8750 \text{ lb/in}^2$$

Figure 2-3. Theoretical Spherical Cavity

where for a typical case

S_c = compressive stress, lb/in.

α = coefficient of thermal expansion $\approx 0.36 \times 10^{-5}$
 $^{\circ}\text{F}^{-1}$ (granite)

$E = 3.5 \times 10^6$ for solid granite

ν = Poisson's ratio = 0.28 (granite)

In granite, depending upon rock conditions, this compressive stress can be from 1800 to 18,000 lb/in².

Figure 2-4 considers only the high strength concrete liner and the thin steel sealing shell inside and bonded to it.

As this assembly is heated and pressurized, several changes occur:

- The concrete liner expands very little (see Figure 2-3a) when heated because it is restrained by the incasing rock mass. Heating to operating temperature causes thermal compressive stress of about 13,000 lb/in² maximum based on no rock deformation, no voids, and no fractures. High strength concrete has an ultimate compressive stress of over 15,000 lb/in.² Table 2-1.
- The steel liner is backed by the concrete liner above and cannot expand appreciably. Thermal heating causes compressive stresses beyond its yield point so it must take a permanent set (see Section 2.6.3).

Figure 2-4. Theoretical Spherical Cavity Liner Stresses

Table 2-1. Thermal Tangential Compressive Stress*

MATERIAL	α , COEFFICIENT THERMAL EXPANSION, $^{\circ}\text{F}^{-1}$	E (lb/in. ²)	ν	ULTIMATE COMPRESSIVE STRENGTH (lb/in. ²)	$\alpha E T_i / (1-\nu)$ $T_i = 500^{\circ}\text{F}$ (lb/in. ²)
GRANITE	0.36×10^{-5}	7.0×10^6	0.28	25,000	17,500
LIMESTONE	0.28×10^{-5}	6.0×10^6	0.21	8000-16,000	10,600-21,200
MARBLE	0.38×10^{-5}	8.0×10^6	0.26	12,000	20,500
SANDSTONE	0.52×10^{-5}	2.5×10^6	0.28	6000	9030
STANDARD CONCRETE	0.60×10^{-5}	3.5×10^6	0.15	3500	12,300
HIGH-STRENGTH CONCRETE (ESTIMATED)	$<0.60 \times 10^{-5}$	$>3.5 \times 10^6$	0.20	15,000-18,000	$\sim 13,000$

* PROPERTIES AT NORMAL TEMPERATURES. PROPERTIES WILL CHANGE AT ELEVATED OPERATING TEMPERATURE CONDITIONS.

From these conditions one can conclude that

1. Adequate lateral in situ compressive rock stress is preferred to insure successful excavation of a large cavity.
2. The internal pressure and temperature generally improve the inner wall rock stress conditions once in operation.
3. Once the heat investment is made into the surrounding rock, the increased temperature causes compressive stresses around the cavity which is a desirable condition.

2.3 CAVITY SHAPE

For best operating results and lowest capital cost it would appear that TESS cavities should have the lowest possible surface-to-volume ratio. This suggests one large spherical cavity of the volume required; however, other factors may indicate another shape is best suited to a given installation. These factors include

1. The magnitude (and sign) of the in situ lateral stress in the rock formation.
2. The maximum allowable roof span.
3. The cavity excavation method.
4. The liner design, materials and installation method.

5. The method of insuring high charge and discharge steam rates.
6. The capital cost of the cavity.

The following cavity shapes have been proposed, discussed and analyzed to some degree during this feasibility study:

- A single sphere
- Multiple small spheres
- Cylinders--horizontal with spherical ends
- Ellipsoids with long axis vertical
- Egg shapes with long axis vertical
- Tori with the main axis vertical

All baseline calculations in this report use a spherical cavity since the variation with other shapes is a secondary effect.

2.4 CAVITY SPAN LIMITATIONS

The historical data on large underground cavities obtained from our consultants [4,5,6], and from organizations specializing in hard rock excavation [7] reveal that deep cylindrical chambers with spans of 130 to 140 ft are considered current state-of-the-art. Much less information is available on man-made, round, dome-shaped cavities, but spans of 150 to 160 are considered practical. Table 2-2 lists some existing larger cavities, but many of them do not have a high overburden load.

Analysis indicates that under the proper conditions spans can be much larger, and this is borne out by some natural cavities and excavations in salt shown in Table 2-2.

Table 2-2. Large Natural and Man-Made Cavities [8]

TYPE	NAME	LOCATION	MAXIMUM WIDTH (ft)	LENGTH (ft)	HEIGHT (ft)	DEPTH TO TOP (ft)	VOLUME (ft ³)	ROCK TYPE	REMARKS	REFERENCE
NATURAL	BIG ROOM	CARLSBAD, N.M.	656	4,260	~330	980	9.2×10^8	LIMESTONE	IRREGULAR	1
	BLACK SALT LAKE	HALLEIN, GERMANY	230	331	--	330	UNKNOWN	SALT	IRREGULAR	2
MINED IN HARD ROCK	LOUISVILLE LIMESTONE MINE	AKRON, N.Y.	400	2,380	~35	<500	7.5×10^6	LIMESTONE	COMPOSITE LENGTH	3
	URAD MINE	CLIFTON, COLO.	298	492	370	~100	9.2×10^8	HYVOLITE	BLOCKED CAVE	4
	OHIO CALCIUM CO.	FRONTON, OHIO	290	5,000	7.8	<500	6.4×10^6	LIMESTONE	COMPOSITE LENGTH	3
	GASSON, MINE	IRON RIDGE, VA.	160	420	35	<500	3.4×10^6	IGNEOUS	IRREGULAR	3
	OLD MILLTOWN QUARRY MINE	MILLTOWN, IND.	150	750	9.5	<500	7.1×10^5	LIMESTONE	IRREGULAR	3
	DARQUHAM POWER HOUSE	ALGERIA	106	240	84	--	2.3×10^7	IGNEOUS	CONCRETE LINED	5
	COMMERCIAL MINE	PRESCOTT, ARIZ.	100	750	~44	<500	2.8×10^7	IGNEOUS	IRREGULAR	3
	CAMP TAYLOR QUARRY MINE	LOUISVILLE, KY.	100	3,332	~27	<500	7.3×10^7	LIMESTONE	COMPOSITE LENGTH	3
	THE "21" BOWANZA-JOKER MINE	MINEVILLE, N.Y.	100	6,664	200	<500	1.0×10^9	IGNEOUS	COMPOSITE LENGTH	3
	ORONGO CIRCLE MINE	ORONGO, MISS.	100	28,500	~13	<500	2.8×10^8	LIMESTONE	COMPOSITE LENGTH	3
	NETTA MINE	PICKER, OKLA.	100	27,600	~55	<500	1.0×10^9	LIMESTONE	COMPOSITE LENGTH	3
MINED IN SALT	CASPARIS MINE	CONNELSVILLE, PA.	100	7,996	55	<500	3.5×10^8	SALT	BEDDED	-
	AVERY ISLAND DOME	NEW IBERIA, LA.	100	200	140	<500	2.8×10^6	SALT	DIAPYRIC	6
	BELLE ISLAND DOME	FRANKLIN, LA.	60	298	80	1,300	1.4×10^6	SALT	DIAPYRIC	6
	GRAND SALINE DOME	DALLAS, TX.	70	200	80	698	1.1×10^6	SALT	DIAPYRIC	6
	HOCKLEY DOME	HOCKLEY, TX.	80	150	90	1,500	1.1×10^6	SALT	DIAPYRIC	6
SOLUTION MINED SALT	BYRON MOUND DOME	BRAZORIA, TX.	~800	~800	1,000	2,000	5.6×10^7	SALT	~CYLINDRICAL	6
	NAPOLEONVILLE DOME	ASSUMPTION, LA.	~650	~650	300	800	4.2×10^7	SALT	~CYLINDRICAL	6
	HULL DOME	LIBERTY, TX.	~200	~200	200	3,200	1.1×10^7	SALT	~CYLINDRICAL	6
	CLARENS DOME	BRAZORIA, TX.	~174	~174	300	2,550	2.8×10^6	SALT	~CYLINDRICAL	6
	SOYRENT DOME	ASCENSION, TX.	~144	~144	800	2,600	5.6×10^6	SALT	~CYLINDRICAL	6
	BYRON MOUND DOME	BRAZORIA, TX.	~128	~128	1,000	2,000	5.6×10^6	SALT	~CYLINDRICAL	6
	GAMBERS HILL DOME	CHANDERS, TX.	~128	~128	1,000	1,900	5.6×10^6	SALT	~CYLINDRICAL	6
	BARBERS HILL DOME	CHANDERS, TX.	~118	~118	1,600	1,800	7.8×10^6	SALT	~CYLINDRICAL	6

NOTES: UNDER MAXIMUM WIDTH, VALUE GIVEN IS UNSUPPORTED SPAN WHERE HORIZONTAL UNSUPPORTED SPAN IN DIRECTION NORMAL TO IT (I.E., THE LENGTH) IS GREATER, EXCEPT IN THE CASE OF SOLUTION-MINED CAVITIES, WHERE NOMINAL DIAMETER OF A ROUGHLY CYLINDRICAL-SHAPED OPENING IS PROVIDED FOR BOTH WIDTH AND LENGTH. IN THE CASE OF MINED CAVITIES IN HARD ROCK, ROCK-BOLTS, LAGGING, OR CONCRETE LINING ARE NOT CONSIDERED "SUPPORT." UNDER REMARKS "COMPOSITE LENGTH" INDICATES THAT VALUE GIVEN UNDER LENGTH IS NOT THAT OF A SINGLE ROOM BUT RATHER THAT OF SEVERAL OR MORE CONNECTED ONES.

REFERENCE SOURCES ARE AS FOLLOWS: (1) MCWINTER AND MCWINTER, 1970; (2) LUBKE, 1958; (3) U.S. DEPARTMENT OF DEFENSE, 1956; (4) KENDRICK, 1970; (5) COOKE AND STRASSBURGER, 1957 AND (6) FENIX AND SCISSON, INC., 1970. MODIFIED AFTER "SITE DEFINITION AND SELECTION FOR PROGRAM PACER," ROBERT R. SHARP, 1974. LOS ALAMOS SCIENTIFIC LAB (WRITTEN COMMUNICATION).

It is noteworthy, however, that even with cavity sizes that are within this current state-of-the-art, TESS is cost competitive with alternate energy storage systems. For example, if eight spheres of 162-ft diameter were used instead of one large sphere of equal volume (325-ft diameter), the capital cost increase is 20 to 40 percent but the system is still competitive. The increase may be reduced if the eight cavities are not installed concurrently so there can be a learning curve cost reduction--especially to reduce the 25 percent underground uncertainty factor.

2.5 GEOTECHNICAL CONSIDERATIONS

2.5.1 General

For large span excavation it is not usually economical to totally support the entire overburden load with a man-made arch structure. The natural arch should provide the basic load-carrying capacity for the most economical design, and in satisfactory rock it can provide this support better than almost any conceivable support system. A possible exception is discussed in Section 2.10.

Geotechnical considerations of suitable properties for siting large span excavations are

- In situ stress conditions
- Strength and structural integrity of the rock mass
- Rock resistance to thermal stress and thermochemical alterations
- Ground water hazards

As a background to a more detailed examination of these geotechnical requirements, it is helpful to identify a few

general guidelines to focus upon the more suitable characteristics and dispense with those geological conditions that have low suitability potential. As previously illustrated selecting sites with sufficient lateral stress to keep the rock surrounding an excavation from developing tensile stress is highly desirable. The rock mass should be characterized by a bulk density that closely approaches the average crystal density of the aggregate mineral components--leading to a rock of low porosity with well-bonded and interlocking mineral grains. This condition tends to maximize the fundamental rock strength and helps to spread the rock stress within the rock mass as stress redistribution takes place during excavation. The combination of low porosity and adequate lateral stress also minimizes the rock permeability to ground water and restricts potential water hazards to finite cracks and structural weaknesses where controls can be affected during excavation. The combination of high strength and microporosity, common to most dense rocks, is expected both to resist induced thermal stresses as well as to allow for small stress adjustments and thermal expansion.

2.5.2 In Situ Stress Conditions

In situ stress information is desirable in evaluating the feasibility of constructing large underground openings. The data base of in situ stress measurements is very sparse and commonly has not been related either to the failure or the stability of underground openings. Fortunately, there are now reasonably accurate methods of making in situ stress determinations using stress relief methods in deep bore holes. The remote sensing of in situ stress variations using geologic and geophysical methods (without drilling) is in the research and development stage, so a reconnaissance indicator of in situ stress conditions is not presently available [4].

In general, the vertical stress component will be approximately that produced by the weight of the overlying rock. If the rock were fully "annealed" or retained the force equilibrium from a previous plastic condition, then the lateral stresses would be equal to the vertical stresses, as in a fluid medium. However, fracturing, shrinkage, folding, or plate movements may affect these lateral forces (and to a lesser extent the vertical ones) to varying degrees. Since all rocks are slightly plastic over long time periods, there is some reason to expect that undistributed layers of great age would tend to have the best equilibrium of stress.

2.5.3 Strength and Structural Integrity of the Rock Mass

If the ideal of homogeneous, isotropic, and elastic materials were to exist in nature, fairly low compressive strengths would be sufficient for large span construction in a well balanced in situ stress field. This ideal is approached in nature in salt domes where spans up to 800 ft have been excavated even though the effective compressive strength is only about 4000 psi. This is possible as there are effectively no structural weaknesses (fractures, joints, bedding planes) because they are eliminated by natural salt recrystallization. Also, the plasticity of salt allows stress isotropy to develop and assists stress redistribution during excavation.

Specifying compressive strengths suitable for large span cavity excavation then involves consideration of differences in elastic-plastic behavior and differences in included weaknesses such as joints, bedding planes, faults, etc., within the rock mass. At the other extreme is massive granitic or basement rocks typically characterized by intact compressive strengths in excess of 20,000 psi. Such materials are nearly elastic

and any creep or closure into an excavated chamber would primarily result from tensile opening of included weakness planes which is resisted by the proper choice of in situ stress conditions. If such weaknesses are sufficiently wide spaced and interlocked, either naturally or artificially by proper mining practice, then the load associated with stress readjustment can be carried by the inherent rock strength. The degree of tolerable fracturing or the frequency of weakness planes depends greatly upon their orientation and the extent of rock bolting and injection grouting. The block size described by the intersection of joint sets should be larger on a side than the spacing of the rock bolt pattern. Also, the shortest rock bolts should be longer than that dimension. Thus, a 3 to 4 ft block dimension is a practical lower limit in fracture spacing for large span consideration. More massive rock with weakness planes separated by greater than 10 ft would be preferred.

Fractures healed by the deposition of silica or injection of other igneous material generally provide sufficient bonding so that the strength of the rock mass is not significantly compromised.

An intermediate condition of massive rock, (between salt and granite, or crystalline basement rock) is represented by carbonate rocks--limestone, dolomite, or marble. Such materials are intermediate in both compressive strength and in elastic-plastic modes of deformation. As long as the rock mass approaches the crystalline density of the carbonate minerals and there is little porosity to weaken the rock, then the distribution of fractures and bedding plane weaknesses would follow similar practical considerations as described for granitic rock, i.e., a preferred spacing of greater than 10 ft.

Massive carbonate rocks with compressive strengths in excess of 12,000 psi should be satisfactory for large span cavity construction. The Carlsbad Caverns in New Mexico are an example of large span chamber stability that has developed slowly under natural conditions.

Common clastic sedimentary rocks (sandstones and shales) are composed of an aggregate of rock and mineral particles that develop strength from the cementing material binding the particles together. Typically it takes very special conditions of fluid chemistry, heat, and pressure to achieve development of strong, low porosity clastic sedimentary rocks. This process commonly takes tens or even thousands of millions of years and generally involves deep burial and subsequent uplift to expose the rock at the depths of our present interest. Commonly, sandstones and shales that have undergone this process of lithification are highly fractured and characterized by thin bedding and considerable anisotropy. Only the more massive sandstone and shales of high strength and low porosity can be considered as acceptable for large span mining. The sandstone-shale described in Appendix B is a good example with compressive strengths in excess of 20,000 psi.

Volcanic rocks such as basalt are typically very strong in small select portions, but the combination of pores resulting from outgassing of the rock melt and shrinkage cracking during solidification generally renders volcanic deposits a poor candidate for large span excavation. The pores and fractures would have to be filled with a high bond strength grout at considerable expense.

2.5.4 Thermal Stress and Thermochemical Alteration

Cavity spans on the order of 125 to 325 ft are being considered for TESS. During construction the cavity would not be pressurized, but during operation internal pressures would be maintained between hydrostatic and lithostatic loads (600 to 2500 psi) depending upon the depth of the chamber and operational variables. The temperature of the water/steam stored in the cavity would be between 485 and 635° F and could cycle daily about 70° F. Conduction would heat both the cavity liner and surrounding rock and induce thermal stress that must be resisted by the strength of the rock and/or accommodated by rock porosity. Selection of suitable rock chemistry is important so as to avoid the possibility of adverse thermochemical alteration.

High strength rocks, such as granite with a compressive strength of 25,000 to 30,000 psi, are expected to resist the induced thermal stresses without failure. Such materials are also resistant to thermochemical alteration in the temperature range of concern. Any free or loosely bound water would diffuse or permeate down gradient since the rate of heating the rock is slow. Rocks with a high clay content and associated high water content would be avoided both because the rocks are typically too weak and because they are prone to chemical alteration. Dense shales and slates have already undergone natural thermochemical alteration and would be more suitable.

The thermal stress problem is more critical to the cavity concrete liner (discussed in Subsection 2.2.1) since this is the region subject to the highest thermal gradients. With a properly designed liner, some thermal stress failure can be

tolerated in the first foot or two of the rock beyond the liner as long as it is limited to small adjustments.

2.5.5 Ground Water Hazards

Ground water not only poses a threat to flooding the underground workings and personnel, but also tends to lubricate weakness planes and prevent the rock mass from achieving its full load carrying capacity. At the planned depths of 1000 to 3000 ft for TESS cavities, it must be assumed that all cracks and pores in the rock will be water-saturated. Not only should site selection place low limits upon the acceptable ranges of expected permeability, but operational planning must provide for dewatering and grout injection both to control water flow and to strengthen these weaker portions of the rock mass.

2.5.6 Rock Requirements Summary

The rock properties considered suitable, but not necessarily mandatory for TESS cavity construction are summarized as follows.

1. In Situ Stress. The vertical stress should be approximately equal to the gravitational load of the overburden for the selected depth; the minimum lateral stress should be greater than 1/2 of the vertical stress; and the maximum horizontal stress should be no more than twice the vertical stress.
2. Massive rock where the physical characteristics of the rock mass vary within about 25 percent of the mean for a distance of twice the desired cavity diameter--both laterally and vertically.

3. Low porosity where the in situ bulk density is of the order of 1 to 5 percent by weight less than theoretical density of the aggregate crystal density of mineral constituents.
4. Fractures with a bond strength of less than 500 psi defining a minimum block dimension greater than 3 ft, but preferably more than 10 ft.
5. Permeability to water where the matrix rock permeability is less than 0.1 millidarcies and where fracture flow is less than 500 gallons per minute for any working surface area exposed during excavation.
6. Compressive strength varies with rock composition and failure characteristics. Minimal compressive strengths for competent rock are given below.
7. Type of rock. The following rock categories which usually have the above characteristics are:
 - "Granite-like" rocks which include most massive intrusive igneous rocks and many coarsely crystalline metamorphic basement rocks such as gneisses (compressive strength <23,000 psi).
 - Carbonate rocks which include thick bedded or massive limestones and dolomites or marble (compressive strength <15,000 psi).
 - Bedded or banded silicate rocks which include silica cemented (siliceous) sandstones and

shales and metamorphic rocks such as relatively massive shist and slate deposits (compressive strength <20,000 psi).

- Massive salt which would include the Gulf Coast salt domes, massive bedded salt such as the Luke and Red Lake, Arizona deposits, and possibly other less massive bedded salt deposits such as occur in New Mexico, Kansas, Utah, Michigan and elsewhere. (Salt is a preferred rock type except for the need for assuring total isolation of salt from the hot water/steam to be stored in the lined cavity for a long time period. This would require special liner designs.)

Table 2-3 is a classification of the rock types that have been discussed. They have been subjectively ranked in decreasing order of suitability potential. This ranking has been used as a guide for evaluating regional TESS siting potential discussed in Subsection 2.6.

2.6 A REGIONAL PERSPECTIVE OF TESS SITING POSSIBILITIES

One of the potential assets of the heated high-pressure water storage concept is that if large span excavation can be successfully demonstrated in a number of geologic settings it would have widespread but certainly not universal application potential. There are, of course, a number of locations where large span excavation is either not feasible or well beyond a reasonable extension of present day state-of-the-art.

In this section the results of a preliminary review of regional geologic conditions are presented--primarily utilizing the data

Table 2-3. General Classification for Varying Degrees of Suitability for Constructing Underground Excavations (Other Conditions of Weak Rock are Considered Unacceptable)

CLASS	LISTED IN DECREASING ORDER OF SUITABILITY
1	MASSIVE "GRANITE LIKE" ROCK AND MASSIVE SALT DEPOSITS. ALSO INCLUDED ARE MANY OTHER INTRUSIVE IGNEOUS AND CRYSTALLINE BASEMENT ROCK TYPES.
2	MASSIVE LIMESTONE, DOLOMITE, MARBLE AND OTHER METAMORPHIC ROCKS SUCH AS SLATE, QUARTZITE, SHIST AND GNEISS THAT HAVE NOT BEEN EXCESSIVELY FRACTURED.
3	WELL CEMENTED (QUARTZITIC) SANDSTONE AND SHALES THAT ARE AT LEAST 75 MILLION YEARS OLD.
4	BASALT OR OTHER VOLCANIC EXTRUSIVE ROCK.
5	A REDUCTION OF CLASSIFICATION ONE OR TWO GRADES BECAUSE OF THE ROCK BEING STEEPLY DIPPING, HIGHLY FRACTURED, OR POROUS-- PRESENTING GROUND STABILITY OR WATER HAZARD PROBLEMS, I.E., FRACTURED BASALT = 5, POROUS LIMESTONE = 3 OR 4 DEPENDING UPON THE DEGREE.

base represented on large scale U.S. Geological Survey and recent American Association of Petroleum Geologist's Maps. This review is limited by the degree of detail represented by the maps and by the necessary extrapolation of generalized information and mapped rock units with depth in areas where drill hole control data are sparse. Despite these drawbacks it is possible to construct a reasonable assessment of regions with poor, intermediate, and high suitability potential. Classes 1 and 2 would represent the most favorable regions, Classes 4 and 5 the least favorable. In addition, there are large areas where unsuitable conditions are likely and these are not listed in the survey at all. Typically, these poorly suited regions are where the rock is expected to be too weak or porous to sustain large span excavation. Excluded from this preliminary assessment are sedimentary rocks younger than 75 million years old or even older if the strata are thin bedded or inhomogeneous.

The regional review is not intended to be an all-inclusive study of U.S. geological variations. Attention was given to examining or estimating the regional subsurface siting potential beneath the nation's larger cities. In regions where the geologic setting is composed of flat lying strata or relatively broad and undissected basement rock the subsurface character at depths of interest (1000 to 3000 ft) can be reasonably well anticipated. This condition exists over much of the midcontinent region and portions of the Great Lakes region and the Atlantic coastal plain. This situation is considerably more complex in most areas of the western states. A number of population centers in the western states do have favorable site conditions indicated in the vicinity (within 50 miles). The Gulf coastal plain of East Texas through the Florida peninsula is underlaid by relatively recent sediments--limestone,

sandstone, siltstone, etc., that are too weak for cavity construction. Within that region piercement salt domes exist which should be favorable for the required large span excavations if impermeable liner construction can be demonstrated. Thus, there are many locations in the southern and western states where favorable conditions are unlikely beneath existing thermal power plants, but where favorable conditions might well be found if subsurface requirements were considered when locating new plants.

Appendix A lists states alphabetically and a few of the major cities in each state where excavation Class 1 to 5 sites might be expected. Emphasis was given to Class 1 to 3 site possibilities and mention of 4 or 5 sites is made only if better options are unlikely in the vicinity of the specified populated areas. It might be expected that many of the Class 1 to 3 potential sites will become Classes 4 and 5 when more site-specific data on fracturing, in situ stress, and other inhomogeneities become known.

In Appendix A only the most general rock types are used--limestone, granite, metamorphic, sandstone, shale, basalt, and salt. These rock types include a number of similar rock types as discussed previously. For example, the carbonate rocks such as limestone, dolomite, and marble are all referred to as limestone in the table. The approximate age of the rock formations is given and reflects an effort to exclude the sedimentary rocks too young to be well consolidated. Age is not an important indicator for salt and intrusive igneous rocks. Most metamorphic rock formations are old and well indurated, but in some regions they may be highly fractured. When they occur in regions with little deformation within the last 100 million years, there is a good chance that many

weakness planes have undergone chemical healing or recrystallization bonding.

Figure 2-5 maps those regions where Classes 1 to 3 are likely to be found. These classes may exist elsewhere, but are less widespread.

This initial survey of site potential clearly indicates that a number of locations exist throughout the country where suitable sites might be found. Where the regional conditions are not excessively complex, such as many parts of the Eastern United States, it is likely that favorable conditions can be found at depths of 1000 to 3000 ft beneath a significant number of existing thermal power plants. In most states favorable site conditions might be found if this is one of the criteria in siting new thermal power plants. The potential of locating significant numbers of acceptable sites warrants refinement of this preliminary evaluation.

2.7 AN EXAMINATION OF SELECTED POWER PLANT SITES

The possibility of finding favorable subsurface conditions below the areas of a few selected nuclear plant installations was looked into in more detail. Table 2-4 lists locations that may warrant further evaluation of suitability for underground thermal energy storage installations.

Figure 2-5. Potentially Suitable Site Regions in the United States

Table 2-4. Selected Nuclear Reactor Site Areas Where Subsurface Geologic Conditions Warrant Further Evaluation for TESS Installations

<p><u>BROWN FERRY 3</u> <u>DECATUR, AL</u> CLASS 2-3 ZONES ARE ANTICIPATED</p>	<p>THE UPPER 3000 ft OF STRATA CONSIST OF LOWER MISSISSIPPIAN TO CAMBRIAN AGE (325 TO 600 MILLION YEARS (MY)) LIMESTONES AND DOLOMITES INTERBEDDED WITH SANDSTONES AND SHALES. THE STRATA ARE RELATIVELY FLAT AND OCCUR TO NORTH-EAST OF THE MORE STRONGLY DEFORMED IGNEOUS AND METAMORPHIC ROCKS OF THE SOUTHERN APPALACHIAN PIEDMONT.</p>
<p><u>ALWIN W. VOGTLE 1-2</u> <u>WAYNESBORO, GA</u> THE SAVANNAH RIVER PLANT, SC</p>	<p>BELOW ABOUT 1500 ft OF SEDIMENTARY ROCK STRATA OF THE GENTLY SLOPING ATLANTA COASTAL PLAIN ARE IGNEOUS AND METAMORPHIC BASEMENT ROCKS THAT ARE TYPICALLY OLDER THAN 450 TO 500 MY. THIS AREA IS EAST OF THE SOUTHERN APPALACHIAN PIEDMONT.</p>
<p><u>SHERON HARRIS 1-2</u> <u>RALEIGH, NC</u> CLASS 1-4 CONDITIONS ANTICIPATED</p>	<p>SITUATED IN THE CAROLINA STATE BELT REGION OF THE APPALACHIAN PIEDMONT, BOTH INTRUSIVE IGNEOUS ROCK (CLASS 1-2) AND METAMORPHOSED SEDIMENTS (CLASS 3-4) ARE LIKELY IN THE REGION.</p>
<p><u>SALEM 1-2</u> <u>SALEM, NJ</u> CLASS 2-3 CONDITIONS ANTICIPATED</p>	<p>BELOW ABOUT 1800 ft OF SEDIMENTARY ROCK, STRATA ARE THE INTRUSIVE IGNEOUS AND METAMORPHIC BASEMENT ROCKS OF THE NORTHERN ATLANTIC COASTAL PLAIN. THIS REGION IS MORE STEEPLY DIPPING THAN AREAS FURTHER SOUTH AND MAY BE EXPECTED TO BE MORE DEFORMED AND FRACTURED.</p>
<p><u>LASALLE CO. #2</u> <u>SENECA, IL</u> CLASS 2-3 CONDITIONS ANTICIPATED</p>	<p>LOWER PALEOZOIC AND UPPER CAMBRIAN LIMESTONE AND DOLOMITE ARE ANTICIPATED AT DEPTHS OF 1000 TO 3000 ft. STRATA IN THIS AREA ARE RELATIVELY FLAT AND NOT HIGHLY DEFORMED.</p>

2.8 EXCAVATION TECHNICAL CONSIDERATIONS

2.8.1 The Application of Advanced Mining Technology

The Underground Construction Research Council says the state-of-the-art of underground excavation in the United States lags behind such world leaders in this technology as Sweden and Australia. Even though the United States has developed and provides the rest of the world with some of the finest mining equipment, it has been slow to try promising approaches that have been proven elsewhere in the areas of contract practices and excavation design. Our oversized excavation support systems severely add to project costs. The need for such oversized support systems results when there is insufficient definition of rock conditions in advance of construction and when the blasting and other mining practices weaken the natural ground arch. There is a great need to develop and practice teamwork between exploration, design engineering, and construction contracting.

Since support designs in hard rock excavations are still highly empirical, there are many advantages and long-term cost savings associated with utilizing and evaluating the results of test sections and monitoring instrumentation. Such practices also help to validate and refine theoretical approaches to excavation and support designs. This inability to quantitatively evaluate design feasibility has been a formidable constraint [9]. A demonstration of the feasibility of constructing the large chambers for TESS applications would thus contribute significantly to advancing effective utilization of underground space for other purposes.

Within the last 15 years there has been considerable advance in rock mechanics, geodynamic processes, exploration geophysics and sensitive ground motion instrumentation. Data interpretation methods as well as theoretical and empirical predictive capabilities have been advanced. Thus, the technological base is at hand for undertaking the challenge of constructing large span underground excavations economically and safely.

2.8.1.1 Advanced Blasting Methods

Because of the importance of taking advantage of inherent rock strength, it is likely that TESS chamber excavation will require blasting in competent rock for adequate fragmentation and economic removal. The most critical area for controlled blasting is along the surface of the final limits of excavation--especially the chamber walls and arch regions. These boundary surfaces should be developed by "smooth-wall" blasting techniques. The concept requires closely spaced drill holes that are lightly loaded with explosives so that little rock crushing occurs and a primary fracture connects the holes to form a controlled fracture plane. Subsequent blasting tends to break up to, but not beyond, this "presplit" surface. Properly executed, competent rock will not be adversely weakened by blasting for distances over a few inches beyond the boundary drill holes.

Another blasting practice is to use timed delays between explosive rounds so that energy deposition for fragmentation and rock heaving is spread over a period of time. This effectively reduces the degree of seismic vibration as well as reduces the acceleration of rock fragments. Appendix B contains a summary of the measurement of mine roof vibrations resulting from production blasts in an operating mine. It

illustrates the effectiveness of delay blasting to control roof stability and provides needed measurements and scaling relations for predicting maximum accelerations as a function of distance for a practical range of explosion yields.

For large span excavation it becomes imperative to know the locations of potential water hazards and highly fractured regions before excavating through such zones. By proper geophysical sensing and exploratory drilling in advance of excavation, one can detect these zones and take preventative measures to assure safe mining operations. Seismic measurements and thermal sensing in competent rock can provide remote evidence of fracture zones and mobile water. This, supplemented by long hole drilling and bore hole logging in advance of excavation, should be routine practice. Where fractured and permeable conditions are encountered, grout injection would be conducted to block water entries and to strengthen the rock.

2.8.1.2 Review of Grouting Techniques

Water control in underground mining and fluid loss control in the exploration and production of petroleum and other subterranean resources has led to the development of a spectrum of materials suitable for sealing water zones and strengthening zones of weakness. With the developing geothermal resources and the necessity for drilling into deeper, hotter zones for petroleum, new high strength, high temperature cements and grouts have also been developed. These latter products will be discussed in the next section because of their special importance in withstanding the thermal environment associated with the high temperature operation of a TESS facility.

For a given grouting requirement or application, consideration must be given to chemical compatibility of the grout with the groundwater it will likely displace to be assured that the material will perform satisfactorily. Consideration must also be given to fluidity, groundwater dilution, setting time, injection pressure, and possibly the advantages of a multiple grouting program (one type followed by other formulations). Also, the pattern of injection holes in grouting operations is important in determining where the grout will penetrate to achieve the required job. Grout classes are described as follows:

- Waterglass - Generally used where maximum penetration into low permeability zones is required.
- Chemical Polymer Grouts - These are quite versatile and can be formulated to set at various rates, have various viscosities, and can be mixed with other special-purpose additives or blended with cement grouts.
- Cement Grouts - These are also versatile but are typically more viscous than chemical grouts. Cements that expand upon setting are especially effective in sealing high flow rate water zones. Some cement formulations are thixotropic (fluid while being pumped and rigid when stopped).
- Special-Purpose Sealants - When it is necessary to assure an absence of moisture leakage, rubber-like elastic polymeric seals exist that can be pumped as a slurry until cross linkage causes the material to set. When the elastic material has set, it has the

capacity to imbibe water and swell to over 150 percent of the original volume (unconfined) producing a water- and air-tight seal. Such materials have been used in difficult-to-control water hazards and in conjunction with sealing underground nuclear explosion test holes.

- High Temperature Cements - Typically used to bond refractory bricks in kilns and furnaces.

Although highly fractured and permeable rock should be minimized in site selection for TESS facilities, it is important that provisions be made in advance to be able to deal with the unexpected. Prior to embarking upon a construction project, the candidate materials should be screened, selected, and tested. Of special importance for TESS are the properties of the grouts at elevated temperatures. It is likely that special high-temperature, high-strength cements and chemical polymers will be required in the rock immediately surrounding the TESS chamber arch region.

2.8.1.3 High-Temperature/High-Strength "Cement"

Two years ago RDA surveyed several high-strength/high-temperature cements that were being developed to withstand temperatures over 1500° F and pressures over 10,000 psi. At that time, such development was well along at the Southwest Research Institute (SWRI) near San Antonio, Texas, and at the Waterways Experiment Station, U.S. Army Corp of Engineers, Vicksburg, Mississippi. The products developed at SWRI are beginning to be used commercially. The high-temperature/high-strength cement development project was not continued by the Corp of Engineers, but the laboratory scale development

did produce a quality cement. In both systems the key to achieving high strength was achieved by developing "cement" systems requiring low water content. The materials also are stable at high temperatures.

The products developed at SWRI are classed as hydrothermal cements and silica polymer cements. Both types resemble a ceramic more than a cement because the resulting binding material is a SiO-O polymer type chain structure that becomes randomly intertwined to form a strong, dense, amorphous material. The hydrothermal cement formulations require setting temperatures in excess of 150° F whereas the more conventional silica polymer cements will set at temperatures as low as 50° F. In both cases strength increases with environmental temperature from over 6000 psi (compression) at the setting conditions to over 10,000 psi at about 600° F. The material continues to increase slightly in strength until devitrification is initiated at about 2000° F. By combining the "cement" as a matrix with selected high-strength granite aggregate and utilizing care during the curing process to minimize porosity due to outgassing, it is possible to achieve strengths up to 20,000 psi at temperatures of 600° F. Ultrasonic vibration and a slow curing rate minimizes inclusions from outgassing.

The silica polymer cements have excellent adhesive properties to metals, other cements, rock and mineral materials. Adhesion is poor to organic materials so metal surfaces must be degreased. Typically the bond strength exceeds the 800 psi tensile strength of the cement. Bond shear strength in pull tests is about 1200 psi, and failure in three-point bonding tests is 600 psi compared with 70 psi for similar tests of Portland cement mortar adhesion to brick panels. About 80 percent bond strength can be regained by self-healing after failure with special additives.

The dense, highest strength formulations require a water content of 11 percent by weight to produce a workable mortar for troweling or pumping in conventional concrete pumps. This is a suitable consistency for pouring a "concrete" liner for a TESS chamber. This material also has a relatively low coefficient of thermal expansion. Other important properties are very low permeability (impermeable to water at the low pressures tested); high hardness (8 Mohs); and after the cured surfaces are flushed of salt residues (excluded from the structure of the cement during curing) the cement is quite inert to reactions with water and other solvents. Further testing would be required to determine the degree of impermeability to high-pressure water and steam as well as the degree of chemical inertness to high-purity, high-temperature water required for TESS operations. Further tests are also needed to characterize more completely the tensile and bonding strengths under TESS conditions.

The high-temperature/high-strength silica polymer "cement" and grout formulations also are adaptable to a wide range of handling procedures. It can be sprayed or frothed into an excellent insulator, applied as shotcrete, or diluted to various viscosities suitable for grout injection into pores and cracks. Table 2-5 lists the degradation of compressive strength of a grout after setting versus the viscosity of the slurry during application.

Although tentative, it appears that the SWRI silica polymer cements are well suited to provide low cost, strong and stable cements and grouts for use in support of constructing large span TESS chambers. The cost of the essential ingredients, exclusive of aggregate or other additives, is claimed to be less than 2¢/lb which makes it competitive with conventional cements and grouts [10].

Table 2-5. Compressive Strength vs Viscosity for Various Silica Polymer Grout Formulations Developed by Southwest Research Institute

SLURRY VISCOSITY (cps)	COMPRESSIVE STRENGTH AFTER GROUT HAS SET (psi)
10	500
100	2500
1000	8000+

NOTE: WATER HAS A VISCOSITY OF 1 cps AND A 1000 cps SLURRY IS PUMPABLE.

2.8.1.4 Rock Bolting and Large Span Stabilization

Once it has been determined that the in situ properties of the rock mass are satisfactory to meet large span excavation feasibility criteria the design of cavity wall stabilization must be considered. One goal is to provide assurance that rock in the roof or keystone area does not ravel (come loose) and precipitate subsequent more massive failures as a result of rapid stress redistribution and slippage along natural weaknesses. Wire mesh, short rockbolts, and shotcrete are used for this purpose. Another goal and extremely critical aspect of arch development and support is to reinforce the capability of the surrounding rock to adjust to and carry the redistributed load caused by the excavation interaction with the prestress conditions. For large spans, it generally is not feasible to expect a relatively thin cavity liner to support the arch; this support must come from the thick rock section. The function of rock bolting and grout injection into weakness planes is to knit the competent rock blocks (bounded by variably interlocked and interconnected weakness

planes) into what approaches a thick monolithic mass especially around the roof or arch region of the large span chamber. The thickness of this arch zone for large spans (150 to 325 ft) should be of the order of 15 to 35 or more feet depending upon the characteristics of the structure and the success of the bolting and grout injection program to approach the desired monolithic character. Such a shell allows the arch region to yield and flex to accommodate stress readjustments while preventing differential slip along weakness planes with the development of stress risers or cracks.

Generally, large span excavation would be planned in regions where there is sufficient lateral compression so that tensional cracking or opening along pre-existing weakness planes would not result from the excavation. It would be prudent to use injection grout with high bond strength (in addition to high temperature stability and high compressive strength) so that any tensile forces that might result from uncertainties and inhomogeneities are resisted (Subsection 2.8.1.2).

Prestressing of rock bolts is not recommended because the amount of prestress to apply is generally not known--and may lead to more harm than good. Full-column grouting of rock bolts with a material that bonds well to both the bolts and the rock is advisable since this tends to spread the stresses over the length of the bolt and helps to achieve the desired monolithic character of the arch. Because the cavity will be lined and heated, it will substantially reduce heat losses if the rock bolts that penetrate deep into the surrounding rock are recessed to minimize thermal conduction by the bolts. Figure 2-5a schematically illustrates the cavity liner and rock bolt, grout-injection cavity stabilization design.

Figure 2-5a. Cavity Wall (Baseline Configuration)

2.8.2 Shaft and Drift Excavation

The proposed method of sinking the shaft is quite conventional. Rock drills will sink the blast holes and then be hoisted out of the way. Powder is loaded and the blasting done. After proper ventilation of the dust and powder gases, two or three special hydraulically powered loaders are used to clean up the rubble and load it in "skips" to be hoisted to the surface. At the surface the broken rock (rubble) is stored in elevated hoppers until it can be loaded into dump trucks and hauled away. To facilitate operations as the shaft working face extends downward, a work cage with several decks is lowered on multiple cables (usually four which also act as guides for hoisting) down to within about 15 ft of the bottom working face as shown in Figure 2-6. This "deck" carries small hoists to handle the drilling machines (jumbos), the powder handling gear, the skip buckets and the skip loaders as well as other equipment. The deck is generally raised for safety during blasting and lowered close to the bottom for muck removal.

The upper stages of the working cage are used to apply protective wire mesh where required and rock bolts as necessary. Above this the slip forms are moved into place so that the concrete lining may be cast in place. This lining will contain provisions for attaching the hoist tracks, ventilation ducts, compressed air piping, steam piping, and other facilities that will later use this main access to the lower tunnels and cavities.

For purposes of this study, conventional proven methods have been used for time schedules and costs although it is believed some study of this problem can result in faster and lower cost shaft-sinking techniques.

Figure 2-6. Typical Shaft Sinking Work Stage

The exact shaft size will be determined by the time schedule, the depth, the type of rock, and the cavity size at the bottom. The shallow small cavity requires about a 15-ft-diameter shaft while the large deeper cavity should have about a 20-ft-diameter shaft to expedite operations. The reinforced concrete liner will be 1 to 1.50 ft thick.

Experienced mining men advise that these shafts can progress at the rate of about 300 ft per month after they are in full operation. Time must also be allowed for building the head-works and installing the necessary hoisting equipment, air compressors and pumps. Large mine hoists require 14 to 18 months for delivery, and about the same time is required for air compressors and an electric power supply.

While under construction two hoists may be installed in the larger shaft, and it is anticipated one will be left for future maintenance. A steel deck will probably be installed about every 20 ft in order to support and inspect the steam lines that pass up this shaft. Permanent lighting, emergency exit facilities and instrumentation to monitor rock strain, water infiltration and rock temperatures as well as adequate dewatering pumps will be installed.

The drifts (blind tunnels) that extend from the shaft out to the top and bottom of the cavity as shown in Figure 2-7 will be large enough to handle diesel-powered rubber-tired muck hauling equipment--at least 12 ft square. These drifts may be extended further to facilitate grouting for water blockage. The drifts will use rock bolts and wire mesh for safety, but they need not be concrete lined in most rock formations under consideration.

Figure 2-7. Description of Excavation Method

It is planned that drift driving can be started as soon as the proper level is reached and can proceed while the shaft work continues to the lowest level.

These deliveries and rates are reflected in the proposed construction schedule shown in Section 7.

2.8.3 Cavity Excavation and Construction

2.8.3.1 Baseline Method

Although a number of different cavity shapes having merit were discussed in Subsection 2.1, and may be used in rock suitable for them, our baseline for costs and other factors use spherical cavities of the required volume. The proposed method of excavating the cavity as described here follows the general recommendations of several experienced mining men or groups (see Cavity Specification table, Table 5-2).

Subsection 2.8.2 described the excavation methods used to attain access to the cavity area. Once drifts above and below the cavity with the necessary operating room have been cleared, a raise boring machine is installed in the upper drift and a small (~12-inch diameter) pilot hole is bored down to the lower drift. This hole is then reamed by a raise boring cutter to about 6 ft in diameter. The cuttings from this operation drop to the lower drift and are hauled to the main shaft muck storage bin by a diesel-powered, load-haul-dump (LHD) unit, as shown in Figure 2-7, Phase I.

Once the bore hole is complete, cavity excavation is started at the top as shown in Phase II. This work will be done so that the floor can be used for the other operations--grout

holes, rock bolting, reinforcing, shotcreting, and lining. This not only protects subsequent operations from overhead rock raveling, but minimizes the need for heavy staging. Once there is an adequate diameter, many separate operations can be done concurrently as illustrated in Figure 2-8, Phase III. It should be noted that the broken rock is shoved or hauled to the center where it falls into the hole and to the lower drift for removal. Once this operation nears the bottom, the mining equipment can be removed as in Phase IV and the pipe attachments and reinforced concrete sealing plugs installed.

All welds would be x-ray inspected before the concrete is pumped in behind the steel plates. By temporarily sealing the open sections around the edges, one can pump grout in behind the steel plates as the work progresses from the top. Until the arch is complete and the cavity is pressurized, rock bolts will hold the fresh concrete and liner in place.

Instrumentation will be imbedded in the rock and liner to measure pressures, leakage, and temperatures with leads to terminals installed in the liner and the outside. Drainage lines will be installed as discussed in Subsection 2.9.5.

Prior to closure, some equipment must be installed in the cavity to insure adequate water circulation both during the charging (condensing) process and the discharging (boiling) process. If guides are installed for the hoist equipment operating from the top, they would be removed.

The cavity will be filled with distilled boiler feedwater. The rate of filling is limited by the distilling capacity of the treatment plant. To minimize this plant size and yet not delay operation, the filling should start as early as possible.

Figure 2-8. Description of Excavation Method

The surface feedwater storage tank can be filled prior to availability of the cavity to reduce this filling time.

2.8.4 Ventilation and Safety Shaft

At the peak of the cavity construction activity there could be well over 100 men underground. The men must have a second exit available to them in case of fire, flooding, cave-in, or any other catastrophe that would block the main shaft ladderways and elevators. Extra ventilation is needed; therefore a second small (46-ft diameter) raise bored shaft is included in our design and costs. Since the raise boring technique requires a pilot hole drilled from the top, it might well be one of the initial exploration holes. This would not only save a second bore, but also would allow the larger reamed hole to be started just as soon as it is reached with the drift. This would make the second exit protection available sooner. Only the ladderway and open grill landings would be provided in this shaft, so it can be used for ventilation. This shaft will handle 10,000 to 14,000 cfm air in a typical installation. At the acceptable standard of 2400 ft³/hr/man, this would be adequate for 250 men.

2.8.5 Spoils Handling

Almost by definition of suitable sites we can assume that a new shaft and cavity must be excavated and that most of the material will be good, hard, broken rock. Also, many installations will be located near metropolitan areas and near a body of water where good rock is always in demand for gravel, aggregate or landfill. Although costs for handling this rubble have been included in the conservative estimates, several contractors advise that this is a marketable commodity. The

rate of removal required may be higher than it can be used so it must be stockpiled; e.g., if the large cavity is excavated in 300 20-hr days, rubble must be removed from the adit at the rate of 25 tons per hour. This removal may be a local and temporary noise problem.

2.9 CAVITY LINING CONSIDERATIONS

2.9.1 Reason for Liner

The water stored in the TESS cavity eventually forms steam which is used directly in the peaking turbine-alternator set. This steam is condensed and stored above ground until recharge occurs, at which time the water must go through the nuclear boilers or the steam generating unit. The water-steam cannot have any contaminants that can cause problems in this equipment. To insure this, the TESS cavity must be lined.

Several liner materials were considered, but aluminum and steel were the preferred candidates. Steel has been used in this report. The steel liner is designed for sealing only and is of minimum practical thickness (about 1/2 inch). A liner of this thickness is unable to withstand the internal operating pressure of 1000 to 2000 lb/in² and must make a smooth load bearing contact with the wall so that their loads carry into the rock (see Figure 2-5a, page 2-37).

To provide a continuously smooth backing for this thin steel liner, high-temperature/high-strength concrete about 1-ft thick will be cast in place between the liner and the rough rock wall with its protective (safety) covering of wire mesh and shotcrete.

2.9.2 Welding

The steel liner is not subjected to high stress, but ductility and resistance to corrosion are desirable; therefore, mild steel with good weld reliability will be used. Its thickness has been selected to permit good welds to be made in one pass and yet withstand outside corrosion for an extended life of 30 years or more. In costing, a 1/2-inch thickness has been used in the large cavities and a 3/8-inch thickness in the smaller cavities, but this can vary for each particular cavity.

These liner plates need not have compound curvature and will be as large as can be handled underground. Each plate will be held in place by attachment to rock bolts and will stand away from the shotcrete wall (about 1 ft) until concrete is pumped behind it and set up. Each plate is seam-welded to adjacent plates, and all welds will be x-ray and pressure inspected before the concrete is poured.

2.9.3 Thermal Expansion

It can be shown that almost no increase in the inner rock dimensions will occur when the cavity is filled and pressurized. This means the inner layer of rock or concrete will be subjected to compressive stress since it is heated and cannot elongate. Table 2-1 shows what these stresses may be in different types of rock formation, and it also indicates the rock strength will be exceeded in some cases. This is not necessarily serious, since all rock voids, 1 percent or so, will be closed by compressive stress. In a few places the rock may fail in compression, but it is still contained. Rock bolting still holds the concrete and steel liner attached to the cooler rock farther from the cavity wall. Internal pressure also holds this equipment in place. These attachments insure uniform deformation of the steel as it is heated.

The increase in the radius of a spherical cavity due to internal pressure located in an infinite expanse of ideal elastic material is given by [15]

$$\frac{\Delta r}{r} = \frac{P}{E} \frac{1 + \nu}{2} \quad (\text{Ref. p. 2-5})$$

$$\frac{\Delta r}{r} = 1.0 \times 10^{-4}$$

and for the largest cavity under consideration

$$\begin{aligned} r &= 50 \text{ m (164 ft)} \\ \Delta r &= 0.50 \text{ cm (0.20 inches)}. \end{aligned}$$

By contrast the thermal expansion of the steel liner is greater.

$$\frac{\Delta r}{r} = \alpha \Delta T$$

where α = thermal expansion coefficient = $0.65 \times 10^{-5} \text{ } ^\circ\text{F}^{-1}$
for steel

ΔT = temperature rise of inner wall on initial charging
= $\sim 500^\circ \text{ F}$

$$\frac{\Delta r}{r} = 0.325 \times 10^{-2}$$

and for the same large cavity

$$\begin{aligned} r &= 50 \text{ m (164 ft)} \\ \Delta r &= 16.2 \text{ (6.4 inches)}. \end{aligned}$$

Since the inner dimensions of the cavity change little when brought up to operating temperature, the steel liner being held against this wall by the internal pressure cannot expand. The steel liner is subjected to the same temperature rise, and the thermal compressive tangential stress (σ_t) is

$$S_c = \frac{\alpha E \Delta T}{1-\nu}$$

$$S_c = 134,000 \text{ lb/in.}^2$$

where E = modulus of elasticity = $30 \times 10^6 \text{ lb/in.}^2$ (steel)
 ν = Poissons ratio = 0.27 (steel).

This stress is far beyond the ultimate compressive strength of the steel liner material. See Figure 2-9 [11,12,13].

Although it appears possible to fabricate the plates with some type of biaxial convolution to accommodate this expansion without exceeding the elastic limit strength, it also is practical to just allow the steel to take a permanent plastic set the first and only time the cavity is brought up to full charge temperature. This is practical because the cyclic temperature variation between the charged and discharged conditions is small (72° F). As Figure 2-9 shows, this cycling induces about $20,000 \text{ lb/in.}^2$ stress, which is within the proportional limits and remains compressive. Fatigue should not be a problem but must be minimized by careful design and operation. One cycle daily for 40 yr is $\sim 15,000$ cycles, whereas the structural steel endurance limit is 10^6 or 10^7 cycles.

Generally, fatigue strength in compression is higher than fatigue strength in tension; however, fatigue strength is lower

under biaxial stress than under uniaxial stress and welded joints exhibit very poor fatigue strength characteristics.

As Figure 2-9 illustrates, problems can occur on shutdown if the cavity is allowed to cool without taking proper precautions to hold the liner against the concrete wall. Cement bonding provides good adhesion but if this is inadequate, slight air pressurization can provide the needed force to prevent the liner from "pulling away" from the inner surface until cooled and plastic flow is complete. Since the liner plastically deforms both on startup heating and shutdown cooling, the number of permissible cycles is limited [14,15]. However, this need only be done every 25 years or so.

2.9.4 Installation and Operation

To start operation of the lined cavity as a thermal storage unit, it would probably first be filled with condensate at atmospheric temperature. The water would then be heated by adding steam with circulation to keep the mass of condensate reasonably uniform. With these conditions the pressure and temperature within the cavity would increase along the steam chart saturation line for water. The rise in temperature of the steel liner will produce a thermal tangential compressive stress in the steel; but, the pressure in the cavity will oppose the tendency of the steel to buckle radially inward.

2.9.5 Cavity Leakage

The task of fabricating a liner and inspecting it carefully to insure zero leakage is prohibitively costly. Means must be provided to remove water that leaks through the liner as

Figure 2-9. Stress and Strain in Steel Liner

well as ground water that leaks from the rock matrix to the surface of the liner. Forming narrow slots in the concrete in a logical pattern has been proposed as a method for drainage. Water collected near the bottom of the cavity would be pumped to a disposal area. The width of the drainage slots would be tied to the thickness of the steel liner since the liner must bridge the slots and withstand a pressure difference of 1000 to 2000 lb/in.² These drainage slots can eliminate the high thermal compressive stresses referred to in Subsection 2.9.3 and prevent liner collapse on depressurization.

Because the water is at high pressure and contains considerable thermal energy, cavity leakage must be held to a minimum. To appreciate this problem, consider the 325-ft-diameter cavity with its 75,000 ft of seam welding in the liner. Despite inspection of all welds by both x-ray and pressure check and the fact that the liner steel is in heavy compression (with plastic deformation) at operating temperature, there will be some leaks.

To illustrate the magnitude of the fluid leak problem, a set of worst conditions were assumed and a calculation of the energy loss made.

If there were a weld flow every 20 ft with flow equivalent to that through a 0.002 inch diameter orifice at a 0.3 flow coefficient with 1000 lb/in.², pressure 545°F temperature water the leakage through the 3750 holes would be 1.0 cu ft per minute. With a heat added content of about 500 Btu/lb this is 5000 Btu/minute or a mere 0.02% daily of the energy storage.

Because the steel takes a compressive plastic deformation and is backed up and bonded to good concrete that has either lithostatic or hydrostatic back pressure, it is felt the leakage will be well below the above figures.

2.10 BACKUP DESIGN OF CAVITY ARCH

As the foregoing sections indicate, there is every reason to expect successful excavation of large spherical cavities in proper rock by the method outlined here. However, if there is an element of urgency to go to large span cavities before small sizes are developed or if it is desirable to install a large span cavity in a site where the rock is somewhat questionable or should serious rock arch problems develop after the cavity is partially excavated, there is a method of insuring a stable cavity arch with proper support at some increased cost. This section describes this method and estimates the extra cost.

The alternate method involved casting a thick high-strength, high-temperature concrete cap in place over about the top 150° of the sphere. This arch-beam would have adequate thickness, together with rock bolting and local reinforcing steel to carry all of the vertical or radial lithostatic overburden load deemed necessary. Figure 2-10 shows how this would appear when completed. If this heavy concrete section is added after excavation of the main cavity has been started and trouble is encountered, probably additional rock would be removed and concrete cast in place by the use of heavy scaffolding. When it is known from the outset that the concrete arch is to be installed, the mining plan would be to excavate the arch shape in the rock and cast it full of high-strength concrete before the main excavation is started. Only when this reinforcement "cap" is in place would the mining plan proceed beneath it.

The following calculation is a bit over-simplified for estimating, but is applicable for most types of loading.

Figure 2-10. Concrete Arch Support

$$t = \frac{dp}{4\sigma}$$

where t = concrete cap thickness (inches)

d = cavity diameter (inches)

p = overburden lithostatic pressure (lb/in.²)

σ = permissible concrete strength (lb/in.²)

For the 325-ft-diameter sphere with 50 percent of the 1333 lb/in.² lithostatic pressure carried by an arch "cap" of special concrete good for 10,000 lb/in.² compressive stress:

$$t = \frac{325 \times 12 \times 1333 \times 0.5}{4 \times 10^4} = 65 \text{ inches}$$

$$\approx 5.5 \text{ ft.}$$

An extra 1.5 ft of thickness must be allowed for rock surface variations. However, this cost, together with rock bolting and steel are already in our cost estimates. If this arch extends down 1/3 diameter of cavity, then

$$\text{Area of cap} = \frac{4}{3} \pi r^2$$

$$\text{Volume of arch} = \frac{4\pi}{3} r^2 t$$

$$\approx 610,000 \text{ ft}^3$$

$$\approx 22,500 \text{ yd}^3 \text{ concrete.}$$

This rather expensive method of mining the shape for the concrete arch may be simplified, but is estimated at \$100/yd³ and the bulk concrete (using the mined rock crushed for aggregate) poured without forms, another \$100/yd³ with reinforcing steel at the top area only. The extra cost of

this feature in the large cavity is 4.5×10^6 direct cost or about 8×10^6 with uncertainties, administration and finance costs added.

This approach is a method of salvaging a cavity that develops rock stress problems as well as installing cavities in sites that are less than ideal. With it some of the subsequent excavation costs are reduced by the elimination of hazards and uncertainties. It does not appear high when considering the overall cost of the peaking plant at \$248 to 314×10^6 (depending upon operating pressure).

SECTION 3. PRINCIPLES OF OPERATION

3.1 THERMODYNAMICS OF THERMAL STORAGE

3.1.1 Basic Principles

In the energy storage system presented here, the energy conversion chain from fuel to electricity is revised at the link between the steam generator and the steam turbine. During periods of low electric power demand, the steam generator unit is operated at a rate greater than needed to supply the power demand, and the heat energy in the surplus steam produced is used to heat pressurized water contained in an underground cavity. During periods of peak electric power demand, steam is withdrawn from over this heated water and delivered to additional (peaking) turbines to supply the peak demand. Capital equipment to generate the steam need now be sized to carry only the average load rather than the peak load. The total turbine and generator capacity still need to be sized for the peak load.

The only storage system that has been installed to date is pumped hydroelectric storage which was explained earlier. Round trip efficiencies for pumped hydroelectric storage are of the order of 65 to 75 percent as shown in Section 6.3.

Thermodynamics of thermal storage promises a considerably higher efficiency since there is but one transformation instead of three. The energy transformation chain from fuel to electric power is modified by the introduction of a pause between the generation of the steam and its admission to the turbines. The steam is stored by its condensation into hot water, and released by its evaporation from this hot water. Figure 3-1 is a schematic of the proposed arrangement.

Figure 3-1. Schematic of Underground Thermal Energy Storage System

Let us consider the discharge cycle first. In the charged state the cavity is almost filled with hot water and saturated steam is in the space above the water. The steam and water are in a condition of thermodynamic equilibrium and so the temperature-pressure relation is determined by the saturation relation for water. The vapor space above the liquid is connected to the peaking turbine inlet manifold by piping of adequate area. Opening the valve to the turbines causes a flow of steam from the cavity and a lowering of the pressure over the water. The system is no longer in equilibrium, the water being superheated relative to the water in equilibrium with its vapor at the new system pressure. Some of the water evaporates, with the heat for the evaporating water being supplied by cooling of the remaining water. A fraction of the heat energy of the water is released in the steam drawn off. The process is known as flashing (generating steam from the sensible heat stored in liquid water by the reduction of system pressure).

During recharge the process is reversed. Steam is supplied to and mixed with the water in the cavity at a pressure slightly above the saturation pressure and it condenses in the water releasing its heat of evaporation to increase the temperature of the water.

If the pressure and temperature differences in the two above processes were infinitesimal, there would be no resulting loss in available energy of the steam. It will be shown later how with careful design these losses can be held to an adequately small value.

During the discharge cycle of the cavity, the pressure and temperature of the available steam fall. To keep the thermal stress cycling of the cavity steel liner within conservative

values, the full temperature swing from charge to discharge has been limited to 72° F (40° C).

The relation governing the flashing can be written as

$$w \, du = h_{\text{evap}} \, dw.$$

This states that the heat of evaporation h_{evap} of the amount of steam dw is supplied from the change in internal energy of the liquid wdu , where w is the mass of liquid and u the specific internal energy. Dividing by w and h_{evap} , the equation becomes

$$\frac{dw}{w} = \frac{du}{h_{\text{evap}}}.$$

Integrating between two states of interest we have

$$\ln \frac{w_2}{w_1} = \int_1^2 \frac{du}{h_{\text{evap}}}.$$

Since the process takes place along the liquid-vapor equilibrium, the integral on the right-hand side can be evaluated numerically by reference to the steam table, since w is a suitable determinant of the thermodynamic state, and therefore of h_{evap} .

This flashing integral was evaluated over the temperature range from 200 to 360° C (392 to 680° F) and is tabulated in Table 3-1 [16].

The mass of steam developed in flashing per unit temperature decrease is larger at the higher initial temperatures due to the higher specific heat of water at the higher temperatures,

Table 3-1. Flashing Integral

TEMPERATURE	$\int_T^{360} du/h_{\text{evap}}$
360	0.000000
350	0.103440
340	0.178025
330	0.237993
370	0.289286
310	0.334129
300	0.374482
290	0.411318
280	0.445389
270	0.477210
260	0.507181
250	0.535593
240	0.562686
230	0.588644
220	0.613624
210	0.637745
200	0.661110

and the declining heat of evaporation with increasing temperature.

3.1.2 Method of Analysis

The questions that one wishes answered follow:

1. How much potential output energy is available per unit of storage volume as a function of the chosen starting and finishing temperature or pressure?
2. How much of the potentially available energy is lost as a consequence of irreversible processes in the execution of the charge/discharge cycle, pipe friction and heat conduction into the surrounding rock?

The method of analysis of the energy yield per unit volume and the intrinsic (rate independent) cycle irreversibility proceeded as follows.

The initial temperature and a cavity filling factor (97.2 percent) were chosen. For analytical purposes a nominal cavity volume of 1 liter was selected. The mass of water, the mass of steam and the total mass are determined from steam values of the specific volume of the vapor and from the liquid at the starting temperature. At the end of the discharge cycle the cavity is partially filled with cooler water and the balance of the vapor space is filled with saturated steam. Its volume is determined, the cavity volume remaining for steam calculated, and the masses of water and steam remaining after the discharge are determined.

From this, the amount of steam that has passed through the turbine and condensed is known. The total energy and entropy of the system before and after the discharge are compared. Under the assumption of isentropic expansion in the turbine, the entropy decrease in the system is rejected in the condenser cooling water. The energy discarded in the cooling water is therefore T_C . Subtracting this from the system energy decrease gives the work delivered by the turbine. This ideal work is then multiplied by the turbine expansion efficiency to get the actual work out, and from this value is derived the energy storage per unit volume.

The recharge cycle is not quite the reverse of the discharge cycle. During most of the recharge, there is a significant pressure difference between the boiler steam available for recharging and the saturation pressure of the cavity water. On detailed analyses it will be discovered that slightly more energy would be available from the steam used to recharge the system if it were immediately used in the turbines than is available from the steam flashed off the hot water in the cavity. In the nuclear plant case [74 bar, 290° C (1075 psi, 555° F) saturated steam available from the steam generator unit] this loss works out to be 3 percent. For the fossil fueled plant [with 128 bar, 550° C (1865 psi, 1022° F) superheated steam available] the loss is 6.7 percent. This loss is greater since the storage system consumes superheated steam in the recharge process, but returns only saturated steam to the turbines.

For example, consider the low-pressure nuclear plant case while discharging.

Initial Charged Condition

$$\text{Nominal cavity volume} = 1000 \text{ cm}^3$$

$$\text{Initial temperature} = 290^\circ \text{ C}$$

$$\text{Mass water} = \frac{V_w}{v_f} = \frac{972}{1.3656} = 711.8 \text{ g}$$

$$\text{Mass steam} = \frac{V_s}{v_g} = \frac{28}{25.57} = 1.095 \text{ g}$$

$$\begin{aligned}\text{Energy in fluid} &= 711 \text{ g} \times 1278.92 \text{ J/g} \\ &= 910,303 \text{ J}\end{aligned}$$

$$\text{Energy in steam} = 1.095 \text{ g} \times 2576 \text{ J/g} = 2820.8 \text{ J}$$

$$\text{Total energy} = 913,124 \text{ J}$$

$$\begin{aligned}\text{Entropy of liquid} &= 711.8 \text{ g} \times 3.1594 \text{ J/g}^\circ\text{K} \\ &= 2248.8 \text{ J/}^\circ\text{K}\end{aligned}$$

$$\begin{aligned}\text{Entropy of vapor} &= 1.095 \text{ g} \times 5.7823 \text{ J/}^\circ\text{K} \\ &= 6.3316 \text{ J/}^\circ\text{K}\end{aligned}$$

$$\text{Total entropy} = 2255.13 \text{ J/}^\circ\text{K}$$

$$\begin{aligned}\text{After flashing to } 250^\circ \text{ C, } \ln \frac{W_{290}}{W_{250}} &= \int_{250}^{290} \frac{du}{h_g - h_f} \\ &= 0.535593 - 0.411318 = 0.124275\end{aligned}$$

$$\text{from Table 3-1, } \frac{W_{250}}{W_{290}} = e^{-0.124275} = 0.88314$$

$$W_{250} = 711.8 \times 0.88314 = 628.6 \text{ g}$$

$$\text{Volume of fluid} = 628.6 \times v_f = 786.5 \text{ cm}^3$$

$$\text{Volume of steam} = 1000 - V_f = 213.5 \text{ cm}^3$$

$$\text{Mass vapor} = \frac{213.5}{v_g} = 4.259 \text{ g}$$

$$\text{Energy in fluid} = 628.6 \text{ g} \times 1080.4 \text{ J/g} = 679,128 \text{ J}$$

$$\text{Energy in steam} = 4.259 \text{ g} \times 2602.4 \text{ J/g} = 11,083.5 \text{ J}$$

$$\text{Entropy of fluid} = 1755.5 \text{ J/}^\circ\text{K}$$

$$\text{Entropy of steam} = 25.87 \text{ J/}^\circ\text{K}$$

$$\text{Energy of condensate} = 13,070.4 \text{ J}$$

$$\text{Entropy of condensate} = 44.73 \text{ J/}^\circ\text{K}$$

$$\text{Total energy} = 690,212 \text{ J}$$

$$\text{Total entropy} = 1781.4 \text{ J/}^\circ\text{K}$$

$$\Delta U_{290-250} = 209,839 \text{ J}$$

$$\Delta S_{290-250} = 429.03 \text{ J/}^\circ\text{K}$$

$$\text{Heat rejected} = T_{\text{cond}} \Delta S = 133,850 \text{ J}$$

$$\text{Work out} = \Delta U - T_c \Delta S = 75,983 \text{ J}$$

$$\text{Efficiency} = \frac{\text{Work out}}{\Delta U} = 0.3621$$

$$\begin{aligned} \text{Specific energy storage} &= \frac{\text{Work Out} \times \text{Turbine Efficiency}}{\text{Cavity Volume}} \\ &= \frac{75,983 \times 0.85}{1000} = 64.6 \text{ J/cm}^3 (0.51 \text{ kWh/ft}^3). \end{aligned}$$

The high-pressure fossil fuel case proceeds in an identical manner. For a temperature drop in flashing from 330 to 290° C the pertinent final results are:

$$\text{Reversible work out} = 88,137 \text{ J}$$

$$\text{Efficiency} = 0.3837$$

$$\text{Specific storage} = 74.9 \text{ J/cm}^3 (0.59 \text{ kWh/ft}^3)$$

This procedure was executed for starting temperatures of 360 330 and 290° C over an extensive range of finishing temperatures, and the results plotted in Figures 3-2, 3-3 and 3-4. Now

consider recharging with energy from a nuclear boiler. In the discharge above, 80.01 g of steam were removed from the cavity, as were 222,912 J of energy. The steam available for recharge has an enthalpy of 2766.2 J/g. The enthalpy does not change in the throttling of the steam from supply pressure to cavity pressure. In this region of the steam state diagram, the specific enthalpy of saturated steam increases with decreasing pressure; as a consequence, the supply steam becomes slightly wet in the throttling to cavity pressure. A little hot water will need to be removed at the end of the charge cycle to balance things out.

Energy decrease	222,912 J
Enthalpy of 80.01 g	221,324 J
Enthalpy deficit	1588.4 J

The enthalpy deficit is equal to the heat of condensation of 1.076 g of steam.

Therefore, by removing 1.076 g of water per unit volume and supplying 1.076 g of steam at the end, one can restore the cavity to the initial energy and mass content, which implies that it is back to the original thermodynamic state. The recharge steam used is 81.09 g, and 1.08 g of hot water are bled off which can be discharged into the feedwater system and the boiler with appropriate credit given for its heat content. The available energy in the recharging steam is $969.5 \text{ J/g} \times 81.09 \text{ g} = 78,621 \text{ J}$. The yield on discharge was 75,983 J, and the apparent loss in available energy is 2638 J. Subtracting from this loss a 327 J credit for the hot water returned to the boiler gives a net loss of 2311 J, which is 3 percent of the cavity cycle yield.

Figure 3-2. Energy Storage Characteristics

Figure 3-3. Energy Storage Characteristics

Figure 3-4. Energy Storage Characteristics

The high-pressure recharge for fossil fuel plants proceeds in nearly the same fashion. Since the steam supply is superheated and there is no merit in subjecting the inter-connecting piping to the maximum system temperature, the recharge steam will be desuperheated at the surface by feedwater injection.

In the discharge of the high-pressure fossil fuel plant cavity, 244,411 J and 90.125 g were removed. Injecting steam and water to restore the initial condition requires satisfying two linear equations:

$$M_g h_g + M_f h_f = \Delta U$$

$$M_g + M_f = \Delta M.$$

For the particular case, $h_g = 3471.5$ J/g and $h_f = 992.3$ J/g. Solving by using the text value of ΔU and ΔM yields:

$$M_f = 27.6 \text{ g}$$

$$M_g = 62.5 \text{ g}$$

Loss = available energy in steam plus available energy
in feedwater less the actual yield

$$\begin{aligned} \text{Loss} &= 67.5 \text{ g} \times 1418 \text{ J/g} + 27.6 \text{ g} \times 195 \text{ J/g} - 88,137 \text{ J/g} \\ &= 5896 \text{ J/g} \end{aligned}$$

$$\text{Percentage loss} = \frac{5896}{88,137} = 6.69 \text{ percent.}$$

These cycle losses are a consequence of the irreversibility of the throttling from the steam supply pressure to cavity pressure and are shown in Figure 3-5.

Figure 3-5. Thermodynamic Cycle Loss Through TESS vs Temperature Drop

3.1.3 Pipe Size and Its Effects

Piping between the cavity and peaking turbine is long--1500 to 4000 ft. It must be adequately large for low pressure drop losses and well insulated for low thermal losses.

Pipe sizes were selected on the basis that the available energy loss at the tail end of the discharge cycle be not more than 5 percent. The pressure drop under this condition turned out to be nearly 30 percent of the cavity pressure and it became clear that acceptance of a larger loss would not decrease the capital cost of the system due to the inconvenience of accommodating an even greater pressure swing at the turbine inlet. The necessary pipe sizes are given in Table 3-2.

Once the pipe size has been chosen to satisfy the extreme condition, it is of interest to calculate the losses in the system over the range of discharge pressures. For the nuclear case at the same flow that has 1000 MW output at a 40 bar cavity pressure, we calculate slightly larger output power and significantly smaller losses during earlier parts of the discharge cycle. The results are summarized in Table 3-3. Table 3-4 shows how the fractional energy loss falls off at part load.

3.1.4 Thermal Losses into Surrounding Rock

The heat accumulation in the rock surrounding the cavity is determined by the heat flow equation in spherical geometry and is given by the expression

Table 3-2. Interconnecting Pipe Sizes
(Pipe Diameter (ID) for 1000 MW at 5 Percent Loss)

PIPE LENGTH (ft)	CAVITY PRESSURE AT FINISH (bars)	ONE PIPE		FOUR PIPES	
		(cm)	(in.)	(cm)	(in.)
2000	40	88.1	35	50.6	20
3000	74	70.3	27.7	40.4	15.9
4000	100	64.8	25.5	37.3	14.7

Table 3-3. Power Output and Losses Throughout Discharge Cycle

CAVITY PRESSURE (bars)	PRESSURE DROP (bars)	ENERGY LOSS (PERCENT)	POWER OUTPUT (MW)
40	12.0	5.0	1000
50	9.0	2.46	1050
60	7.0	1.44	1080
70	5.9	1.14	1100

Table 3-4. Energy Loss versus Power Output

PRESSURE DROP (bars)	POWER LOSS (PERCENT)	POWER OUTPUT (MW)
1.0	0.33	322
2.0	0.66	450
4.0	1.38	624
8.0	2.93	845
12.0	5.00	1000

$$E = 4\pi\rho C_p T_w \left[\frac{4r_o^2\sqrt{t}}{\pi} + r_o a^2 t \right]$$

where t = the time elapsed from the initial establishment of the temperature T_w which is measured relative to the average rock temperature before heating.

ρ = rock density = 2.6 g/cm³

C_p = rock specific heat = 0.9 J/g

k = rock thermal conductivity = 0.023 W/cm/°C

a^2 = thermal diffusivity = $k/\rho C_p$ = 0.01 cm²/sec

r_o = cavity radius = cm.

The $r_o a^2 t$ term may be looked on as a steady state heat flow to infinity and the preceding term describes the establishment of the temperature distribution. A characteristic time for the problem may be determined by finding the time where the two terms are equal.

$$\frac{4r_o}{\pi} = a\sqrt{t}$$

$$t = \frac{16r_o^2}{\pi^2 a^2} = \left(\frac{5000}{0.01} \right)^2 \frac{16}{\pi^2} = 4.05 \times 10^{10} \text{ sec} = 1284 \text{ yr.}$$

The first term dominates for the expected life of the cavity. For a 50 m radius cavity and granite of average properties, the energy storage is: $E = 35,000,000\sqrt{t}$ with E in kWh and t in years. If we take 5 mils/kWh_t as the cost to the utility for energy, the heat investment schedule in the rock is:

<u>Time (yr)</u>	<u>Cumulative Heat Investment</u>
1.0	\$ 175,000
2.0	247,500
3.0	303,000
4.0	350,000
5.0	391,500
10.0	553,500
20.0	782,500
40.0	1,107,000

The derivation of the heat storage relation follows. The heat flow equation is

$$\nabla^2 T = \frac{1}{a^2} \frac{\partial T}{\partial t}$$

and assuming spherical symmetry of the initial heat distribution and the boundary conditions, we write

$$T(r,t) = \frac{u(r,t)}{r}.$$

By substitution in the equation we find

$$\frac{\partial^2 u}{\partial r^2} = \frac{1}{a^2} \frac{\partial u}{\partial t}$$

whose solution is well known [17] and is

$$u = T_w r_o \left(1 - \phi \left[\frac{r - r_o}{2a\sqrt{t}} \right] \right)$$

with

$$\phi = \frac{2}{\sqrt{\pi}} \int_0^{(r-r_o)/2a\sqrt{t}} e^{-z^2} dz.$$

The temperature distribution is thus,

$$T(r,t) = \frac{T_w r_o}{r} \left(1 - \phi \left[\frac{r - r_o}{2a\sqrt{t}} \right] \right)$$

and integration over r gives the expression for the heat storage given previously.

When the cavity is cycled 300 times yearly between full charge and discharge for 5 yr, a typical short write off period, the heat investment in the surrounding rock is equivalent to a 0.07 percent cycle inefficiency.

3.2 OPERATION OF TESS

These cavities must have the capability of supplying steam to the peaking turbine at very high rates if they are to be used effectively. They must also be capable of absorbing recharge steam at high rates if they are to be fully charged in the minimum time condition or the steaming capacity available. These steaming and condensing conditions require examination.

The analysis and description given briefly here indicates these high rates can be attained using only natural phenomena in the hot water with very little superheat and minimum attendant loss. However, since these specific conditions have not been demonstrated on the scale needed here, some

alternate methods of assuring adequate steam-water transfer rates are also shown.

3.2.1 Conditions in Cavity

Figure 3-6 is approximately to scale for the 325 ft diameter spherical cavity. The high and low water levels for a 40° C (72° F) temperature swing from fully charged to fully discharged are at depths of 10 m (33 ft) and 30 m (100 ft) from the top of the sphere. The water level variation is some 20 m (67 ft).

This large variation in liquid level makes it undesirable to charge with steam at the bottom only because the hydrostatic head is too high, so two steam distribution rings are used during recharging. Initial recharging is through the lower ring some 91 m (300 ft) from the top. When the hydrostatic back pressure becomes so great that steam flow slows, it is valved to the upper distribution ring which is only 25 m (82 ft) below the cavity top and submerged much less.

Figure 3-6 is a schematic representative system only, not a realistic design. In it a central ring (chimney) about 30 m (100 ft) in diameter is hung about 10 m (33 ft) below the free water surface. This ring directs the convective flow pattern of the water.

3.2.2 Charge Cycle

During most of the charge cycle the water is heated by bubbling steam through the lower distribution ring as ample pressure head is available. The rising bubbles, as well as the temperature differential, reduce the fluid density outside the chimney compared to the inside causing vigorous circulation

Figure 3-6. Schematic of Equipment in Cavity (Alternate B)

of the entire water mass. Since the free surface pressure equals the saturation pressure at the water surface temperature and this temperature is close to the bulk water temperature, the pressure at the distribution rings is the steam cavity pressure plus the hydrostatic head above the ring. In the case of the lower ring, steam flow stops where the surface conditions are about 5 bars (72 psi), which is the hydrostatic head, below the inlet steam conditions. This is 285° C (545° F) and 69 bars (1000 psi).

At this time the water level has risen to within 5 m (16 ft) of the fully charged condition. Recharge steam is then valved to the upper distribution ring which has 15 m (50 ft) submergence below the free surface when fully charged. The upper rings permit adding steam until the saturation pressure is within 1 bar (14.5 psi) of the steam supply pressure.

Using this approach, 1 bar pressure and allowing 1 bar (14.5 psi) for pipe friction pressure drop results in a 1 percent reduction in storage capacity.

3.2.3 Steam Discharge Cycle

During discharge, bubbles of steam will nucleate on surfaces where the water is superheated at the ambient temperature and pressure. Data of Chichelli and Bonilla [18] show easy nucleation on solid surfaces at pressures above 500 psi for superheating of 1 to 2° C. Analysis of bubble growth in superheated water indicates that adequate vapor generation will take place if the pressure is reduced enough to cause 2 to 3° C (3.6 to 5.4° F) superheat at the surface, and probably 1° C (1.8° F) superheat is enough. At a water temperature of 270° C, a 1° C superheat leads to a 0.36 percent cycle loss.

Screens or other suitable surfaces should be provided to nucleate bubbles. These small bubbles will be about 7 m (23 ft) below the surface. The time to rise to the surface is about 30 sec as they grow to a diameter of 0.8 m (0.31 inches). At the full steam rate the void portion at the surface is only 0.35, and vapor liquid separation should present no problems. The velocity of the steam rising from the surface is a modest 1.1 cm/sec. The nucleation means should be disposed to cause the bubbles to rise in a ring about the center, leaving the center for downflow of the water that has been cooled by the evaporation of the steam. The chimney is to assure that the circulation takes place in a single large convective cell. Further details on nucleation and bubble growth are given in Appendix C.

3.2.4 Alternate Mixing Methods

Although the nucleate boiling system described appears to be simple, effective and efficient there are other methods of ensuring high evaporation and conduction rates. Figure 3-7 is intended to be representative of any method of stirring the water during charge or discharge to expose adequate surface condensing or evaporating processes. This may be done with pumps, propellers, water jets or steam jets. Probably the circulation would be done internally for reliability and because of the high flow rates required.

Figure 3-7. Schematic of Equipment in Cavity (Alternate B)

3.3 POWER EQUIPMENT

3.3.1 Equipment in Generating Station

One of the advantages of TESS lies in the similarity of the actual power generating equipment to that in the main plant, i.e., they both operate on the Rankine steam cycle. If it is a new installation, the turbine and auxiliary equipment can be similar to, but probably not identical with the main turbines. The alternator(s) and condensers can be identical if they are for the same output. This means that operator and maintenance training applies to both the main load and peaking system. Spares can cover both sets of equipment. There are no special heat exchanges to be maintained.

Because the power equipment is like the main system, each utility will have its own preferences, so this study shows only typical equipment in the cost estimates. The costs are based on a separate turbine bay near the main units so that recharging steam lines and electrical output bus lengths and other connections are minimal. Besides the turbo-alternator, the installation includes the steam condenser with stainless steel tubes, the steam jet ejectors, the condensate and cooling water pumps as well as the large cooling water piping. Cooling tower costs are shown separately. The costs include foundations, interconnections and installation.

An insulated steel condensate holding tank located at the power plant is included. This tank must hold about 15 percent of the cavity water at condenser temperature. It must be covered and necessary precautions taken to insure feedwater purity until it is reheated and returned to the cavity during recharging, i.e., it should have an internal floating roof.

Because some TESS installations may be retrofits where the main power plant must remain operational during the TESS construction period, separation of the shaft adit and the peaking turbine was established at 1000 ft (conservative) and 500 ft (realistic). Care in blasting, especially when the shaft is shallow, must be exercised to avoid disturbing the long, heavy rotating mass in the turbine alternator, but the seismic design requirements far exceed any construction disturbances.

3.3.2 Equipment in Cavity

Although a number of alternate designs and materials have been considered, the following description covers the currently preferred design for a typical installation. While it is felt that there is a possibility that the hot water can be stored in an unlined cavity in some rock or concrete liner types without serious deterioration of SGU feedwater quality, we have included a thin steel sealed liner.

After the reinforcing mesh is attached and before the initial shotcrete liner is blown against the rough rock inner surface, steel drainage piping will be attached. This piping will be smaller at the top of the sphere than it is in the lower hemisphere where the water flow may be greater. Transducers and wiring to indicate rock conditions will also be installed before the first concrete work is applied.

At this juncture, steel plates of the largest manageable dimensions will be attached to the wall by special connections to the rock bolts. There may be as much as 12 inches clearance between the shotcreted surface and the flat steel plates. The plates will be arc-welded together as they are put in place, and all welds will be x-ray inspected and pressure-tested.

After a sufficiently large area has been steel lined and checked, the edges will be temporarily sealed off and high-temperature, high-strength grout will be pumped into place. This grout may have permeable or even soluble separators to produce slots every few feet to accommodate thermal expansion in this rock as it is heated and to vent water from any leak. This drainage system would be used to avoid external over-pressure prior to dropping the cavity pressure and temperature for a repair.

The steel liner will be much heavier around the accesses and will be thinned in several steps to avoid stress concentrations.

Proper baffling or inducer equipment may be installed to insure good mixing of the reheat fluids with the water in the cavity. Although there can be many variations of the cavity design to meet specific conditions, the alternate described here is shown in Figure 3-6 and has been the model used for cost estimating.

3.3.3 Interconnecting Lines

The high-pressure steam lines with their valves, supports, expansion joints and insulation become a major consideration in these installations because they are much longer than normal plant lines. Depending on the cavity depth, the distance from the cavity to the surface can be 1000 to 2500 ft. It is also felt imprudent engineering to locate the shaft adit close to the main power plant; therefore we have included 500 to 1000 ft of separation. This minimizes the effects of the blasting on the main plant, allows for separation of activities and precludes the risk of main plant damage should there be a catastrophic TESS failure--however remote. This means the total steam line length can be 2000 to 3000 ft.

Multiple pipes will be used in the large sizes as they will be more reliable, more economical and more available than a large single line. Support of the hot, heavy, high pressure lines in the vertical shaft is quite practical, but a cost reduction study is needed on the support and expansion joint system. Obviously the sizing can only be an approximation because the exact length, bends, expansion-joints and valves are unknown.

Table 3-5 is included as a ready reference on the line sizes for typical peaking power outputs. The material for these thick walled pipes will be carbon steel since there is no appreciable gain in performance or cost in using special alloys. For costing purposes we have calculated the thickness based on 11,000 lb/inches² tensile strength which is within most applicable codes.

All steam piping must have adequate insulation since it is long and may stand idle for extended periods. Even so, both pressure drop losses and thermal leakage loss can be held below 1%.

Table 3-5. Steam Pipe Size Estimates

TYPICAL PLANT PRESSURE (lb/inches ²)	1000	2000
TYPICAL LINE LENGTH (ft)	2000	3000
TERMINAL CAVITY PRESSURE (lb/inches ²)	485	950
PIPE--NUMBER AND ID (inches)		
POWER (200 MW)	2-15	1-14
POWER (500 MW)	2-20	1-21
POWER (1000 MW)	3-22	2-24

SECTION 4. ENVIRONMENTAL AND SAFETY ISSUES

Thermal electric power plants contribute important benefits to society, which are deemed of sufficient value that we accept the environmental detriments that they bring with them. Such plants take up large areas of land, impair the view, heat up the surrounding air and the water, and bring heavy loads of pollution. Storage of off-peak energy for meeting later peak demands is an attractive possibility for such power plants if the kilowatt capacity thus added requires less investment than adding a completely new plant. In this section we compare the environmental and public safety aspects of adding storage capacity to an existing plant with those resulting from adding new generating units.

The thermal underground storage system is our main concern, but to give perspective, comparison is made with the principal commercially available alternates: pumped hydro storage, gas turbine peaking units and a new steam generating unit. Some aspects of such a comparison would be highly site-specific and cannot be included here, but the overall characteristics are readily seen. As shown in Table 4-1, we compare the systems on the basis of land use, water effects, atmospheric effects, noise production, energy efficiency and public safety.

4.1 LAND USE

A pumped hydro system using surface reservoirs at two elevations requires by far the largest amount of land. At least one of these reservoirs must have a fluctuating water level, which greatly impairs its use for recreation, etc., and often leaves unsightly banks. A new power station, though

Table 4-1. Representative Environmental and Safety Issues

ASSESSMENT AREAS	LAND USE	WATER	AIR	NOISE	ENERGY FACTORS	SAFETY
ENERGY STORAGE CONCEPTS						
UNDERGROUND HOT WATER STORAGE CAVITY	<ul style="list-style-type: none"> STORAGE CAVITY CAN BE LOCATED AT DISCLOSED POWER FACILITY AND NEAR HEAVY ENERGY USERS PLEASING ESTHETICS OF LAND ABOVE UNDERGROUND CAVITY. APPROX 2000 FT FROM POWER FACILITY. MAY BE USED FOR NON-RESIDENTIAL APPLICATIONS NO CHANGE IN GROUND SURFACE TEMPERATURE REQUIRES ADDITIONAL SURFACE FACILITIES: <ul style="list-style-type: none"> LARGE WATER TANK - 1000 FT DIAMETER 1000 FT OF SURFACE PIPES FEEDWATER TREATMENT PLANT REQUIRES EXTRA: <ul style="list-style-type: none"> COOLING TOWERS OR OTHER COOLING METHOD PEAKING TURBINE ALTERNATOR SYSTEM EXCAVATED ROCK FROM CAVITY IS GENERALLY IN DEMAND. MAY REQUIRE TEMPORARY STORAGE SITE ISOLATION AREA ABOVE THE CAVITY IS MINIMAL 	<ul style="list-style-type: none"> REQUIRES WATER SOURCE FOR INITIAL FILLING OF CAVITY NEED A WATER DEPOSITORY OR DISPOSAL SITE WHEN DRAINING UNDERGROUND CAVITY (RARELY REQUIRED) NEGLECTIBLE WATER POLLUTION ISSUES, SINCE BOILER FEED WATER CAN BE USED FOR DRINKING NEGLECTIBLE DEGRADATION OF EXISTING WATER QUALITY HEAT ADDED TO COOLING WATERS (IF USED) 	<ul style="list-style-type: none"> SOME ADDITIONAL HEAT ADDED TO ATMOSPHERE IF COOLING TOWERS ARE USED 	<ul style="list-style-type: none"> BESIDES SOME CONSTRUCTION ASSOCIATED NOISE (1-2 YEARS) THE OPERATION IS ESSENTIALLY SILENT NEGLECTIBLE OPERATING NOISE ASSOCIATED WITH NORMAL PLANT OPERATION 	<ul style="list-style-type: none"> INPUT-OUTPUT ENERGY EFFICIENCY OF PEAKING FACILITY IS: <ul style="list-style-type: none"> FOSSIL POWER PLANT - 45% NUCLEAR POWER PLANT - 40% ENERGY DENSITY IS APPROXIMATELY 0.5 KWH/FT³ 	<ul style="list-style-type: none"> SAFETY PROBLEMS ASSOCIATED WITH CONSTRUCTION OF A DEEP UNDERGROUND CAVITY, WATER FLOODING, COLLAPSE OF CAVERN POSSIBLE STORAGE VAPOR FOR CONTAMINATED FLUIDS RESULTING FROM A CATASTROPHIC NUCLEAR SHUT-DOWN STANDARD GENERATING PLANT OPERATING PROCEDURES WILL MINIMIZE SAFETY HAZARDS
HYDRO PUMPED STORAGE RESERVOIR	<ul style="list-style-type: none"> LIMITED APPLICATION DUE TO UNIQUE TOPOGRAPHICAL REQUIREMENTS REQUIRES TWO WATER RESERVOIRS OR EQUIVALENCE USE OF LIMITED LAND RESOURCES FOR COMPETITIVE USE, EX. RECREATIONAL, FARMING, WILDERNESS UNATTRACTIVE ESTHETICS ASSOCIATED WITH DAMS, POWER LINES, FLUCTUATING WATER LEVEL POSSIBLE RECREATIONAL ADVANTAGE OF SURFACE RESERVOIR 	<ul style="list-style-type: none"> POSSIBLE SIGNIFICANT WATER RELATED PROBLEMS, SUCH AS: <ul style="list-style-type: none"> FLUCTUATING RESERVOIR WATER LEVEL BIOLOGICAL, FISHING, etc EXTREMELY SITE DEPENDENT 	<ul style="list-style-type: none"> NEGLECTIBLE AIR POLLUTION ISSUES ASSOCIATED WITH PEAKING FACILITY 	<ul style="list-style-type: none"> SAME AS ABOVE 	<ul style="list-style-type: none"> ROUND TRIP ENERGY EFFICIENCY IS APPROXIMATELY 75 TO 80 PERCENT ENERGY DENSITY IS APPROXIMATELY 4.5 KWH/FT³ FOR HEAD OF 500 FEET 	<ul style="list-style-type: none"> NO UNUSUAL CONSTRUCTION SAFETY ISSUES, SINCE MUCH EXPERIENCE HAS BEEN OBTAINED FOR CONSTRUCTION OF DAMS, WATER STOCKS, etc POTENTIAL PROBLEMS DUE TO POWERHOUSE FLOODING (IF UNDERGROUND) POTENTIAL DAM FAILURE DUE TO EARTHQUAKES
INCREASE CAPABILITY OF INSTALLED FACILITY (WITHOUT PEAKING PLANT)	<ul style="list-style-type: none"> REQUIRES ADDITIONAL FACILITIES: <ul style="list-style-type: none"> BOILER-TURBINES COOLING TOWERS OR OTHER COOLING METHOD FOSSIL OR NUCLEAR FUEL SUPPLY ASSOCIATED POLLUTION EQUIPMENT LIMITED LAND USE PROBLEMS DUE TO SIMILAR EQUIPMENT ADDITIONS 	<ul style="list-style-type: none"> NEGLECTIBLE DEGRADATION OF EXISTING WATER QUALITY 	<ul style="list-style-type: none"> ADDITIONAL AIR POLLUTION DUE TO INCREASED BURNING FOSSIL FUELS COOLING TOWER OR COOLING SOURCE HEAT ADDED TO ATMOSPHERE 	<ul style="list-style-type: none"> SAME AS ABOVE 	<ul style="list-style-type: none"> ENERGY EFFICIENCY OF OVERSIZED POWER FACILITY IS REDUCED DUE TO PART LOAD OPERATION 	<ul style="list-style-type: none"> STANDARD GENERATING PLANT OPERATING PROCEDURES

requiring less land, has an even greater adverse visual impact, especially if it requires large fuel storage bins or tanks, ash blowdown pits, large scrubbing units, tall stacks, etc. In contrast, the addition of an underground thermal storage unit or a gas turbine peaking unit has minimal surface requirements, essentially those of the turbine generator units themselves. The interim water storage tank of the thermal system and fuel oil tank of the gas turbine are relatively small, and could be a few feet below the surface to improve land appearance. The ground temperature above the TESS cavity is no higher than surrounding land and it can be used for any purpose.

During the construction phase, all power stations and other major construction projects have a temporary adverse environmental impact. The hoisting of excavated rock from the underground thermal cavity would be a smaller activity perhaps than the earthmoving required for a surface reservoir, but it might be located closer to other urban activities. The underground shaft and cavity blasting can barely be noticed at the surface and would not disturb the adjacent power station. The rock removed from the cavity is, by requirement, high grade aggregate for other concrete uses, but it will be removed at a rate greater than needed so temporary stockpiling will be required.

4.2 EFFECTS ON WATER

The cumulative effects on water temperatures from the heat rejection activities of a power station will not be greatly affected by any type of storage system if the total kilowatt hour output is the same. Effects on pollution depend more upon the type of fuel consumed than on any other factor, and thus again would not be much different for the different storage options except their efficiency changes the amount of fuel used.

4.3 ATMOSPHERIC EFFECTS

Effects on the atmosphere from energy storage are smaller than those on water to a first approximation in that they depend more upon the total quantity of energy produced and the type of fuel used. However, there is an important distinction in the time of release which affects the atmosphere more than the water in some cases. At the time of peak demand, which might be a summer afternoon, energy can be retrieved from storage without immediately consuming more fuel. Starting up a gas-turbine peaking plant or adding more load to an online station adds to the immediate burden to the atmosphere in transporting stack gases and pollutants, cooling tower heat dissipation, etc. This burden falls at a time when the atmosphere is already carrying the maximum levels of pollution, air-conditioner heat, industrial effluent, and pavement reflection. With the storage system the extra load can be deferred to a period when the effects of extra fuel consumption would be minimal, such as after midnight. On this basis, a thermal storage system is preferable to any fuel-consuming peaking method, and a pumped hydro system is preferable to either, since its heat-release as well as its combustion products can be deferred.

4.4 NOISE

As far as the general public is concerned, none of the options for meeting peaking power demands are especially noisy, except during plant construction. During this phase the earthmoving required for a pumped storage reservoir and the rock disposal from excavating a deep thermal cavity would both have temporarily adverse effects. The degree of such effects would be dependent on the site, since the impact of

the same quantity of noise would vary with the proximity of other community activities.

4.5 ENERGY EFFICIENCY

The efficiency of electric power generation is a concern to the public and to the environment, since it determines the overall impact of using energy, including mining and transport of fuel, depletion of resources, pollution levels, etc. In the case of the United States, consumption of imported oil is a factor in national survival, since dependence on a foreign source of supply could make our basic economy highly vulnerable and continual drain of capital resources could impair our ability to maintain financial control of our economy.

From this point of view, the construction of a new power plant to handle a peak demand and then running at a low-load factor is as much a drain of U.S. capital as is importing foreign oil. An energy storage system of any type is a direct step in conservation, but the efficiency with which the stored energy is recovered can add an important factor. A gas turbine peaking plant is a mixed blessing in this regard, since it has a low capital cost but consumes inefficiently the most expensive low-sulfur imported oil.

The deep underground hot water storage system is apparently superior to all other options on this score, for it has a low capital cost (especially in larger sizes), preempts a minimum of scarce resources and can recover 90 to 95 percent of the energy input. In contrast, pumped hydro storage systems average about 70 percent recovery. This 25 percent difference in fuel cost could amount to over a million barrels of oil

equivalent saved each year for a large storage capacity used daily (see Section 6.3).

4.6 PUBLIC SAFETY

We have identified no areas of concern about public safety in the thermal underground water storage system. The static pressure of the overlying rock exceeds the internal pressure of the storage cavity, so that once completed and filled a major failure is almost impossible. The multiple pipes leading to the surface are all subject to failure, but multiple valves, partitions and seals make such failures controllable. In the remote chance that the stored water should somehow find a vent to the surface, there would be a negligible public risk. The high purity water would escape heated and partially vaporous and the hot plume would rise harmlessly to mix with the upper atmosphere. Any local rain would be warm but not damaging.

Pumped hydro systems in some locations could constitute a public hazard if an elevated reservoir were breached; also the fuel stored for a conventional plant or gas turbine peaking unit is a mild fire hazard.

4.7 SUMMARY

On balance, the thermal underground storage system exhibits a generally benign environmental, conservational and safety aspect. There are no outstanding contrasts with other methods of meeting peak demand except from the issues of land use and energy recovery factor. The thermal storage system is superior in both of these respects.

SECTION 5. CAPITAL COSTS

5.1 COSTING BREAKDOWN

The cost estimations have been made so that intermediate size estimations can be done. A peaking power plant of any size output that stores any desired capacity can be estimated for either a high-pressure (fossil fuel) or a low-pressure (nuclear fuel) system within the limits under consideration. To do this the peaking power output costs both on the surface and underground are separated from those costs associated with the storage capacity, i.e., the cavity proper. All summary costs include contingencies, engineering, management, legal, environmental and financing costs as factors added to the direct cost.

A recap of the costs is shown in Table 5-1 as well as in Figure 5-1 where the complete installed capital is shown. Figure 5-2 is the capital cost of the filled and charged underground spherical cavity plotted against storage capacity, i.e., the size of the cavity, while in Figure 5-3 the cost is plotted against the maximum power output of the plant peaking equipment.

5.2 CAVITY COST

Costing for the cavities is based on a spherical shape that was excavated by the method described in Section 2 with adequate rock bolting, wire mesh, personnel protection and shotcreting; to this is added a high-strength, high-temperature concrete shell and a steel liner that is welded in place to form a pressure tight chamber. All welds are checked by x-ray photographs. Deep grout holes and injection of water sealant are included. Although some methods of excavation will not require it, steel staging has been included and is not removed

Table 5-1. Specific Costs*
(Capital Cost Range of Estimates in 1976 Dollars)

NUCLEAR PLANT HEAT SOURCE				
PEAKING POWER OUTPUT (MW)	200	500	1000	
SURFACE EQUIPMENT (\$/kW)	231-290	166-198	139-156	
UNDERGROUND EQUIPMENT (\$/kW)	60-130	31-62	20-39	
SUBSTATION COST (\$/kW)	5-10	5-10	5-10	
TOTAL COST RANGE (\$/kW)	296-430	202-270	164-205	
CAVITY DIAMETER (ft)	125	200	275	325
CAPACITY (kWh _e × 10 ⁶)	0.52	2.13	5.5	9.14
STORAGE COST (\$/kWh _e)	19.51- 26.63	14.36- 14.81	10.96- 12.76	8.63- 11.39

FOSSILE FUEL PLANT HEAT SOURCE				
PEAKING POWER OUTPUT (MW)	200	500	1000	
SURFACE EQUIPMENT (\$/kW)	231-291	168-199	141-157	
UNDERGROUND EQUIPMENT (\$/kW)	78-184	41-95	29-66	
SUBSTATION COST (\$/kW)	5-10	5-10	5-10	
TOTAL COST RANGE (\$/kW)	314-485	214-304	175-233	
CAVITY DIAMETER (ft)	125	200	275	325
CAPACITY (kWh _e × 10 ⁶)	0.60	2.46	6.45	10.68
STORAGE COST (\$/kWh _e)	16.86- 23.06	12.42- 12.83	9.47- 11.63	7.47- 9.83

*Two detailed cost breakdowns were made: one very conservative with all forecast conditions covered, the other on what is believed to be a most probable basis. Costs include 20 percent or more of direct cost for uncertainties, 25 percent for engineering and administration, and 20 percent additional on all costs for financing costs during construction.

Figure 5-1. Total Installation Costs

Figure 5-2. Variation in Storage-Related Specific Cost with Capacity

Figure 5-3. Variation in Power-Related Specific Costs with Size

so that possible future liner repairs can be readily made. Rubble disposal costs are also included even though it can be sold in many places where it is needed.

The costs of filling each chamber with high grade boiler feedwater and the initial thermal investment into heating adjacent rock are included.

Specific costs used in the first cost estimate and the source of data are listed below:

1. Excavation--rock drilling, blasting, mucking and hauling to surface at $\$1.30/\text{ft}^3$ ($\$35/\text{yd}^3$). Major mining equipment manufacturer estimate less than half this cost [19].
2. Protective wire mesh in place at $\$2.50/\text{ft}^2$, based on steel weight and labor per Guthrie [20].
3. Rock bolting at $\$4.50/\text{ft}$ for hole, bolt and grout. Eight foot average depth from RDA mining consultants [5,8].
4. Steel liner in place but not welded at $\$1/\text{lb}$ --basic data from U.S. Steel Corporation.
5. Linear welding and x-ray checking at $\$20/\text{ft}$ --from Lincoln Electric Company.
6. Rubble disposal at $\$4/\text{yd}^3$ --consultants advise this frequently can be sold [4,5].
7. Standard concrete in place with rebar at $\$150/\text{yd}^3$ --per local concrete supplier.

8. High-strength concrete for high-temperature (no rebar required) in place at \$200/yd³--differential cost per SWRI [10].
9. Steel staging at \$1.50/lb in place. .
10. Drainage piping--average cost in place at \$1.50/ft per local contractors.
11. Charge feedwater at \$0.25/ft³--Aqua Chem Corp. [21]. Complete writeoff of capital equipment on first charging.
12. Allowance for subterranean uncertainties--25 percent on direct cost.
13. Engineering, management, legal and environmental costs--25 percent on direct cost.
14. Financing costs--20 percent added on total of above costs.

The general specifications of the spherical cavities are in Table 5-2 and a cost breakdown in Table 5-3.

5.3 UNDERGROUND POWER-RELATED COST DETAIL

Since the size and depth of the shaft as well as the equipment and steam piping installed therein are related more to the type and size of the power generating equipment than to storage cavity size, they are cost evaluated separately. Within the scope of this feasibility study, we have not made cost allowance for rock variations. Since nuclear power plants generally operate at a lower pressure and temperature than modern fossil

Table 5-2. Specifications of Spherical Cavities

CAVITY SIZE--DIAMETER (ft)	125.0	200.0	275.0	325.0
VOLUME (ft ³ x 10 ⁶)	1.02	4.18	10.86	17.93
INSIDE SURFACE (ft ² x 10 ⁴)	5.0	12.60	23.70	33.20
STEEL LINER THICKNESS (inches)	0.37	0.37	0.50	0.50
STEEL LINER WEIGHT (lb x 10 ⁶)	0.78	1.95	4.89	6.83
LENGTH OF WELDING (ft x 10 ⁴)	2.0	5.0	9.5	13.0
NUMBER OF ROCK BOLTS x 10 ³	12.0	32.0	60.0	80.0
NUMBER OF GROUT HOLES x 10 ³	5.0	10.0	20.0	30.0
VOLUME OF CONCRETE BETWEEN ROCK AND LINER (yd ³)	2,800	7,000	13,000	18,500
IMBEDDED DRAINPIPE (ft x 10 ³)	10.0	25.0	45.0	65.0

Table 5-3. Cavity Cost Breakdown--Estimates
in 1976 Dollars x 10⁶

CAVITY SIZE--DIAMETER (ft)	125	200	275	325
EXCAVATION	1.33	5.43	14.12	23.31
WIRE MESH--INNER SURFACE	0.13	0.32	0.59	0.83
ROCK BOLTING	0.43	1.15	2.16	2.88
STEEL LINER	0.78	1.95	4.89	6.83
LINER WELDING	0.40	1.00	1.90	2.60
RUBBLE DISPOSAL	0.15	0.62	1.61	2.66
SHOTCRETE	0.14	0.35	0.65	0.92
HIGH STRENGTH CONCRETE	0.38	0.93	1.73	2.47
STAGING	0.13	0.53	1.38	2.28
WATER REDUCTION--DRILL & GROUT	0.85	1.70	3.40	5.10
DRAINAGE SYSTEM	0.02	0.03	0.05	0.07
CONCRETE PLUGS	0.02	0.02	0.03	0.03
FEEDWATER CHARGE	0.26	1.05	2.72	4.48
HEAT INVESTMENT IN ROCK	0.01	0.02	0.05	0.07
DIRECT COST	5.03	15.10	35.28	54.53
SUBTERRANEAN UNCERTAINTIES (25%)	1.26	3.78	8.82	13.63
OVERHEAD* (25%)	1.26	3.78	8.82	13.63
TOTAL	7.55	22.65	52.92	81.80
FINANCING COST (20%)	1.51	4.53	10.56	16.36
TOTAL COST THIS PORTION	9.06	27.18	63.50	98.16
SPECIFIC COST (\$/ft ³)	8.88	6.50	5.85	4.47
(\$/kwh) 1000 lb/in ²	16.44	12.04	10.83	10.13
2000 lb/in ²	14.10	10.32	9.29	8.68

*Overhead includes engineering, management, legal and environmental.

fueled steam plants, two pressures (depths) have been selected as shown in the specifications in Table 5-4. Three sizes of peaking equipment output have also been used to cover the range where this concept appears applicable.

The cost estimate in Table 5-5 includes all of the following items in place and installed. Specific costs for these items are listed in Section 5.2.

1. Adequate staging area at the surface--based on property costs near metropolitan areas.
2. Construction facilities at the shaft head. Hoist and frames, rock handling facilities, air compressors, personnel changing rooms, etc.
3. Exploratory core drilling at the site with adequate test gear and analysis of the results therefrom [4,5].
4. Excavation of the shaft and tunnels as well as adequate space for handling equipment and muck from the cavity. Estimates used are based on major contractors, major mining equipment manufacturers and previous RDA work. Shaft sinking is based on \$1500 per foot of depth.
5. As soon as possible a small bore ventilation and emergency exit shaft will be driven to the surface from the access tunnel as shown in frontispiece. Costs from Reference 19.
6. Both shaft and tunnel estimates include adequate rock bolts, protective wire mesh and all shot-creting. The shaft has a concrete lining (using

Table 5-4. Power-Related Underground Specifications

OPERATING PRESSURE (lb/in. ²) CAVITY DEPTH TO TOP (ft) POWER PEAKING CAPABILITY (MW _e)	+ 1000 + + 1250 +			+ 2000 + + 2450 +		
	200	500	1000	200	500	1000
SHAFT DEPTH (vft)	1400	1500	1600	2600	2700	2800
DRIFT LENGTH (ft)	700	800	900	700	800	900
SHAFT DIAMETER (ft)	15	17	19	16	18	20
TUNNEL SIZE (ft)	12	12	12	12	12	12
VENTILATION SHAFT DIAMETER (ft)	5	5	5	6	6	6
SURFACE AREA, SHAFT AND TUNNEL (ft ²)	90,000	110,000	135,000	150,000	180,000	210,000
SHAFT LINING THICKNESS (ft)	1.2	1.3	1.5	1.2	1.3	1.5
VOLUME RUBBLE REMOVED (ft ³ x 10 ⁵)	3.3	4.3	5.7	5.9	7.8	9.9
ROCK BOLTS REQUIRED (x 10 ⁴)	1.6	2.0	2.4	3.3	3.8	4.3
STEAM FLOW AREA IN PIPE (in. ²)	400	800	1520	400	800	1256
PIPE SIZES AND NUMBER (Section 3.3.3)	2-15	2-20	3-22	1-14	1-21	2-22
PIPE WALL THICKNESS (in.)	0.68	0.91	1.0	1.27	1.91	2.0
PIPE WEIGHT (lb/ft)	110	205	269	207	474	517

Table 5-5. Shaft and Tunnel Cost Breakdown--Conservative Estimate in 1976 Dollars x 10⁶

CAVITY DEPTH (ft) POWER OUTPUT (MW)	+ 1200 +			+ 2400 +		
	200	500	1000	200	500	1000
SURFACE CONSTRUCTION FACILITIES	0.80	0.90	1.00	0.80	0.90	1.00
EQUIPMENT STAGING AREA	0.40	0.40	0.40	0.40	0.40	0.40
CORE DRILLING (6 HOLES)	0.90	0.90	0.90	1.10	1.10	1.10
SHAFT HEAD EQUIPMENT	3.00	3.25	3.50	3.25	3.50	3.75
ROCK EXCAVATION--SHAFT	2.10	2.25	2.40	3.90	4.05	4.20
--TUNNEL	0.30	0.33	0.37	0.30	0.33	0.37
SHAFT LINING AT \$180/yd ³	0.35	0.42	0.50	0.70	0.85	1.00
STEEL REBAR AND MESH AT \$2.50/ft ²	0.23	0.28	0.33	0.38	0.45	0.54
ROCK BOLTS AT \$20/BOLT	0.41	0.54	0.66	0.80	0.90	1.08
DEWATERING SYSTEM COMPLETE	0.24	0.25	0.26	0.30	0.31	0.32
VENTILATION (BLOWER AND DUCTS)	2.50	2.50	2.50	2.80	2.80	2.80
MUCK DISPOSAL AT \$4/yd ³	0.46	0.64	0.84	0.85	1.15	1.46
STEAM PIPING TO SURFACE COMPLETE AT \$2.50/lb	1.10	2.36	5.25	1.66	3.79	8.27
VENTILATION AND SAFETY HOLE	0.25	0.25	0.25	0.45	0.45	0.45
DIRECT COST	13.04	15.27	19.16	17.69	20.98	26.74
SUBTERRANEAN UNCERTAINTIES (10%)	1.30	1.53	1.92	1.77	2.10	2.67
OVERHEAD* (25%)	3.26	3.81	4.79	4.42	5.24	6.69
TOTAL COSTS	17.60	20.61	25.87	23.88	28.32	36.10
FINANCING COST (20%)	3.52	4.12	5.17	4.78	5.66	7.22
TOTAL COST THIS PORTION	21.12	24.73	31.04	28.66	33.98	43.32
SPECIFIC COST (\$/kW)	105.65	49.46	31.04	143.30	67.96	43.32

*OVERHEAD INCLUDES ENGINEERING, MANAGEMENT, LEGAL AND ENVIRONMENTAL.

slipforms) with provisions for hoists and levels to install, inspect and repair the high-pressure steam piping system.

7. Ventilation systems are included that are adequate for the cavity excavation and lining.
8. A temperature and water leak detection system for the eventual hot-water-filled, pressurized cavity is included. This is an estimate by RDA with adequate rock drilling allowance for placement of transducers.
9. Multiple steam lines from the cavity to the surface are included with expansion joints, supports, valves, insulation and special supports for hanging the piping in the vertical shaft. Cost estimates are from steel suppliers, valve and joint manufacturers.
10. One of the hoists with associated equipment will be left in the shaft for inspection and maintenance.

5.4 SURFACE POWER-RELATED EQUIPMENT

Baseline costs on the power-related equipment have been included for completeness and comparisons, even though all of this is currently available commercial equipment and many organizations will have better cost data for their particular conditions than those presented in Tables 5-6 and 5-7.

For costing purposes it is assumed that the peaking equipment is located adjacent to the main steam plant and is operated by that personnel. A turbine bay complete with crane and all auxiliary equipment is provided for the turbine-alternator-

Table 5-6. Power-Related Surface Specifications

OPERATING PRESSURE (lb/in. ²)	← 1000 →			← 2000 →		
SIZE, POWER OUTPUT (MW)	200	500	1000	200	500	1000
TURBINE BAY AREA (ft ²)	7000	9000	13,000	7000	9000	13,000
TURBO, ALTERNATOR FOUNDATION (yd ³)	2000	3000	5000	2000	3000	5000
CONDENSER WATER (gpm x 10 ³)	224	310	620	116	290	580
CONDENSATE WATER (gpm)	4400	11,000	22,000	4300	10,500	21,000
COOLING WATER PIPE LENGTH (ft)	1000 ft TWO WAYS					
TURBO ALTERNATOR WEIGHT (TONS)	200	250	300	200	250	300
STEAM PIPE FROM SHAFT TO TURBINE (ft)	500	500	500	500	500	500
STEAM PIPE SIZE	2-15	2-20	3-22	1-14	1-21	2-22
FEEDWATER STORAGE TANK (ft ³ x 10 ⁶)	0.37	0.92	1.83	0.33	0.84	1.67

Table 5-7. Power-Related Surface Equipment - Cost Breakdown
(Conservative Estimate) in 1976 Dollars x 10⁶

PRESSURE RANGE (lb/in. ²) POWER OUTPUT (MW)	+ 1000 +			+ 2000 +		
	200	500	1000	200	500	1000
ADDITIONAL PROPERTY 300 ft SQUARE AT \$10/ft ²	0.87	0.87	0.87	0.87	0.87	0.87
TURBINE BAY BUILDING (\$50/ft ²)	0.35	0.45	0.65	0.35	0.45	0.65
OVERHEAD CRANE WITH COLUMNS AND RAYS	0.50	0.55	0.60	0.50	0.55	0.60
TURBO-ALTERNATOR EXCAVATION AND FOUNDATIONS AT \$400/yd ³	2.40	3.20	4.80	2.40	3.20	4.80
TURBINE AND ALTERNATOR W/STOP VALVES	16.50	28.00	43.00	16.50	28.00	43.00
SHIP AND INSTALL TURBO-ALTERNATOR	1.60	2.25	2.90	1.60	2.25	2.90
AUTO CONTROLS AND AUXILIARIES	1.50	1.75	2.00	1.50	1.75	2.00
PIPING-NINE SHAFT TO TURBINE AT \$2.50/lb	0.28	0.52	1.00	0.25	0.59	1.29
MAIN CONDENSER WITH TUBES	3.70	8.85	17.20	3.66	8.02	17.14
CONDENSATE PUMPS (2)	0.04	0.07	0.12	0.04	0.07	0.12
CONDENSER COOLING WATER PUMPS (2)	0.25	0.59	1.10	0.24	0.58	1.00
PIPING COOLING WATER AT \$2.00/lb	0.26	0.55	1.00	0.23	0.52	0.95
VACUUM PUMPS (2)	0.10	0.15	0.20	0.10	0.15	0.20
EXTRA FEEDWATER PLANT (100 DAYS)	1.03	2.57	4.12	1.03	2.57	4.12
LOW VOLTAGE LINES TO SUBSTATION	0.05	0.13	0.25	0.05	0.13	0.25
STARTUP AND TRAINING COSTS	2.00	2.25	2.50	2.00	2.25	2.50
DIRECT COSTS	31.75	53.38	83.49	31.62	53.35	83.54
INSTALLATION UNCERTAINTIES (20%)	6.35	10.67	16.69	6.32	10.67	16.70
OVERHEAD (25%)*	7.93	13.34	20.87	7.90	13.33	20.88
TOTAL COST	46.03	77.39	121.05	45.84	77.35	121.12
FINANCING COST (20%)	9.21	15.48	24.21	9.17	15.47	24.22
TOTAL COST THIS PORTION	55.24	92.87	145.26	55.01	92.82	145.34
SPECIFIC COST (\$/KW)	276.00	185.00	145.00	275.00	186.00	145.00

*OVERHEAD INCLUDES ENGINEERING, MANAGEMENT, LEGAL

condenser assembly. Condenser cooling water pumps and two-way piping are included, but the cooling tower is shown as optional equipment. A feedwater surface storage tank to hold 15 percent of the cavity water and feedwater processing equipment is also included. In the conservative estimate this plant remains on the site. After the cavity has been filled, only a fraction of the feedwater processing equipment is needed and that not used is sold in the realistic estimate. Multiple high-pressure insulated steam lines from the shaft adit to the turbine 500 to 1000 ft away are included as part of the surface power plant equipment. Transformer and substation equipment are included in the recap (see Table 5-1).

SECTION 6. COMPARISON TO OTHER STORAGE SYSTEMS CHARACTERISTICS, COSTS, AND EFFICIENCIES

6.1 ACQUISITION OF COMPETITIVE COSTS

Because there are relatively few large energy storage systems for electric utility use in this country, good reliable data on capital cost and operating characteristics are scarce. This is especially true in getting reliable cost data with details on how it is made up so comparisons can be made on the same basis.

Table 6-1 compares the capital cost estimates of several storage systems. In all cases this includes all power generation equipment and auxiliaries as well as the energy storage equipment. A baseline conventional fossil fueled steam plant and a battery of gas turbines are also shown for comparison. The table also indicates an energy recovery factor relative to the baseline steam plant. The "round-trip" efficiency into storage and back is not exactly applicable to the gas turbine and stored air turbine system, but we have shown an equivalent efficiency for comparison.

To make a complete assessment of the total real cost of each system we have added the present value of the fuel cost for a 20-yr life at 10 percent interest to the capital cost of the complete plant. This is shown in the last column and shows clearly that underground TESS is cost competitive. Much of this data comes from the PSE&G report [1,22].

The variation of generation costs with daily or weekly demand has not been taken into account. Using a fixed power cost tends to overstate the savings compared to other storage systems and understate the savings compared to gas turbine peaking units.

Table 6-1. Comparison of Peaking Plant Costs^a

TYPE OF SYSTEM	COMPLETE PLANT COST RANGE (\$ x 10 ⁶)	ENERGY RECOVERY FACTOR (PERCENT)	COST ADJUSTED FOR EXTRA FUEL USED ^b
FOSSIL FUELED STEAM PLANT (BASELINE)	470-670	100	470-670
PEAKING GAS TURBINES	160-200	82 EQUIV	712-765
COMPRESSED AIR STORAGE WITH GAS TURBINES (UNDERGROUND)	248-431	83 EQUIV	622-839
PUMPED HYDRO			
SURFACE TYPE	140-260	67	291-411
UNDERGROUND TYPE	170-335	67	321-486 ←
MOLTEN SALT WITH HEAT EXCHANGERS	440-930	80	517-1007
HOT OIL WITH HEAT EXCHANGERS	400+	80	477+
TESS			
SURFACE PRESSURE VESSELS	640-985	89	678-1023
UNDERGROUND CAVITIES	238-320	89	276-358 ←

^a DATA FROM REFERENCED SOURCES AND BASED ON 1000 MW PEAKING OUTPUT FOR 10 hr DURATION, 2000 hr ANNUALLY.

^b PRESENT VALUE OF INCREMENTAL FUEL COST FOR 20 yr AT 10 PERCENT INTEREST ADDED.

6.2 COMPARISON OF COSTS

Table 6-2 compares several other characteristics of these same systems. The very high power-in power-out efficiency of the underground hot water storage system enhances its value. For example, if fossil fuel power costing 18 mill/kWh_e is stored and used daily the annual savings using TESS instead of pumped hydro is \$2.53/kWh. The total power cost with pumped hydro at 67 percent in-out efficiency is \$9.81 per year whereas underground TESS at 84 percent in-out efficiency costs only \$7.38. In each case the value of the power at the output base is \$6.57. The present worth of this operational saving over a 20-yr life is over \$21/kWh stored and used daily (at 10 percent interest). While the usage and costs will change for each installation, this illustrates that improved efficiency should be a major consideration in the initial cost comparison.

The capital cost of TESS will also be influenced by the physical location, the geology at the site and the type of power plant it is working with--old or new, nuclear or fossil fueled.

6.3 EFFICIENCY COMPARISON

The terms "round-trip" or "in-out" efficiency are not always clear when applied to all peaking power storage systems, so Figure 6-1 represents an effort to clarify these values.

This chart schematically follows the energy flow in each system from fuel to wire and shows the component efficiency of each item in each of the peaking power arrangements through which power must pass. Representative efficiencies were selected and each will vary with the type of equipment and the load on it, but the same values are used in all cases so the comparison error is minimal.

Table 6-2. Comparison of Storage System
Operating Characteristics

SYSTEM TYPE	RELIABILITY OR AVAILABILITY	STARTUP OR TURNAROUND TIME	IN-OUT EFFICIENCY	COMMENTS
UNDERGROUND TESS NUCLEAR	UNKNOWN BUT SHOULD BE EXCELLENT	SAME AS MAIN TURBINES	93-95 PERCENT	CAVITY SEALING NOT YET PROVEN
FOSSIL		STARTUP ~30 min	90-92 PERCENT	"
SURFACE VESSEL HOT WATER STORAGE	SAME AS ABOVE	SAME AS ABOVE	SAME AS ABOVE, BUT SOME HEAT LOSS WITH TIME	FABRICATION LIMITS VESSEL SIZE
PUMP HYDRO STORAGE	87 PERCENT	{ PUMPING TO GENERATING 2-20 min GENERATING TO TO PUMPING 5-40 min	66-75 PERCENT 70 PERCENT MOST LIKELY	CURRENT SYSTEMS DO NOT HANDLE LOAD VARIATION WELL. LONG USEFUL LIFE. LIMITED SITING.
UNDERGROUND PUMPED HYDRO	PROBABLY LOWER THAN PUMP HYDRO STORAGE			
UNDERGROUND COMPRESSED AIR STORAGE	POOR AVAILABILITY DUE GAS TURBINE	~30 min STARTUP TIME	VARIABLE--FUEL BURNED IN AIR BEFORE EXPANSION	SHORT LIFE ON GAS TURBINES-- LIMITED SIZE
MOLTEN SALT STORAGE	DEPENDS ON HEAT EXCHANGER	SAME AS MAIN TURBINES	{ 80 PERCENT DEPENDS ON STORAGE TIME AND HEAT EXCHANGER EFFICIENCY	NOT YET DEVELOPED
HOT OIL STORAGE	SAME AS ABOVE	SAME AS MAIN TURBINES		NOT YET DEVELOPED

Figure 6-1. Efficiency Comparison

The Rankine cycle and steam turbine efficiencies have been kept the same for simplicity when in reality they vary with pressure, temperature, size, plant detail and many other factors. All power is transformed to high voltage for transmission, and for alternates C and D the transmission lines may well be long enough to incur a loss (~1 percent). Other component efficiencies are from current literature [1,2].

From Figure 6-1 it becomes evident that the storage "round-trip" efficiencies or its equivalents are:

Baseline	A	$\frac{0.33}{0.33} = 100$ percent
	B	$\frac{0.27}{0.33} = 82$ percent
	C	$\frac{0.275}{0.33} = 83$ percent
	D	$\frac{0.22}{0.33} = 67$ percent
	E	$\frac{0.29+}{0.33} = 89$ percent.

The compressed air storage system (C) efficiency is based on high air compression ratio (50), high temperature gas inlet (2460° R) and good recuperator effectiveness (80 percent) as well as excellent compressor performance over a wide range (85 percent). By adding about 4000 Btu of fuel to the gas turbine burners to each kilowatt hour of compressed air stored, the turbine output is 1 kWh output for 11 lb stored air. With all transmission and translation losses taken into account, the fuel-to-wire efficiency is 27.6 percent. Both (B) and (C) gas turbine units burn a costly fuel--\$12 to \$15/bbl.

The thermal energy storage system includes a 0.91 efficiency, which covers the losses incurred during charging and discharging

by pressure and temperature drops (see Section 3.1). This figure is for the high-pressure fossil fuel condition where recharging is done with superheated steam which is desuperheated before use. For a nuclear or low superheat plant this efficiency value rises to 0.93. Cavity and line losses by both water and heat leakage are each included at 1 percent in the efficiency comparison. Steam line losses are based on the extraction of full peaking output at the very end of the discharge period. An examination of most demand charts show this to be an unlikely occurrence.

TESS "round-trip" efficiency is 89 percent for high pressure systems and 90 percent for low-pressure (nuclear) systems.

The equivalent barrels of oil have been estimated to handle 10,000 MW through each storage system 2000 hr/yr.

About 8000 MW of peaking power are now in operation (United States only) with 40,000 MW predicted by 1993 [2]. Average usage is 2500 hr/yr.

On the above nationwide basis, TESS would save 13×10^6 barrels of oil annually over a pumped hydro storage system. Current value is over $\$156 \times 10^6$.

6.3.1 Fuel Saving Comparison

An estimation of the present worth of improved "round-trip" efficiency is shown by the following comparison of TESS with pumped hydro storage. This comparison is based on the following:

Pumped hydro "round-trip" efficiency = 67 percent

Nuclear TESS "round-trip" efficiency = 90 percent

Fossil fueled TESS "round-trip" efficiency = 89 percent

Nuclear energy cost = 9 mills/kWh_e
 Fossil energy cost = 18 mills/kWh_e
 55 percent charge usage
 365 days/yr
 20-yr life
 10 percent interest rate
 10 hr storage capacity system.

Then:

$$\text{Lost power} = 365 \frac{1 - \eta}{\eta} \text{ kWh/yr/kWh stored}$$

Storage system

Pump hydro = 179 kWh/yr/kWh
 Nuclear TESS = 40 kWh/yr/kWh
 Fossil TESS = 45 kWh/yr/kWh.

Present value of power saved for a nuclear supply plant is

$$(179 - 40) \times 0.009 \times 1000 \times 0.5 \times 10 \times 8.5 = \$53,000/\text{MW}$$

hence 200 MW = $\$10.6 \times 10^6$ saving
 500 MW = $\$26.5 \times 10^6$ saving
 1000 MW = $\$53 \times 10^6$ saving.

By this same method a fossil fueled supply plant has a present value of the savings over pumped hydro storage of:

200 MW = $\$21 \times 10^6$
 500 MW = $\$54 \times 10^6$
 1000 MW = $\$105 \times 10^6$.

The greater savings is due to the higher fuel cost.

SECTION 7. CONSTRUCTION SCHEDULE

At this feasibility study stage a construction schedule can only be an estimate of the time required from initiation to completion of an installation built after the demonstration unit is operational.

To make this schedule, the mining consultants and related industrial representative groups supplied excavation rates and delivery of components deemed critical. Figure 7-1 is a schedule for the deep hole (2450 ft) and large cavity (325 diameter) and has allowed for delays to handle excess water, cave-ins and other mining and construction problems; however, any truly extraordinary occurrences may extend the completion time shown. Figure 7-1 does indicate that construction time of TESS installations is much like competitive alternates.

Test core drilling, sinking the main vertical shaft and excavating the cavity rock are typical critical time items that must be done sequentially. Further studies should include efforts to minimize execution time of these operations and to see how and where overlapping can be done to reduce the overall construction period.

NOTE: BASED ON A LARGE CAVITY AT FULL DEPTH

"O" INDICATED ORDER CRITICAL MATERIAL OR EQUIPMENT

Figure 7-1. Construction Schedule

SECTION 8. CONCLUSIONS

After completion of this preliminary study, RDA has determined that the following conclusions are justified:

1. Storing energy as hot water under high pressure to be partially flashed to steam when needed is technically feasible in the large sizes required for many electric utilities.
2. Using underground cavities as high pressure vessels to store this hot water is technically feasible. The demonstrated state-of-the-mining-art currently is limited to cavities with 130 to 150 ft arched spans. There appears to be no technical reason why well-designed and instrumented cavity spans much larger than current practice cannot be built at a number of sites using existing technology.
3. A technically and economically acceptable "back-up" system exists to insure the success of a cavity even when difficult rock conditions are encountered.
4. Preliminary geologic assessment indicates there are many areas of the continental United States (as well as the world) where the underlying rock formations appear suitable for large cavities. Many are under or near metropolitan areas and existing power plants.
5. The economics of this energy storage system compares favorably with other alternatives in most cases. The initial capital cost is competitive with a typical pumped hydro installation and the

higher energy recovery factor results in fuel savings.

6. This underground thermal energy storage system is most competitive in large sizes--generally above a 200-MW peaking capacity and a 500 MWh storage capacity.
7. The energy "round-trip" efficiency (into storage and back) is higher than any other energy storage system. When properly designed, this efficiency should be over 90 percent (versus 65 to 75 percent for pumped hydro). The capitalized value of the fuel saved can offset any higher initial storage capacity capital cost.
8. There are a few areas where current state-of-the-art does not cover the problems presented in this concept; so the following work is recommended:
 - Actual tests on high-temperature concretes and grouts.
 - Optimization of attachment of the cavity liner to the concrete wall.
 - Water mixing techniques in the cavity to get maximum charge and discharge rates at high efficiencies.
 - Startup (heating) and shutdown (cooling) techniques.

9. Analysis (perhaps including finite element stress analysis) and experimentation are required to reduce the unknowns and uncertainties when excavating large span underground cavities.
10. Large single cavity underground chambers (not porous rock) have not been used for high pressure, hot storage before so the application will have to be proven.

SECTION 9. RECOMMENDATIONS

This feasibility study definitely indicates that underground cavities can be used as large high-pressure vessels for the storage of thermal energy in saturated hot water. The concept appears technologically and economically sound and competitive with other methods of energy storage. RDA recommends serious consideration be given to a continuing program that can lead to a demonstration unit at the earliest possible time. The many advantages of this concept (refer to Section 1.3) justify governmental sponsorship of the first demonstration cavity so the utilities can have confidence to apply it to their own network. Convincing the utilities of this practicability should be the objective of any future effort.

A continuing effort should include the following program so that an actual operating unit can be achieved expeditiously.

1. Cavity liner development and confirmation. This effort includes detail design and analysis toward optimization. Laboratory testing of liner elements peculiar to these requirements would be done. Either a mathematical or hydraulic model would be made to verify operation at our high boiling and condensing rates.
2. Selection of several candidate sites and cooperating utilities. Work on the most likely candidates includes specific geophysical study followed by test core drilling and in situ properties measurement.
3. Operation of a small test cavity. By using an existing shaft in an appropriate rock formation,

a ~20 ft diameter cavity can be in operation in ~18 months. It would be instrumented and operationally complete to verify all design features. Data from this small test cavity would be invaluable before the first demonstration unit. A small steam generator would charge the cavity and steam would be expended on discharge. Testing may be continued to obtain reliability characteristics.

4. During this period, a mining plan suitable to the sites selected and to the contractors who would do the excavation would be developed. Long delivery equipment and material can be selected so orders can be placed promptly when appropriate.

It is noteworthy that a site with a small demonstration cavity can easily be designed to accommodate an additional larger cavity for expansion after the concept is proven.

Although it is not required for the first demonstration unit, RDA recommends that a generalized method of site analysis be developed to enable any utility to evaluate this concept for their particular conditions from both technical and economic viewpoints.

Appendix A. A Preliminary Regional Survey of Areas
Where Underground Excavation For Hot Water Storage
Might Prove Feasible [23,24]

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>ALABAMA</u>				
BIRMINGHAM	LIMESTONE	450-600	2	REGIONAL
MONTGOMERY	GRANITE	270+	1-2	REGIONAL, ALSO METAMORPHICS
<u>ALASKA</u>				
ANCHORAGE	SANDSTONE	170	3-4	REGIONAL
FAIRBANKS	METAMORPHICS	+600	2	REGIONAL
<u>ARIZONA</u>				
TUCSON	GRANITE	135	1-4	IN THE VICINITY
PHOENIX	METAMORPHICS	+600	2-3	IN THE VICINITY
	SALT (MASSIVE)	50?	1	IN THE VICINITY
<u>ARKANSAS</u>				
LITTLE ROCK	LIMESTONE	325	2-3	REGIONAL
	SHALE			
FT. SMITH	SANDSTONE	300	3	REGIONAL
	SHALE			
<u>CALIFORNIA</u>				
LOS ANGELES	GRANITE	190	2-3	EAST OF SAN
	METAMORPHICS	+600	2-3	GABRIEL VALLEY TO COLORADO RIVER
SAN DIEGO	GRANITE	190	1-2	INLAND FROM COAST
CENTRAL VALLEY CITIES	GRANITE	190	1-2	EASTERN BORDER OF VALLEY (SIERRA NEVADA)
<u>COLORADO</u>				
DENVER, BOULDER, COLORADO SPRINGS	SHALE, LIME- STONE, SAND- STONE	275	3-4	REGIONAL
PUEBLO	LIMESTONE, SHALE	100	3	REGIONAL
<u>CONNECTICUT</u>				
HARTFORD	GRANITE	270+	1-2	IN THE VICINITY
NEW HAVEN	GRANITE	270+	1-2	IN THE VICINITY
NEW BEDFORD	GRANITE	270+	1-2	IN THE VICINITY
<u>GEORGIA</u>				
ATLANTA	GRANITE	270+	1-2	REGIONAL
AGUSTA/MACON	GRANITE OR METAMORPHICS	450+	2-3	REGIONAL

Appendix A. (Continued)

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>HAWAII</u> HONOLULU/HILO	BASALT	0.1-2.5+	4-5	REGIONAL
<u>IDAHO</u> BOISE	GRANITE	140	1-2	IN THE VICINITY
IDAHO FALLS/ TWIN FALLS	BASALT	1	4-5	REGIONAL
COUR D'ALENE	METAMORPHICS	600+	2-3	REGIONAL
POCATELLA	METAMORPHICS	350-600+	2-3	REGIONAL
<u>ILLINOIS</u> SPRINGFIELD	LIMESTONE, SANDSTONE, SHALE	300	3	REGIONAL
<u>INDIANA</u> INDIANAPOLIS	LIMESTONE	400	2	REGIONAL
<u>IOWA</u> DEBUQUE	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
SOUIX CITY	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
<u>KANSAS</u> KANSAS CITY	LIMESTONE	550	2	REGIONAL
WICHITA	LIMESTONE	290	2	REGIONAL
<u>KENTUCKY</u> LOUISVILLE	LIMESTONE	500	2	REGIONAL
FRANKFORT	LIMESTONE	500	2	REGIONAL
<u>LOUISIANA</u> NEW ORLEANS	SALT DOMES	-	1	IN THE VICINITY
SHREVEPORT	SALT DOMES	-	1	IN THE VICINITY
BATON ROUGE	SALT DOMES	-	1	IN THE VICINITY
<u>MAINE</u> PORTLAND	GRANITE	450+	1-2	IN THE VICINITY
AUGUSTA	GRANITE	450+	1-2	IN THE VICINITY
<u>MARYLAND</u> BALTIMORE	GRANITE, METAMORPHICS	350-600+	1-2	REGIONAL
<u>MICHIGAN</u> DETROIT	LIMESTONE	500	2	REGIONAL

Appendix A. (Continued)

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>MINNESOTA</u>				
MINNEAPOLIS/ ST. PAUL	METAMORPHICS	600+	2	REGIONAL
ROCHESTER	METAMORPHICS	600+	2	REGIONAL
<u>MISSISSIPPI</u>				
JACKSON	SALT DOMES	-	1	IN THE VICINITY
HATTIESBURG	SALT DOMES	-	1	IN THE VICINITY
<u>MISSOURI</u>				
KANSAS CITY/ ST. LOUIS	LIMESTONE	300+	2-3	REGIONAL
JOPLIN	GRANITE, METAMORPHICS	600+	1	REGIONAL
SPRINGFIELD	GRANITE METAMORPHICS	600+	1	REGIONAL
<u>MONTANA</u>				
GREAT FALLS	METAMORPHICS	500+	2-3	REGIONAL
HELENA/BUTTE	GRANITE	40	1	REGIONAL
MISSOULA	METAMORPHICS	500+	2-3	REGIONAL
BILLINGS	SHALE	100	3	REGIONAL
<u>NEBRASKA</u>				
LINCOLN/OMAHA	METAMORPHICS	600+	2	REGIONAL
<u>NEVADA</u>				
LAS VEGAS	GRANITE, LIMESTONE, METAMORPHICS	20, 270, 600+	1-3	IN THE VICINITY
RENO	GRANITE	190	1-2	IN THE VICINITY
<u>NEW HAMPSHIRE</u>				
CONCORD	GRANITE, METAMORPHICS	600+	1-2	IN THE VICINITY
PORTSMOUTH	GRANITE, METAMORPHICS	600+	1-2	IN THE VICINITY
<u>NEW JERSEY</u>				
TRENTON	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
<u>NEW MEXICO</u>				
ALBUQUERQUE/ SANTA FE	METAMORPHICS	600+	2-3	IN THE VICINITY
ROSEWELL/ CARLSBAD	LIMESTONE	250	2	REGIONAL
ALAMOGORDO	LIMESTONE	275	2	REGIONAL
FARMINGTON	SHALE	100	3	REGIONAL

Appendix A. (Continued)

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>NEW YORK</u>				
NEW YORK CITY	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
WATERTOWN	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
UTICA	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
BUFFALO	LIMESTONE	500	2	REGIONAL
<u>NORTH CAROLINA</u>				
CHARLOTTE	GRANITE	270	1	REGIONAL
GREENSBORO	GRANITE	270	1	REGIONAL
WINSTON-SALEM	METAMORPHICS	350+	2-3	REGIONAL
RALEIGH	METAMORPHICS	350+	2-3	REGIONAL
FAYETTEVILLE	METAMORPHICS	270+	2-3	REGIONAL
<u>NORTH DAKOTA</u>				
GRAND FORKS/ FARGO	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
<u>OHIO</u>				
CINCINNATI	LIMESTONE	500	2	REGIONAL
CLEVELAND	LIMESTONE	450	2	REGIONAL
COLUMBUS	LIMESTONE	500	2	REGIONAL
<u>OKLAHOMA</u>				
OKLAHOMA CITY	LIMESTONE	290	2	REGIONAL
TULSA	LIMESTONE, METAMORPHICS	470-600+	1-2	REGIONAL
<u>OREGON</u>				
PORTLAND/ EUGENE	BASALT	20-50	4-5	REGIONAL
ALBANY/BEND	BASALT	20-50	4-5	REGIONAL
<u>PENNSYLVANIA</u>				
PHILADELPHIA	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
PITTSBURGH	LIMESTONE, SANDSTONE, SHALE	300	3	REGIONAL
<u>RHODE ISLAND</u>				
PROVIDENCE	GRANITE, METAMORPHICS	600+	1-2	REGIONAL

Appendix A. (Continued)

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>SOUTH CAROLINA</u>				
GREENVILLE	GRANITE, METAMORPHICS	270+	2	REGIONAL
COLUMBIA	GRANITE, METAMORPHICS	270+	2	REGIONAL
CHARLESTON	SHALE	100-270+	3	REGIONAL
<u>SOUTH DAKOTA</u>				
STOIX FALLS	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
RAPID CITY	GRANITE, METAMORPHICS	600+	1-2	IN THE VICINITY
<u>TENNESSEE</u>				
NASHVILLE	LIMESTONE	500	2	REGIONAL
KNOXVILLE	LIMESTONE	500	2	REGIONAL
CHATTANOOGA	LIMESTONE	450	2	REGIONAL
<u>TEXAS</u>				
AUSTIN	SHALE	305	4	REGIONAL
DALLAS	LIMESTONE, SHALE	80	3-4	REGIONAL
FT. WORTH	LIMESTONE	100	2-3	REGIONAL
AMARILLO/ LUBBOCK	SANDSTONE, SHALE	-	4-5	REGIONAL
HOUSTON/ GALVESTON	SALT DOMES	-	1	IN THE VICINITY
CORPUS CHRISTY/ BEAUMONT	SALT DOMES	-	1	IN THE VICINITY
<u>UTAH</u>				
SALT LAKE CITY	LIMESTONE	300	2-3	IN THE VICINITY
OGDON	LIMESTONE	300	2-3	IN THE VICINITY
PROVO	GRANITE, METAMORPHICS	600+	1-2	IN THE VICINITY
KANAB	LIMESTONE	325	2	REGIONAL
<u>VERMONT</u>				
BURLINGTON	LIMESTONE, SHALE, SAND- STONE, META- MORPHICS	300-600+	2-4	REGIONAL
RUTLAND	LIMESTONE, SHALE, SAND- STONE, META- MORPHICS	300-600+	2-4	REGIONAL

Appendix A. (Continued)

STATE & CITY	PROBABLE ROCK TYPE	APPROX. AGE (MILLION YR)	EXCAVATION CLASS	REMARKS
<u>VIRGINIA</u>				
CHARLOTTESVILLE	GRANITE, METAMORPHICS	350+	1-2	REGIONAL
ROANOKE/ ARLINGTON	GRANITE, METAMORPHICS	350+	1-2	REGIONAL
RICHMOND	GRANITE, METAMORPHICS	350+	1-2	REGIONAL
<u>WASHINGTON</u>				
SPOKANE	METAMORPHICS	600+	2	REGIONAL
OLYMPIA	BASALT	20-50	4-5	REGIONAL
<u>WASHINGTON, DC</u>	GRANITE, METAMORPHICS	350+	1-2	REGIONAL
<u>WEST VIRGINIA</u>				
CHARLESTON	SANDSTONE, SHALE, COAL	280	3-5	REGIONAL
WHEELING	SANDSTONE, SHALE, COAL	280	3-5	REGIONAL
<u>WISCONSIN</u>				
MADISON	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
SPARTA/OSHKOSH	GRANITE, METAMORPHICS	600+	1-2	REGIONAL
<u>WYOMING</u>				
CASPER	LIMESTONE, SHALE, SANDSTONE	275	3	REGIONAL
LARAMIE	LIMESTONE, SHALE, SANDSTONE	275	3-4	REGIONAL

APPENDIX B. VIBRATIONS OF ROOF SPANS FROM UNDERGROUND BLASTS

An especially important consideration in excavating a stable underground chamber of large arch span is the dynamic loading of the roof during blasting operations of the adjacent unexcavated material. The following summarizes findings obtained by the U.S. Bureau of Mines in a study of roof vibrations caused by blasting [25]. Quantitative data of this type is very important because the primary cause of fatalities in underground mining is from rock falls. These experiments were conducted at the White Pine Copper Mine in upper Michigan. The principal rock types are dense, fractured sandstones and shales. Such rocks would be comparable to excavation classes 3 and 4 (Ref. page 2-22). The general characteristics of the rock properties and the underground workings are listed in Table B-1.

Explosive blasting to fragment rock for excavation in this vibration study was typically conducted in a 14-ft high, 28-ft wide working face with each round taking a 12-ft-thick rock segment. The timings of the explosive charges were delayed 25 msec, with the initial charge being 38 to 39 lb of either ammonium nitrate/fuel oil (ANFO) or dynamite. As many as ten delays of 25 msec each make up the total production round, totalling an explosive charge of 270 lb spread over 43 holes. The delay blasting technique is used commonly to reduce seismic vibrations and damage potential, with the greatest peak-to-peak acceleration associated with the zero-delay charge (in this example, 38 to 39 lb/round). In actual production operations at the mine, several such rounds are commonly fired simultaneously without initiating roof failure.

Table B-1. Characteristics of White Rock Mine Used
For USBM Roof Vibration Experiments

MINING METHOD	ROOM AND PILLAR	NO SMOOTH WALL BLASTING
PILLAR SIZE	15 TO 20 ft x 40 TO 70 ft	
FLAT ROOF SPANS	28 TO 50 ft	
ROCK BOLT SPACING	2.5 ft CENTERS AVERAGE	
JOINTING AND FAULTING	VARIABLE BUT COMMON-- TYPICALLY STRUCTURAL DEFECTS SEPARATED BY 2 TO 10 ft	
AVERAGE ROCK PROPERTIES	SANDSTONE	SHALE
DENSITY (g/cm ³)	2.59	2.73
LONGITUDINAL VELOCITY (fps)	16,800	16,400
TORSIONAL VELOCITY (fps)	10,300	9,800
TENSILE STRENGTH (psi)	1,700	1,000
COMPRESSIVE STRENGTH (psi)	21,500	27,000
YOUNG'S MODULUS (STATIC) (psi x 10 ⁶)	6.6	6.2

Table B-2 lists some average peak vertical accelerations and seismic vibration frequencies at different distances from the working face. All gauges were mounted in the roof. There is considerable variation in the data caused by variation in the orientation of the heading of the working face, the degree of preblast fracturing of the rock and the type of explosive used. Generally, slightly less seismic vibration is associated with ANFO in contrast to dynamite.

An important contribution of the study for future underground blasting operations is the close-in, empirically determined propagation equation for maximum accelerations from production-sized blasts:

$$AW^{1/2} = 50,000(R/W^{1/2}) - 2.21$$

where A = peak-to-peak vertical acceleration in g's

W = zero-delay charge weight in lb

R = distance from the blast in ft.

Table B-2. Average Vertical Accelerations and Seismic Vibration Frequencies as a Function of Distance from the Explosions (Zero-Delay Charge Weight 38-39 lb)

DISTANCE (ft)	ACCELERATION (g)	FREQUENCY (Hz)
50	45	2500
100	15	1400
200	3.1	440
300	2.5	290

APPENDIX C. NUCLEATE BOILING INITIATION

Bubble growth in a homogeneously superheated liquid is fairly well understood both experimentally and theoretically. The results are reported in TONG, Boiling Heat Transfer and Two Phase Flow [26], and he gives for the time dependence of the bubble radius

$$R(t) = 2C_1\sqrt{\alpha_e t} ,$$

where C_1 = the growth constant which is a function of the Jakob number and

α_e = the thermal diffusivity in the liquid.

The Jakob number is the ratio of the energy of superheat of unit volume of the liquid $\rho_e c_e (T_{\text{sup}} - T_{\text{sat}})$ to the energy $\rho_v h_{fg}$ needed to create a unit volume of vapor. For 1° C, superheat at our temperature and pressure, the Jakob number is ~0.1 and the corresponding C_1 is 0.25. Inserting these values we find $r = 0.077t^{1/2}$. Equating drag to buoyancy, we find $v_{\text{rise}} = 50.9r^{1/2}$ cm/sec. Thus a bubble is born, and rises through the liquid while growing and eventually breaks through the surface. These results may be summarized in Table C-1.

If the surface pressure is reduced 1.0 bar from the saturation pressure, the depth of water placed in the superheated condition is 13 m, it can be seen that bubble nuclei found in the depth region between 3.5 and 13 m, with a final radius between 0.3 and 0.5 cm when breaking through the surface can play a significant role in supplying the steam. The average bubble can be born between 6.5 and 7.5 m below the surface to rise to the surface in 27 sec, and to carry 0.27 cm^3 of steam out

Table C-1. Growing and Rising Bubble History

AGE (sec)	RADIUS (cm)	RISE DISTANCES (m)	RISE VELOCITY (cm/sec)	VOLUME (cm ³)
0.42	0.05	0.04	11	0.00052
1.7	0.1	0.22	16	0.0042
6.7	0.2	1.23	23	0.034
15.0	0.3	3.4	28	0.11
27.0	0.4	7.0	32	0.27
42.0	0.5	12.0	36	0.52
61.0	0.6	19.0	40	0.91
83.0	0.7	28.0	43	1.44
108.0	0.8	39.0	46	2.14

of the water. The bubble birth rate needed in the cavity is 240 million/sec which is 4.2/liter/sec. A cubical lattice of 1/4-inch-diameter reinforcing bar of 4-inch center should easily satisfy the nucleation requirements.

Dergarabedian [27] found that 6° C superheat was sufficient for bubble nucleation at 100° C at atmospheric pressure. All data show that bubble nucleation gets much easier at higher temperatures and pressure.

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