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COST ANALYSIS OF PACKED BEDS FOR THERMAL-ENERGY STORAGE

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Abstract

A cost analysis of packed beds for thermal-energy storage (TES) in an adiabatic compressed-air-energy storage system is given. Capital costs based on the conceptual design of a TES unit are estimated and their sensitivity to system parameter variation is studied. Two TES conceptual designs were considered for: (a) an excavated cavity, and (b) an abandoned mine. A cost comparision is made between surface-sited and underground TES. A cost model was constructed to study the effect of pebble size, insulation thickness, temperature, storage pressure, storage capacity, and other TES components on the TES capital cost.

CONTENTS

SUMMARY AND CONCLUSIONS

The concept of packed beds for thermal energy storage in an adiabatic compressed-air-energy storage (ACAES) system is discussed in a series of reports.(1-5) Topics include a literature survey, materials catalogue compilation, heat and mass flow analysis, and a conceptual design of a packed bed as the thermal part of such a storage system.

In this final report, the cost analysis, which treats TES siting in an abandoned mine or in an excavated cavity as two separate cases, considers the capital costs incurred for a packed bed for TES based on the conceptual design developed by MIT/ Lincoln Laboratory.(5) It was found that a pebble diameter of around one-half inch is suitable for the packed bed as it gives a compact bed, ensures good heat transfer, and forms a small fraction of the overall TES cost. In comparing one large TES unit with an equivalent combination of smaller beds in parallel, the former was the most economical unit, having the least surface area. Surface-sited TES units are far too expensive, requiring costly pressure vessels for containment.

Insulating firebrick and diatomaceous earth, used in the design as a container/insulator combination for the bed, are by far the cheapest materials available and are suitable for an underground TES unit that requires protection from the cavity rock and flowing groundwater. Corrugated iron silos and insulating firebrick provide the cheapest and most suitable combination to contain the bed in an abandoned mine, where geological conditions are well known and relatively safe.

The optimum insulation thickness required for thermal protection of the bed was calculated for both siting situations discussed above. A cost model was constructed and used to plot the variation of TES capital costs versus hours of storage and pressure ratio. Using this model, a study of the TES component costs showed that the greater the temperature and hours of storage, the lower the storage capital costs. For an excavated and lined cavity, the liner dominates the cost. By comparison, in an abandoned mine when no liner is required, the TES costs are approximately halved.

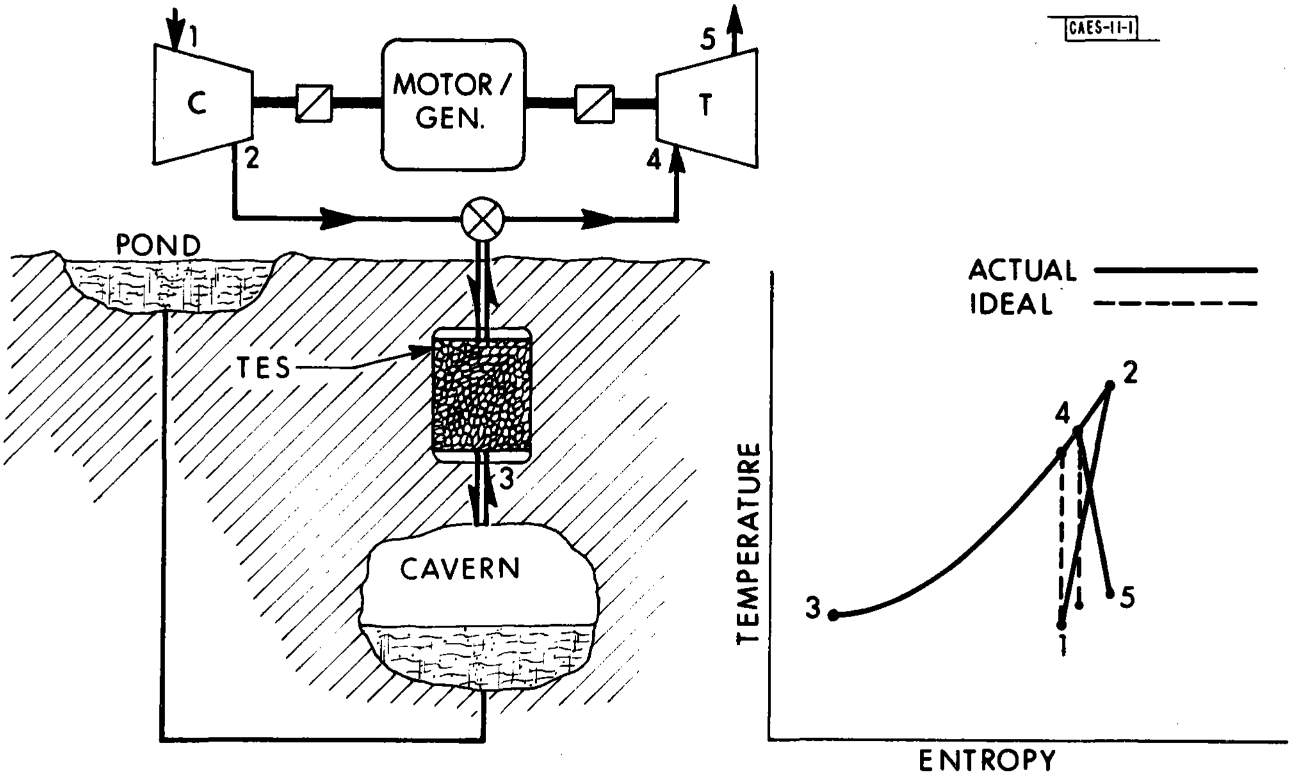

Fig. 1. Single-stage adiabatic CAES cycle.

COST ANALYSIS OF PACKED BED THERMAL-ENERGY STORAGE FOR USE IN AN ADIABATIC COMPRESSED AIR ENERGY STORAGE SYSTEM

1. Introduction

This report completes the study on packed beds for thermal-energy storage (TES), and represents part of a larger investigation by MIT/Lincoln Laboratory into adiabatic compressed-air-energy storage (ACAES).(1) The capital costs for such a TES unit based on a conceptual design(5) developed by MIT/Lincoln Laboratory are considered. In the MIT system concept, a motor draws off peak power from the electrical grid to drive an air compressor which drives the air through an underground packed bed, thereby withdrawing the heat of compression, and finally sending it—cooled—to an underground storage cavern. Upon release, the air returns through the bed, regains the heat of compression, and enters the turbine at a sufficiently high pressure and temperature to produce the necessary peak output. The basic ACES concept, using one stage of compression, one TES unit, and one turbine expansion stage is shown in Fig. 1.

In Fig. 2, two different packed bed TES design concepts are illustrated. In Fig. 2a the design (a) concept is suitable for an underground TES cavity, yet to be excavated. The packed bed is housed and insulated by insulating firebrick and diatomaceous earth. The rock bolts, steel lining and concrete shell, and the sealed grout holes take into account underground uncertainties such as geological stability and flowing groundwater, respectively. In Fig. 2b the design (b) concept is suitable for use in an abandoned mine (Fig. 3) where such uncertainties are eliminated an no cavity lining or support is required. The basic plant size being considered in this cost analysis is a 73-MW_e system with 12 hours of storage capacity.

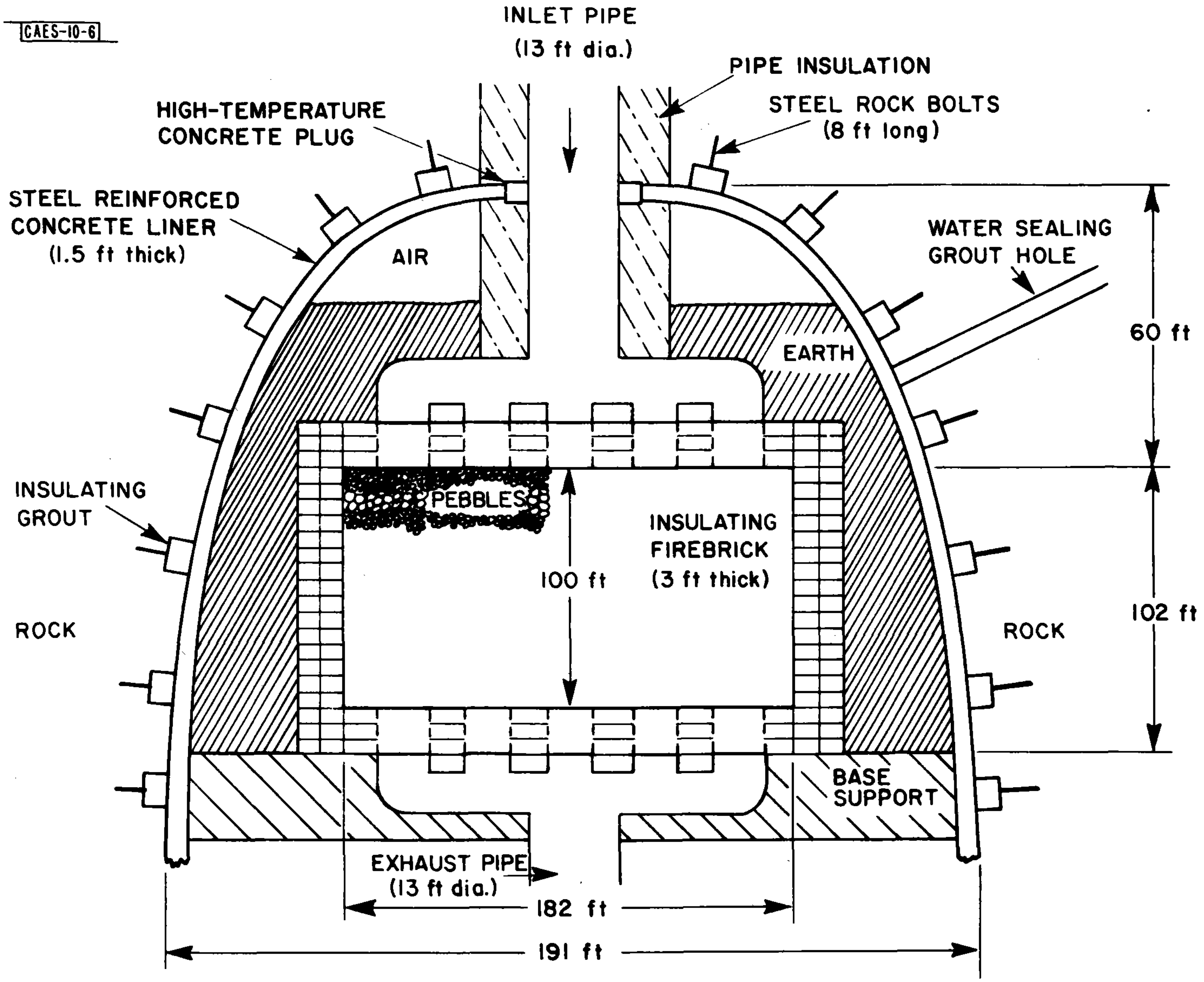

Fig. 2a. Design (a): Conceptual design of a packed bed for an excavated cavity.

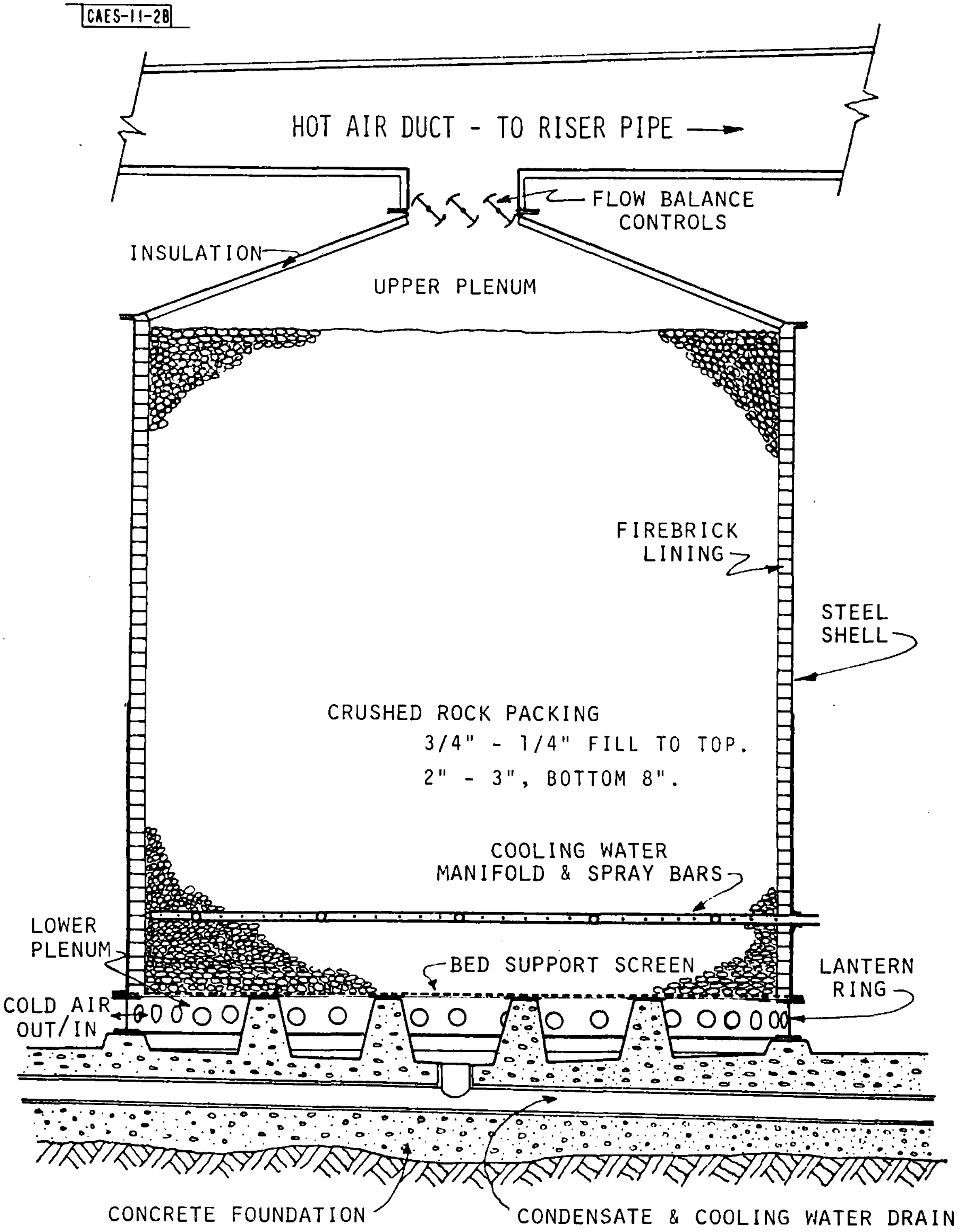

Fig. 2b. Packed-bed-TES free-standing silo concept.

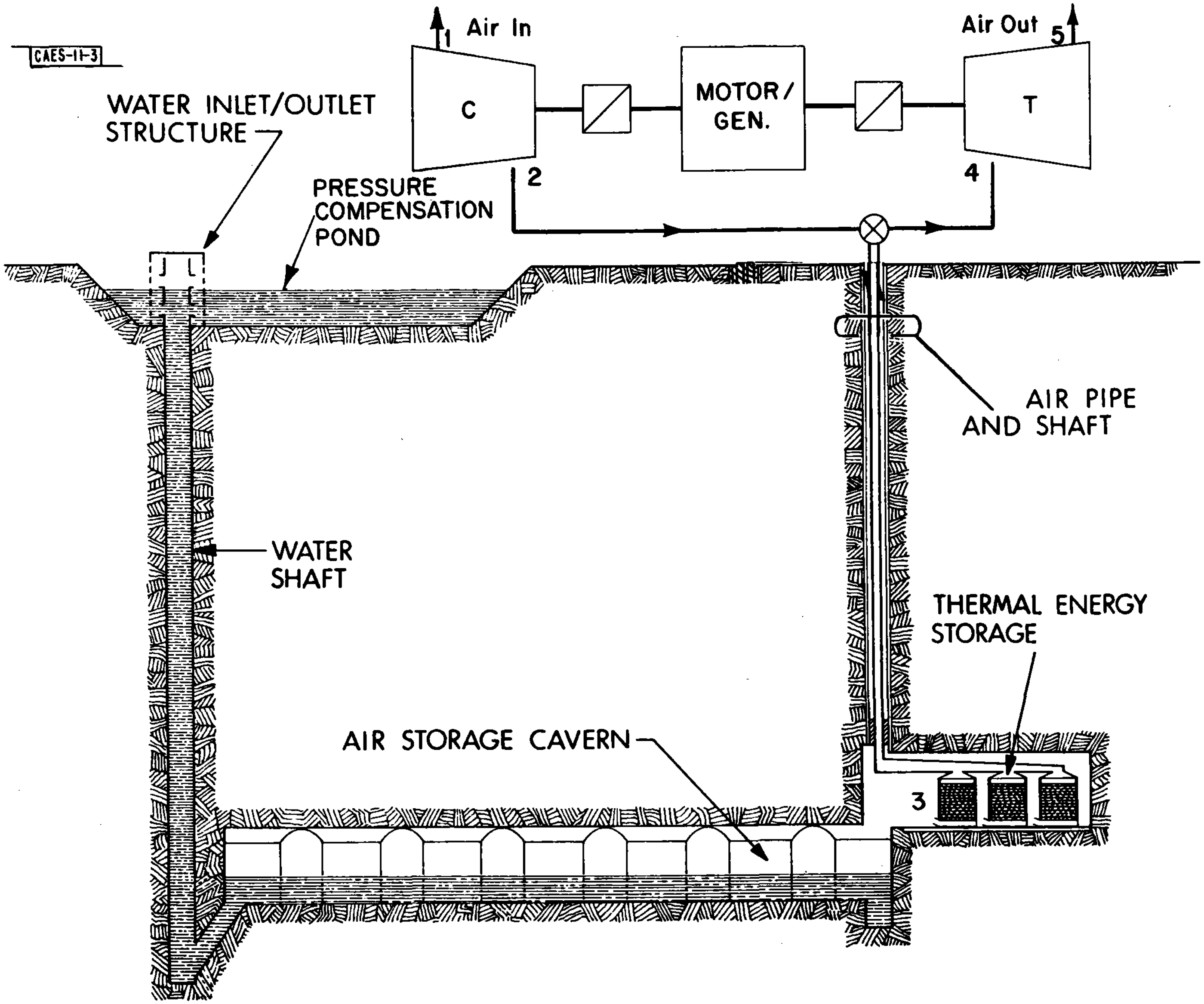

Fig. 3. Two-stage adiabatic CAES plant.

For the sake of clarity, this report treats the cost analysis of designs (a) and (b) separately using a cost model, and then compares the two cases. However, before the cost model is developed, a brief discussion on the choice of TES insulation and containment materials is presented to illustrate the difference between the two designs.

2. Effect of Packed Bed Length-to-Diameter (L/D) Ratio and Bed Shape

The effect of the L/D ratio and bed shape on the cost of the TES is discussed in detail in the design of the TES unit.(5)

3. Insulating Materials and Container Selection Based on Cost

The following criteria were used as guidelines in the choice of the TES insulation and containment materials (Table I):

a. Ability to withstand repeated temperature cycling up to 1500°F.

b. Ability to withstand condensation in the bed; i.e., the presence of water or water vapor must not cause corrosion nor reduce the insulating effectiveness.

c. Ability to accommodate to expansion and contraction of the storage material, the container, and the insulation.

d. Costs must be kept reasonably low.

Table I lists the possible insulation and container types for a TES unit. The operating temperature range applies to the insulating materials and the comments apply to their cost. The comments on the containment type refer to the container or container/insulation combination and its cost. Only two design combinations emerged as suitable candidates: (a) insulating firebrick lining inside a metal container, and (b) diatomaceous earth surrounding the firebrick. The first case is more suited to a geologically sound abandoned mine where corrugated silos can simply be placed in the cavity or in an excavated cavity that requires no cavity liner or structural support. The diatomaceous

TABLE I
INSULATING MATERIALS AND CONTAINMENT COSTS

Insulation Type (Cost)	Maximum Operating Temperature	Relationship to Container	Containment Type (Cost)			
			Steel or Corrugated Iron Tank (Fair to Costly, Depending on Material)	Concrete (Inexpensive)	Gunite (Very Expensive)	Insulating Firebrick (Moderate Cost)
Fiberglass (Moderate)	1000°F	Outside because of condensation in TES	Tank not protected thermally; will undergo high thermal cycling stress. Poor combination.	Cracks above 300°F. Very poor combination	Needs structural support. Very poor combination	Fiberglass redundant. Fair combination.
Gunite (Very Expensive)	2000°F	Inside	Gunite is expensive. Fair combination.	Very expensive to thermally protect concrete. Poor combination	Very expensive. Needs structural support. Poor combination.	Gunite can be replaced by insulating firebrick, which is less expensive. Fair combination.
Asbestos Cement (Inexpensive)	500°F	Inside	Cannot stand high temperatures. Asbestos particles foul up system. Poor combination.			
Insulating Firebrick (Moderate)	2000°F	Inside	Rugged. Condensation of metal container possible. Good combination.[*] (Costly if steel is used.)	Much insulation required to reduce thermal gradient across concrete. (Fair combinations)	Replace gunite with insulating firebrick which is cheaper.	Little room for expansion of pebbles with firebrick. (Insulating firebrick and diatomaceous earth cheaper.) Fair combination.
Diatomaceous Earth (Very Expensive)	2000°F	Outside because of condensation	Tank not thermally protected; will undergo high thermal cycling stress. Poor combination.	Cracks above 300°F. Very poor combination.	Need some structural support for gunite. Fair combination. (Fairly expensive)	Robust. Permits expansion of storage material and container. Very good combination.[†] (Inexpensive)

[*] Corrugated iron silos can be substituted for steel to reduce the cost.

[†] Suitable for cavity walls that require reinforcing.

earth/insulating firebrick combination is suitable for cavities requiring a lining and structural support, and is the cheaper of the two candidate combinations. Costs associated with both candidate combinations are discussed in Sections 5 and 6.

4. Cost Model

The cost of the TES unit may be broken up into four components:

- Cavity wall liner
- Cavity excavation
- Rock storage and insulation
- Inlet and outlet piping and insulation.

Each calculation depends on the bed diameter and length, except for the piping calculation, which is determined by the bed diameter only. The calculation procedure is as follows:

> Having selected the power rating, storage capacity, and pressure ratio, the optimum L/D ratio is calculated from the design curves.(5) The dimension of the cavity arch may be selected based on the calculation of cavity stresses(5) and the TES cost calculated directly from the cost model.

4.1 Liner Calculation

Surface area of the arch:

$$A = \frac{\pi}{4} (S^2 + 4h^2)$$

where $h = S/3$ (height of arch)

S = Cavity diameter (bed diameter + insulation)

Total height of TES cavity = bed length + h + insulation.

Surface around bed:

$$A = \pi S L$$

where L = Bed length

Surface area of TES cavity is the sum of the two previous equations; i.e.,

$$\pi \left(\frac{S^2}{4} + h^2 + SL \right)$$

Recognize that the bottom of the TES is not lined, but insulated only.

Liner cost per square foot of cavity surface area:

Total liner cost = [welding cost/ft^2 + (no. of rock bolts/ ft^2 x cost/ft^2) + grout hole/ft^2) cost/ft^2 + concrete cost/ft^2 + wire mesh cost/ft^2 + steel liner cost/ft^2] = B (\$/ft^2)

4.2 Excavation

$$\text{Excavation cost} = C \left[\frac{\pi h}{6} \left(\frac{3}{4} S^2 + h^2 \right) + \frac{\pi S^2}{4} L \right]$$

where C = Cost of excavation (\$/ft^3).

4.3 Rock Storage and Insulation

Rock:

$$\text{Cost/ft}^3 = \left(\frac{\pi D^2 L}{4} \cdot \frac{\rho(1 - \epsilon)}{2000} \cdot \chi \right) \$$$

where ρ = Rock density

ϵ = Void fraction

χ = Cost/ton(\$) of rock; typically, \$4/ton if the excavated rock is used and then screened; \$6/ton if the rock is purchased.

Insulation:

$$\text{Surface area of bed} = \pi D \left(\frac{D}{2} + L \right) \text{ft}^2$$

Insulation cost = cost/ft^2 + labor cost/ft^2; i.e.,

$$\text{Insulation cost} = \frac{\pi D^2}{2} \times F + \pi D L G = \pi D \left(F \frac{D}{2} + GL \right)$$

where F, G = cost (\$/ft^2) for top, bottom, and side insulating portions, which may have different thicknesses.

4.4 Piping

Surface area of piping is $(h + 4D)\ \pi\ D_p (ft^2)$.
Piping cost is (surface area of piping) x cost ($\$/ft^2$), i.e.,

$$= H\ (h + 4D)\ \pi\ D_p\ (\$)$$

where H = Piping cost ($\$/ft^2$) including labor
D_p = Pipe diameter.

Summing the results of items 4.1, 4.2, 4.3, and 4.4:

$$\text{TES cost} = \pi \left\{ B\left(\frac{S^2}{4} + h^2 + SL\right) + \frac{C}{2}\left(\frac{S^2 h}{4} + \frac{h^3}{3} + \frac{S^2 L}{2}\right) + \frac{x\ D^2\ L\ \rho(1 - \epsilon)}{8000} + D\left(F\ \frac{D}{2} + GL\right)\right\} \qquad (1)$$

Using Eq. (1), the variation of TES costs, or component cost with the system parameters, may be studied.

5. Cost Analysis for TES Siting in an Excavated Cavern [design (a)]

5.1 Effect of Pebble Size and Void Fraction

Pebble size and void fraction are related to the TES volume, and hence, to TES costs. Given an average pebble diameter of 0.05 feet and bed diameter of more than 100 feet the void fraction in the bed is 0.3. It is reasonable to assume little variation in the void fraction throughout the bed (apart from the bed walls(4)) for bed diameter/particle diameter ratios of 200 or greater. If the void fraction were reduced from 0.3 to 0.1, a saving of 18 percent in the TES volume would result. However, as $\epsilon = 0.2595$ is the theoretical lower limit for packed spheres and $\epsilon = 0.3$ is the practical lower limit for bed diameter/particle size ratios of more than 200, using a smaller particle diameter will have little effect on the void fraction. By using a pebble size smaller than 0.05-feet diameter, little gain in bed heat transfer is achieved as the pressure drop(4) and cost per ton of rock increases as noted in Table II. The price of rock depends on the degree of screening required. A typical cost range is as follows:

TABLE II

ROCK COST PER TON ($/TON)

Rock Size (in. dia.)	Cost ($/ton)
1/2	6.34
3/4	5.18
1-1/4	5.00

Using design (a) for a 12-hr, 73-MW_e daily cycle TES system operating at 750°F, cost increases were incurred in using the smaller pebbles (Table III).

TABLE III

EFFECT ON PEBBLE SIZE ON TES COSTS

Pebble Size (in. dia.)	Cost ($/ton)	Change in Rock Cost (%)	Fraction of TES Cost (%)
1-1/4	5.00	—	2.99
3/4	5.18	3.6	3.09
1/2	5.34	26.8	3.78

Although there is a 26.8-percent increase in rock storage material, the increase in the rock cost as a fraction of the TES cost is only 0.79 percent, and the overall increase in TES cost is negligible. Thus the 1/2-inch-diameter rock is preferred, giving better heat transfer and temperature uniformity, and so reducing the possibility of micro-cracking within the pebbles.

5.2 Cost Comparison Between an Excavated Underground and Surface-Sited TES Bed

If a TES unit were to be surface-sited, steel or reinforced concrete emerge as the only candidates suitable to contain the TES packing.(7)

I. Glendenning of the Central Electricity Generating Board

(CEGB, United Kingdom) has formulated the costs for a surface-sited TES bed using either reinforced concrete or steel as a high-pressure containment vessel for the packed bed.(7) For comparison, a 100-MW_{th}, 12-hr storage system operating at 750°F on a daily cycle is chosen. The air-mass flow rate used is 1.94×10^6 lb/hr = 245 kg/s.

a. Concrete Pressure Vessel and Storage Material

The cost formula for the prestressed concrete pressure vessel with Denstone fill (storage material) is:

$$\$ \left[1.8 \frac{\dot{m}}{1000} (15 + 0.396\ p) \frac{\tau}{8} 10^6\right] = \$13.4 \times 10^6$$

where $\dot{m}$ = Air-mass flow rate, $kg^{-1}s$

τ = Charge time, hours

p = Design pressure, atmospheres

1.8 = Exchange rate factor from British pounds to U.S. dollars.

The steel and concrete estimates used are based on U.S. prices while the Denstone fill is based on the U.K. price.

Subtracting the cost of the Denstone from $\$13.4 \times 10^6$, and adding in the cost of piping, insulation, and rock storage, the adjusted surface-sited TES cost—using a concrete vessel—amounts to $\$7.0 \times 10^6$. The equivalent underground TES cost is $\$3.60 \times 10^6$.

b. Insulated Steel Pressure Vessel with Denstone Fill

The cost formula for an insulated steel pressure vessel with Denstone that is surface sited is:

$$\$1.8 \frac{\dot{m}}{1000} (9.18 + 1.24\ p) \frac{\tau}{8} \times 10^6 = \$16.9 \times 10^6$$

Subtracting the cost of Denstone, and adding in the piping and rock storage costs, the adjusted surface-sited TES cost amounts to $\$9.5 \times 10^6$. Table IV summarizes the cost comparisons of underground and surface-sited TES designs for daily cycle storage (100 MW_{th}, 12-hr system), and weekly cycle storage (280 MW_{th}, 44-hr system, 1000°F, and 3.7×10^6 lb/hr).

TABLE IV

UNDERGROUND AND SURFACE-SITED TES COST ($\$ \times 10^6$) COMPARISON

Cycle	Underground TES	Surface-Sited TES	
		Concrete Vessel	Steel Vessel
Daily	3.6	7.0	9.0
Weekly	12.0	68.0	140.0

Clearly, surface-sited TES designs are too costly. The higher the operating pressure, the greater the disparity between surface-sited and underground systems. Possibly, at pressures below 10 atmospheres, the surface containment becomes feasible, but the operating temperature of the bed will be low (below 600°F), thus escalating the TES capital cost per unit of energy stored (Fig. 6). Secondly, it is uncertain whether the concrete could withstand repeated high-temperature cycling without cracking and disintegrating.

5.3 Cost Comparison of a Large TES Bed with Several Beds in Parallel for a Single-Excavation Cavity

The cavity surface area depends on the number of beds (one or more) connected in parallel. As this directly affects the cavity liner, structural support and excavation cost, the cavity surface should be minimized.

Table V compares the surface area of the cavity for one large bed with that prepared for several beds in parallel for a 200-MW_e weekly-cycle system that uses 44 hours of storage. Each combination has the same TES volume, but occupies a different cavity volume. The percentage change in liner costs for the parallel beds compared to one bed is also included. In Fig. 4, the shaded areas represent the minimum cavity cross-sectional area needed to house the beds, however, from a structural point of view a larger cavity cross section is usually required (Fig. 4).

The higher the number of beds in parallel with a constant TES volume, the closer their cavity surface area approaches that of

TABLE V

COST COMPARISON OF SEVERAL SMALL BEDS IN PARALLEL WITH ONE LARGE BED

No. of Beds in Parallel	Cavity Surface Area (ft^2)	Increase in Liner Cost (%)
1	109,208	—
2	185,612	70
3	145,142	33
4	125,664	15

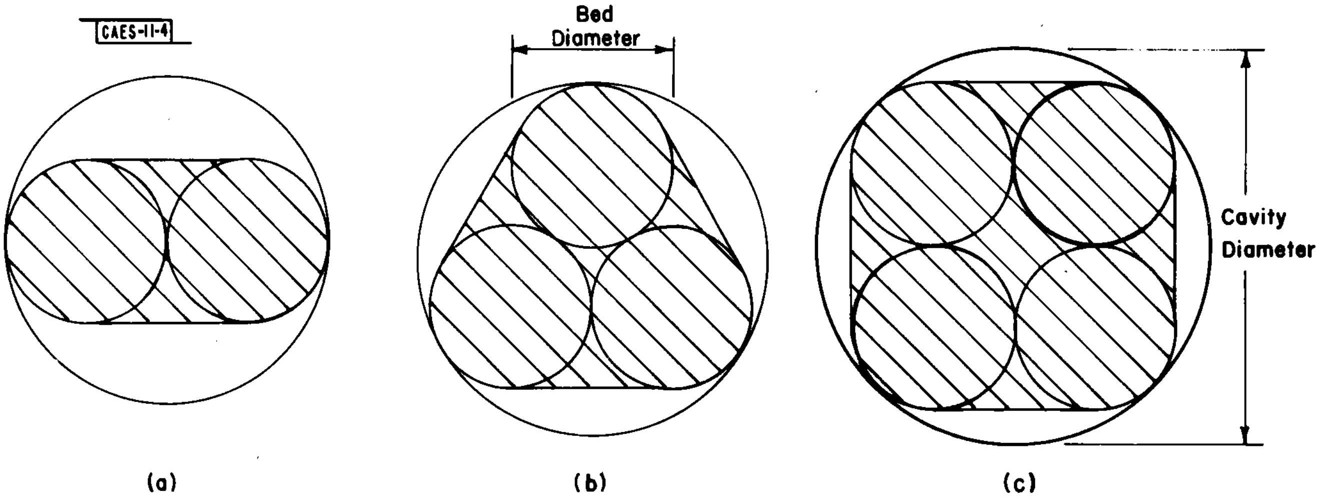

Fig. 4. Horizontal cross-sectional areas of (a) two, (b) three, and (c) four beds in parallel.

one large bed for the same TES volume. However, the more beds in parallel, the greater the piping and piping insulation costs. Clearly, a single TES is suitable for a large excavated cavity, but where tunneling is necessary or in the case of an abandoned mine where horizontal shafts already exist, the diameter of one large TES bed would be larger than the existing mine shafts, and several beds in parallel would have to be used.

5.4 Insulation Thickness

Referring to Fig. 2a, the design shows a steel cavity wall liner backed by concrete for reinforcement. The TES material is contained and insulated by the insulating firebrick and the space between the firebrick and cavity wall liner is filled (to provide an expandible backing support for the firebrick) by another insulator, diatomaceous earth. Since the firebrick and diatomaceous earth have virtually the same U-factor or rate of heat loss (Btu/ft^2 hr ^{o}F), and the diatomaceous earth is considerably cheaper, sufficient firebrick is required only to give structural support to the rock bed.

Consider, as an example, insulation requirements for a TES unit in a 73-MW$_e$, 12-hr storage system. Now, the thermal stresses induced in granite or limestone approach the ultimate compressive strength at around 400^{o}F, therefore, to minimize cavity wall and liner stresses the liner temperature should be in the 100^o—150^{o}F region or lower. This is achieved by providing three feet of insulation (U-factor = 0.028 Btu/ft^2 hr ^{o}F) between the rock and cavity wall liner. In this case, calculations show that the wall liner and cavity excavation account for about 80 percent of the TES cost. Of this the liner accounts for 50—60 percent and the excavation claims 20—30 percent of the overall TES cost. The liner (steel and concrete) is thus the most expensive item, and hence, as mentioned in the above section, the cavity surface area should be minimized. The TES shape and L/D ratio of the rock bed take this into account.(5) The firebrick container and insulation account for 8—9 percent of the TES cost.

The TES cost is increased by 3—4 percent by providing three feet of insulation (this necessitates a larger cavity to house the insulation) as compared to the TES cost without insulation, but the resulting reduction in heat loss is considerably greater than 3—4 percent. Thus the insulation is cost-effective in terms of TES storage cost up to a thickness of three feet. Further increases in insulation thickness do not save much more heat per cycle, and larger excavation and liner costs are incurred. For example, increasing the insulation thickness from three to four feet decreases the heat loss per cycle for the 12-hour system by 0.3 percent; but increases the TES cost by more than two percent. More importantly, for the weekly cycle (280 MW_{th}, 44 hours of storage), when a 182-foot bed diameter is used, further increases in the insulation thickness beyond four feet would increase the cavity span and possibly require expensive cavity-arch reinforcement.(8) Thus further increases in the TES insulating capacity beyond three feet do not appear justified as the temperature drop due to insulation losses is a few degrees Fahrenheit and the overall heat loss per cycle is around one percent.

5.5 TES Specific Volume and Storage Pressure

The volume required for the TES cavity per unit of electrical energy output; i.e., the energy specific storage volume (ESSV in ft^3/kWh_e) and its variation with storage pressure (atmospheres) between 4 and 44 hours of storage capacity for a 73-MW_e system are shown in Fig. 5. For example, a 73-MW_e system with 12 hours of storage capacity operating at 750^oF (equivalent to 12 atmospheres) has an ESSV of 0.979 ft^3/kWh_e. To achieve the same energy density at eight atmospheres, the storage capacity of the system would have to be increased to 20 hours. The values of the ESSV for a 73-MW_e, two-stage system with 12 hours of storage having an overall pressure ratio of 55, would be 1.26 ft^3/kWh_e for the lower pressure (11 atmospheres) TES; and 1.9 ft^3/MWh_e for the high-pressure (55 atmospheres) TES. If the ESSV calculations were based on the packed-bed volume rather than the TES-cavity volume, the ESSV obtained would be almost half as much in magnitude. Clearly, to lower the TES capital costs ($\$/kWh_e$), the TES-cavity volume per unit of electrical energy output must be reduced. To

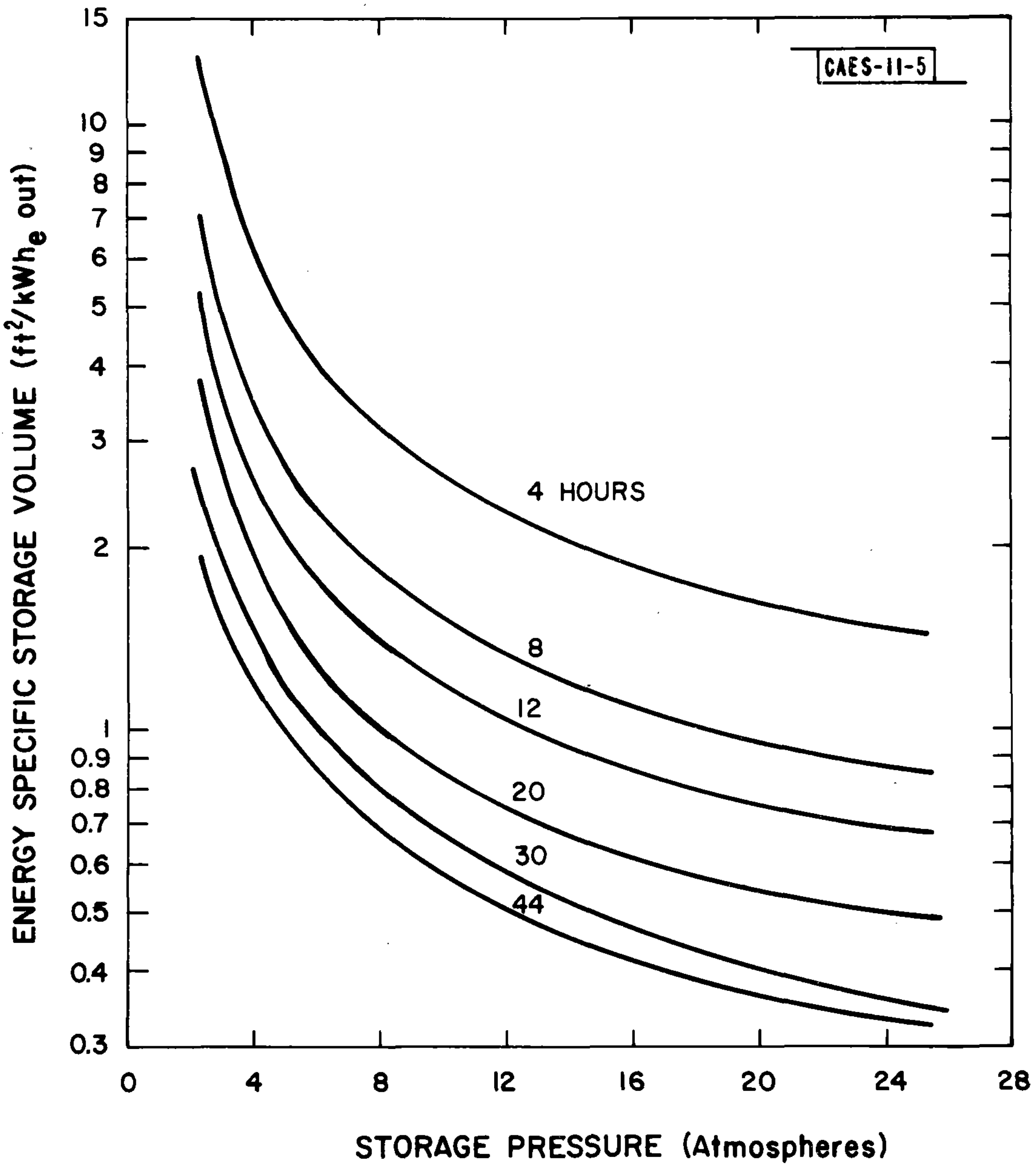

Fig. 5. TES specific volume (ft^3/kWh$_e$ out) vs. storage pressure (atmospheres) for single-stage adiabatic, 73-MW$_e$ system.

achieve this, both the storage pressure (or TES storage temperature) and storage capacity must be increased. Note that although the overall ACAES system capital cost is reduced by going from a single- to a two-stage system,(9) the TES storage capital cost per stage increases.

5.6 TES Capital Cost vs. Storage Pressure and Storage Capacity

Before the TES component cost breakdown is analyzed, a summary of the TES capital costs versus storage pressure and storage capacity is presented in Fig. 6 for a 73-MW_e, single-stage system. Initially, the change in operating pressure does cause a significant reduction in storage capital cost, but above 16 atmospheres the curve becomes very steep, affording little gain in TES cost reduction when measured against the increase in operating pressure. Consequently, when considering the TES element alone, there would be little economic advantage to trying to extend the single-stage compression ratio beyond 16:1, the present limit in single-stage compressors. Instead the benefit of going beyond a

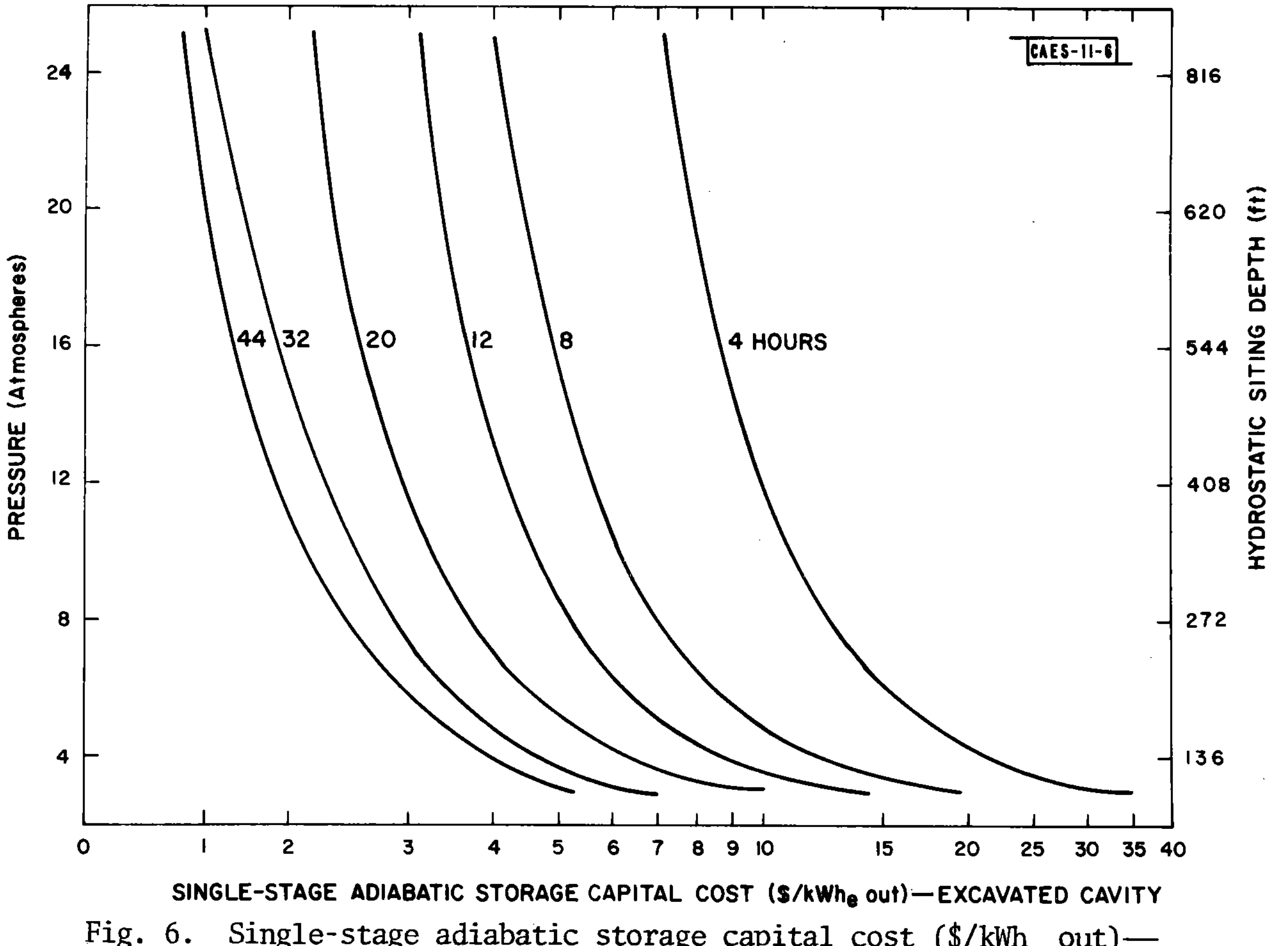

Fig. 6. Single-stage adiabatic storage capital cost ($/kWh$_e$ out)—excavated cavity. Power rating = 73 MW_e out.

16:1 single-stage compression ratio would be realized through the reduction in the underground air cavern volume, and hence, reduction in overall system storage cost.

5.7 TES Component Costs vs. TES Storage Temperature

Figure 7 shows the variation of four TES component costs with input charging temperature for a 73-MW_e, 12-hr storage system. The liner includes the cost of injection grouting in the

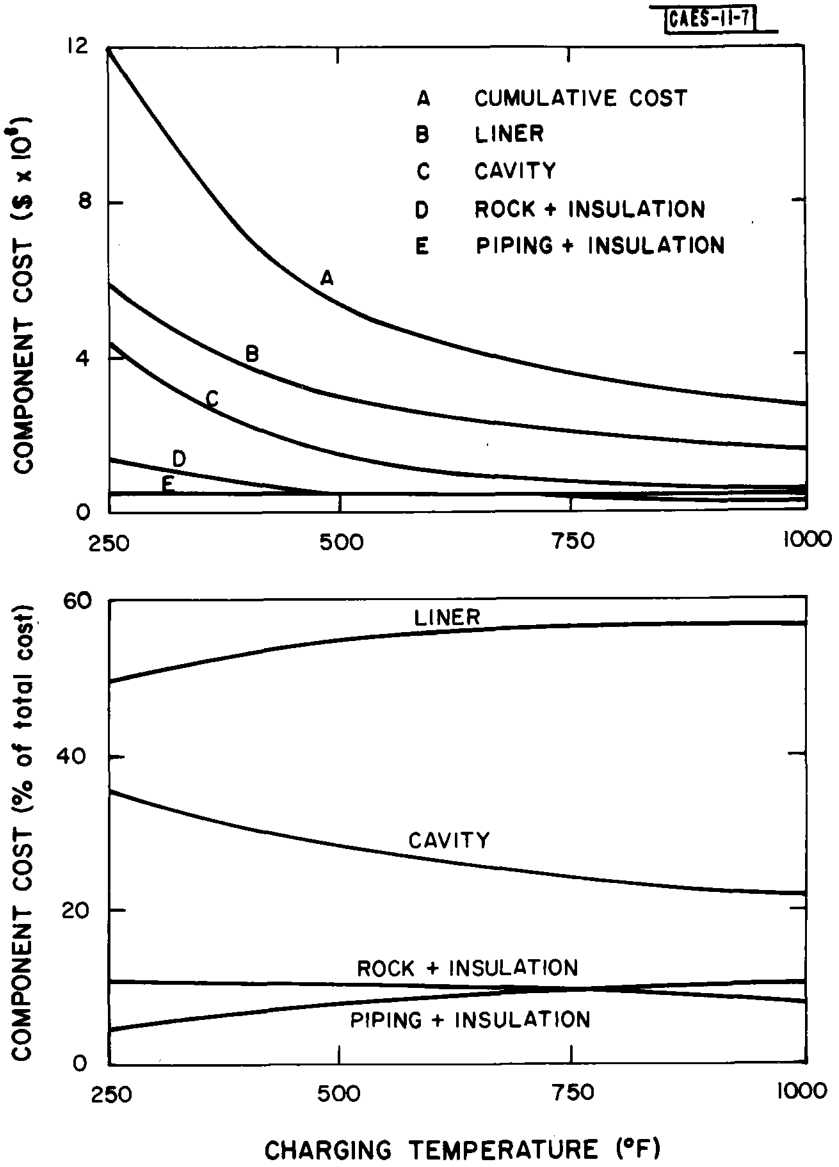

Fig. 7. TES component cost ($\$ \times 10^6$) vs. charging temperature for single-stage adiabatic systems with 73-MW_e power rating and a 12-hr storage capacity.

rock, rock bolting, shotcrete as a base support for the steel liner, and the steel liner itself with welding and construction included. The cavity component is the excavation cost. Rock and insulation refers to the storage material, insulating firebrick, diatomaceous earth, and labor costs. Piping-and-insulation refers to the insulated ducting into and out from the bed. The costs reduce with temperature for a given power rating and storage capacity. The relative cavity excavation cost clearly decreases with increasing bed input temperature and the relative liner cost, which increases from 250°–1000°F, accounts for 57 percent of the overall TES cost at 1000°F. Note that beyond 1000°F, when a cavity liner becomes essential, the relative liner cost and the liner cost hardly change at all.

5.8 TES Component Cost vs. Storage Capacity

In Fig. 8, the variation of TES component cost with storage capacity for a 73-MW_e system operating at 750°F is shown. Although the component costs increase with increasing storage capacity, the relative component costs decrease or level off (with the exception of rock and insulation) with increasing storage capacity. However, the relative liner cost, though reduced with increasing storage capacity, still remains as the dominant cost factor.

Figure 9 is similar to the previous case except that the liner cost has been removed. The container in this case would simply be a steel housing for the packed bed. Now the component costs increase more rapidly with increasing storage capacity, and the relative container component cost decreases with increasing storage capacity. It appears that beyond 3400 MWh_e, the container and rock plus insulation lines will cross.

In Figs. 8 and 9 the relative liner and container costs decrease by some 4 to 5 percent as the storage capacity varies from

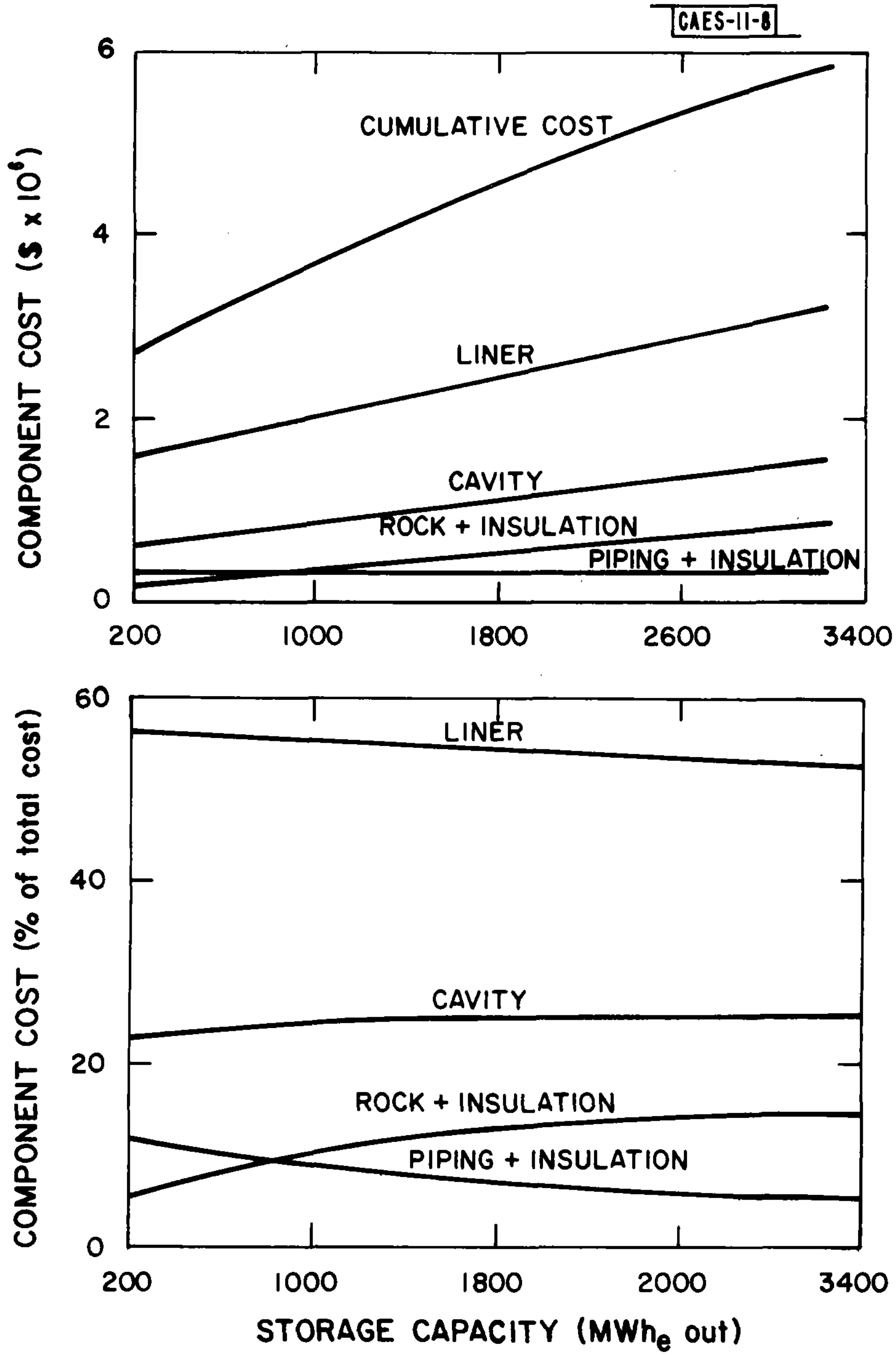

Fig. 8. TES component cost (4 x 10^6) vs. storage capacity (73 MWh$_e$ out) for single-stage adiabatic system with 750°F bed-charging temperature.

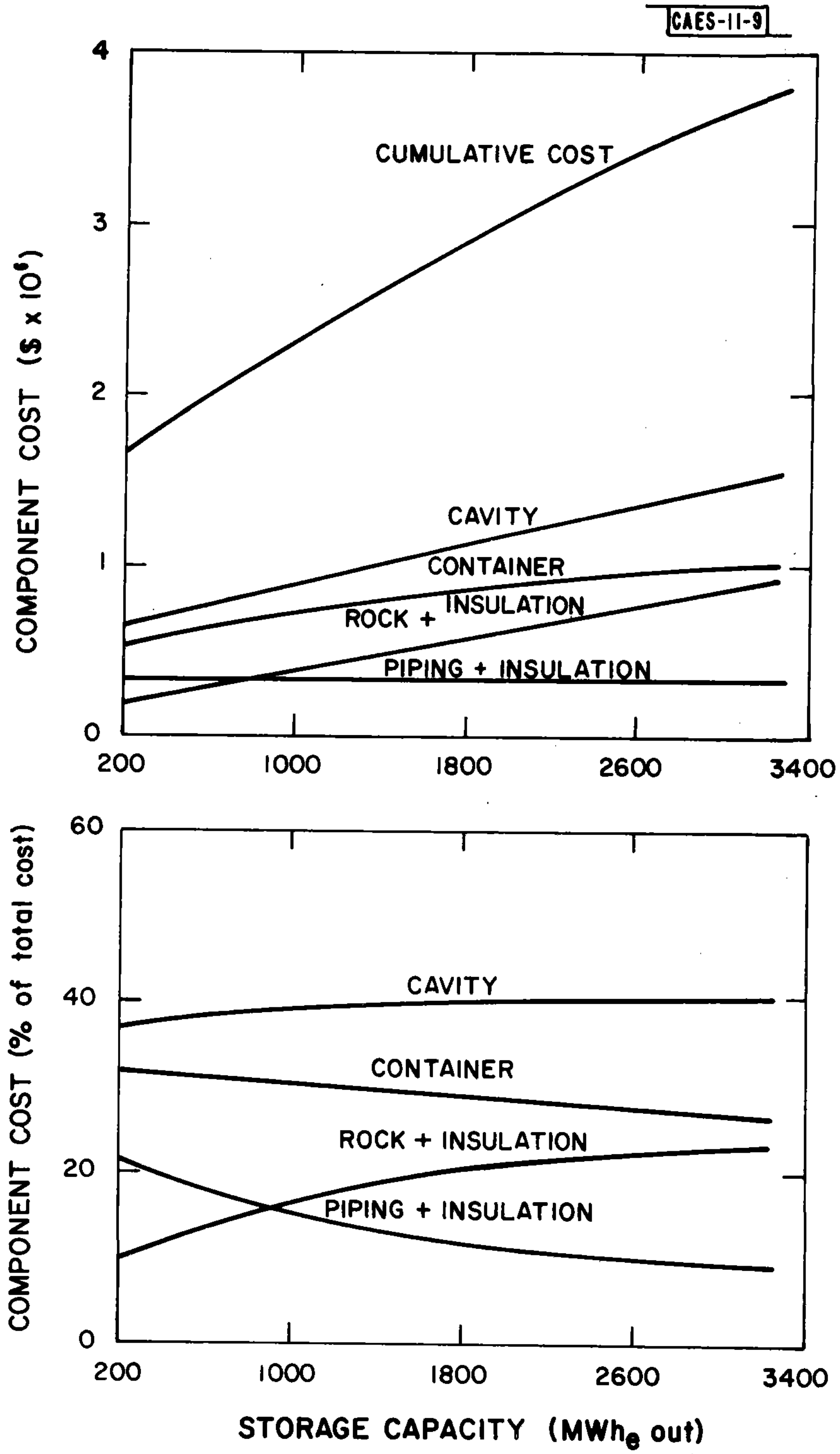

Fig. 9. TES component costs vs. storage capacity (73-MW$_e$ out) for single-stage adiabatic system. No liner used. Bed input temperature = 750°F.

4 to 44 hours. However, in Fig. 9, the container cost does not dominate the overall TES cost and it would clearly be advantageous if the TES cavity liner could safely be omitted. A steel container could be used to house the TES packing.

6. Cost Analysis for TES Siting in an Abandoned Mine [design (b)]

Whether the TES cavities consist of several horizontally mined cavities as shown in Fig. 3 or whether one large TES cavity is used as in Fig. 2a, it is unlikely that a TES unit sited in a single excavated cavity with a large span of 120 feet or more could be built without providing structural support for the cavity ceiling or that the horizontally mined shafts would not require steel or concrete lining.(10) Therefore, a second design type [design (b)] is considered for the abandoned mine case where the cavity is secure and relatively dry and no liner is needed. In this case, the pebble bed is insulated by firebrick and contained in corrugated iron silos.

The results presented in Section 5 concerning the effect of void fraction on TES costs are applicable here, except that the pebbles form a larger fraction of the TES cost (4.8–6 percent). In calculating the effect of the number of beds in parallel on TES cost, the contents of Section 5.3 apply equally to the abandoned mine case, and will not be repeated here.

6.1 Insulation Thickness

Referring to Fig. 3, there is an air gap between the steel container. Heat will be lost to this large volume of air surrounding the TES, and although the air is an excellent insulator, it absorbs the heat and the TES would experience a significant temperature drop per cycle as the air is discharged if it were not additionally insulated. Using a power rating of 73 MW_e and a storage capacity of 12 hours, the insulating costs account for 18 percent of the total TES cost. The metal container represents 51 percent of the TES cost with no excavation required.

In Fig. 10, the heat loss per cycle for a 73-MW$_e$, 12-hr system operating at 750°F, is shown for different bed insulation thicknesses. The corresponding relative TES storage capital cost, defined as,

$$\frac{\text{TES storage capital cost for a given insulation thickness } (\$/\text{kWh}_e)}{\text{TES storage capital cost without insulation } (\$/\text{kWh}_e)}$$

is also shown on the same graph. In looking at the variation of TES cost with insulation thickness, it is seen that the initial increment in TES cost is heavily outweighed by the magnitude of the decreasing heat loss as insulation thickness is increased, and a rapid drop in TES capital cost results. However, between 0.5- and 2-feet insulation thickness, the TES capital cost curve is relatively flat. The minimum is at one foot where a relative reduction of 15 percent in TES costs is achieved. Beyond two feet the TES capital cost begins to increase more rapidly. The overall heat loss per cycle (daily cycle) at 0.7-feet insulation thickness is

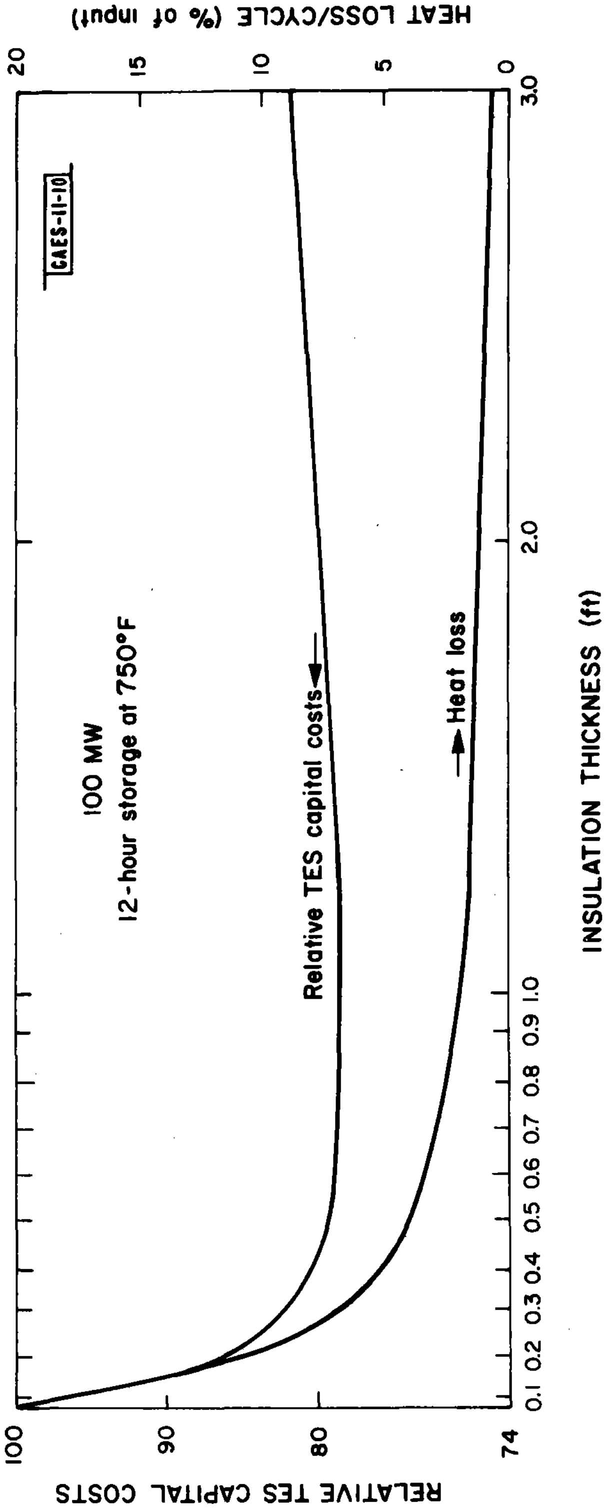

Fig. 10. Optimum insulation for TES: abandoned mine case.

three percent, but at one foot the heat loss per cycle is reduced to just under two percent, which is acceptable. For this design, one foot of insulation is the most economic thickness and very little change in bed temperature occurs (drops a few degrees per cycle). The higher the TES temperature or the greater the TES heat-storage capacity the greater the optimum insulation thickness will be.

6.2 TES Component Costs vs. Storage Capacity

To illustrate the differences in TES costs between the excavated and abandoned mine cases, a graph showing the variation in TES component cost with storage capacity at 750°F for a 73-MW$_e$ system is included in Fig. 11. Note that for an abandoned mine, no excavation costs are present. Again, as with the excavated cost, the component cost increases with increasing storage capacity are linear, but the line slopes are less steep than in Fig. 9. The relative component costs show the rock plus insulation becoming the most expensive item beyond 3400-MWh$_e$ storage capacity.

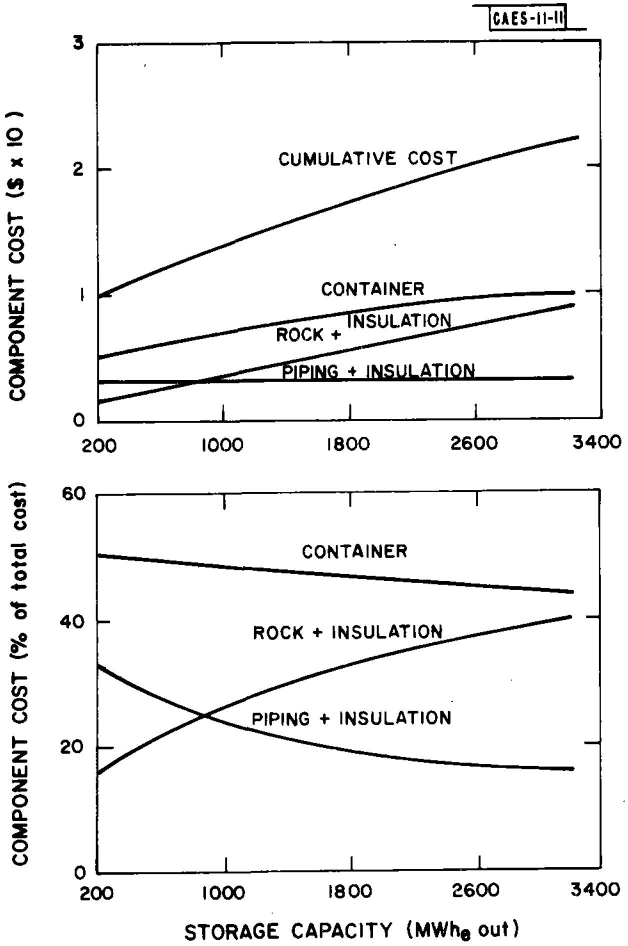

Fig. 11. TES component costs vs. storage capacity (73-MW$_e$ out) for single-stage adiabatic abandoned mine. No liner. 750°F operating temperature.

6.3 TES Siting Comparison Between Surface and Underground Abandoned Mine Sites

The formulation for surface-sited TES units, discussed in Section 5.1 will not be repeated here. Instead, the results of a comparison between a surface and an underground abandoned mine siting are given in Table VI. System specifications (power rating, capacity) are the same as for Table IV.

TABLE VI

UNDERGROUND ABANDONED MINE AND

SURFACE-SITED TES COST ($ x 10^6) COMPARISON

Cycle	Underground TES	Surface-Sited TES	
		Concrete Vessel	Steel Vessel
Daily	1.333	7.0	9.0
Weekly	4.50	68.0	140.0

The disparity between the surface and underground sited TES costs in this case is very large, and it would be difficult to justify a surface-sited TES when an underground abandoned cavity has a suitable space available for the packed bed.

7. Cost Comparison Between an Excavated TES Siting and an Abandoned Mine TES Siting

Three cases:

a. TES siting in an excavated and lined cavity
b. TES siting in an unlined excavated cavity
c. TES siting in an abandoned mine

were considered for comparison in a plot of TES capital cost versus hours of storage for a 73-MW_e system and a storage temperature of 750^oF (Fig. 12). The TES costs are very sensitive to storage capacity between 4 and 20 hours, but after 20 hours the curves tend to flatten out and the relative difference beween the curves is reduced. In examining the similarities between an excavated TES siting and an abandoned mine TES siting in Figs. 5 to 12 it is clear that increasing the storage capacity achieves a lower storage capital cost ($/$MWh_e$). The relative costs of excavation, piping and insulation, and containment costs all decrease with increasing storage capacity and temperature while the rock plus insulation costs increase with storage capacity initially and then

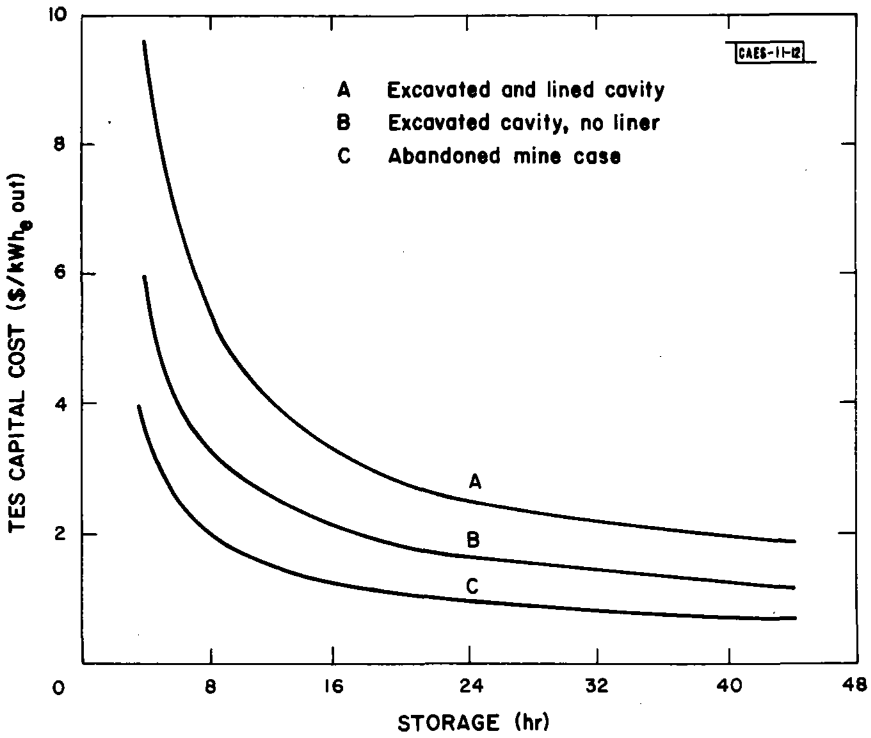

Fig. 12. TES capital costs for 73-MW$_e$, 750^{o}F, excavated and lined, excavated and unlined, and abandoned mine cases.

level off. The relative liner cost (expressed as a percentage of TES cost) is virtually insensitive to the changes in storage capacity.

In looking at the differences between excavated and abandoned mine TES siting costs, the cost ratio between cases a, b, and c given previously is approximately 2.7:1.75:1. The cavity excavation and liner costs virtually dominate the TES costs in case a, which is not true of case c.

Figure 13 shows the variation of TES capital costs ($/kWh$_e$) with the number of hours of storage for different operating bed temperatures. As in Figs. 7 and 8, the TES cost drops with increasing bed input temperature and hours of storage. The abandoned mine case, c, was included for comparison with case a, the TES design requiring cavity excavation and lining for a 49-MW$_e$ system operating at 750^{o}F. At 12 hours of storage, the abandoned mine case costs about half that of the excavated and lined-cavity design. The variation of TES storage capital cost with

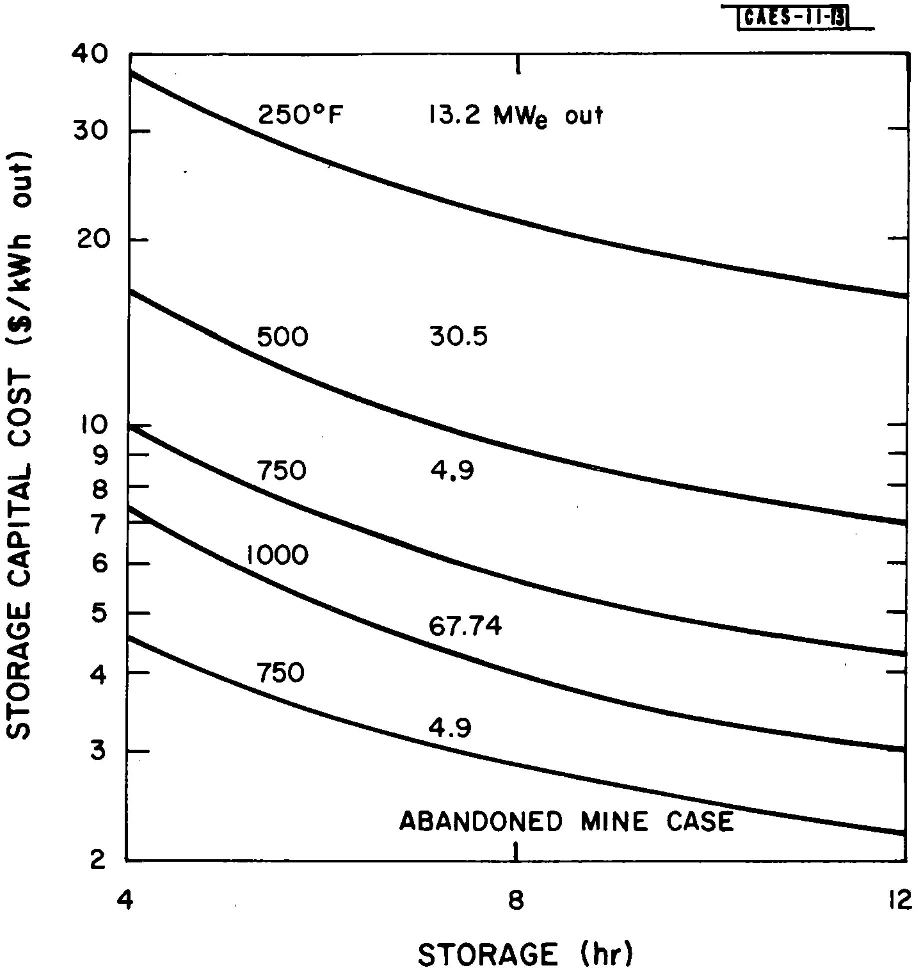

Fig. 13. TES capital costs ($/kWh$_e$) vs. hours of storage for different operating temperatures.

power rating (MW$_e$) shows a rapidly decreasing cost the greater the MW$_e$ rating of the system.

The information in Table VII was drawn from Figs. 12 and 13 and summarizes the differences between cases a and c when the storage capacity and power rating are varied. The operating temperature is held constant, but the flow rate is varied to produce the change in power rating.

The figures under the heading "Storage Capacity" represent the TES cost ($/kWh$_e$). The percentage figures in parentheses represent the relative TES cost reduction in going from 49 to 73 MW$_e$ for a given storage capacity. For case (a) the TES cost reduction is small at 4-hours capacity (5 percent) and does not change much at 12 hours (7 percent). Case (c) shows a consider-

TABLE VII

TES COST COMPARISON ($/kWh$_e$) BETWEEN CASES a AND c

TES Siting (case)	Power Rating (MW$_e$)	Storage Capacity		Relative TES Cost Reduction in Going from 4 to 12 Hours of Storage (%)
		4 hours	12 hours	
	49	10.0	4.3	57
a		(5%)	(7%)	
	73	9.5	4.0	58
	49	4.5	2.4	47
c		(20%)	(37.5%)	
	73	3/625	1.5	58

ably larger cost reduction over the same power range, and a significant increase in the cost reduction in going from 4-to 12-hours capacity (20–37.5 percent). Thus, case (c) enables TES costs to be significantly reduced by increasing the power rating for a given storage capacity. This effect is more pronounced as the storage capacity is increased.

For case (a) there is a 57-percent cost reduction when the storage capacity is increased from 4 to 12 hours for a 49-MW$_e$ plant. A similar figure, 58 percent, is obtained for the TES cost reduction at 73 MW$_e$ when the storage capacity increased from 4 to 12 hours. However, for case (c), the increase in storage capacity for a given power rating does not produce quite as large a cost reduction as with case (a). To sum up, TES costs for cases (a) and (c) are reduced more by increasing the storage capacity than by increasing the power rating.

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