AIR STORAGE PEAKING POWER PLANTS -
UTILIZING MODIFIED INDUSTRIAL
GAS TURBINES AND CAVITIES CREATED
WITH NUCLEAR EXPLOSIVES

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By
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ABSTRACT

Efforts to reduce the cost of peaking power have led to a reconsideration of the air storage type peaking plant. In this peaking plant concept air is compressed and stored in a chamber during low demand periods. During peak demand periods air is withdrawn from the cavity, mixed with fuel, heated in a combustion chamber, and expanded through a turbine producing electrical power. This report summarizes a preliminary economic and technologic assessment of an air storage peaking power plant utilizing a modified industrial gas turbine and air storage cavities created with nuclear explosives.

Cost estimates indicate that the air storage plant based on current gas turbine technology could produce peak power at significant savings over other types of plants, provided: (1) air storage temperature is kept low; and (2) site rock properties are conducive to the production of a high void volume per kiloton of explosive. Cost estimates based on 1980 gas turbine technology indicate that the air storage system is clearly economically competitive to other peaking systems -- even under the worst possible conditions of air storage temperature and rock properties.

INTRODUCTION

Electrical power demands undergo wide daily and seasonal fluctuations. Economic operation of the electrical power supply system requires that large, efficient, nuclear, fossil-fueled and hydraulic power plants operate at high use factors supplying the base load. Currently, peaking plants which employ gas turbines, older steam turbines, special peaking steam turbines, and pumped water storage, are used to supply the fluctuating

portion of the load. Although these peaking plants are characterized by low investment costs, running costs are high and plant factor low. This results in excessive power costs in terms of mills/kw-hr.

Efforts to reduce the cost of peaking power have led to a reconsideration of the air storage type peaking plant which was patented in 1949.^(1,2) One particularly attractive variation of the air storage plant has been recently proposed⁽³⁾ in Sweden. This method utilized an underground compressed air storage cavity between the compressor and combustion chamber of a gas turbine plant. Air is compressed and stored in the cavity during low demand periods. This is done with a compressor driven by a motor taking power from the electrical grid. The compressed air is stored until needed during a peak load period. During a peak period, the air is withdrawn from the cavity, mixed with fuel, heated in a combustion chamber and expanded through a turbine. Near constant pressure is maintained in the cavity with a hydrostatic head. This design has the same capability as the conventional pumped water plant in storing off-peak-power for use as valuable peak power. However, it has the ability to produce additional power by burning fuel in the air as it is withdrawn from storage.

Cost estimates for this system were based on the use of hard rock mining techniques and Swedish economic and technologic conditions. Plant costs were estimated at \$43/kw for a 220 MW plant with a 5 hr/day generating capacity. At off-peak-power costs of 2 mills/kw-hr and 1500 operating hr/yr, production costs would total approximately 6.5 mills/kw-hr. These costs are unquestionably low⁽⁴⁾ in comparison to power costs for other peaking systems.

It has been suggested that nuclear explosives might be applicable to the construction of underground cavities suitable for air storage power systems.⁽⁵⁾ The cost of peaking power from air storage plants based on technologic and economic conditions prevailing in the USA is also of considerable interest due to the increased demand for peaking power. This study was undertaken in an attempt to identify some of the problems and answer some of the questions regarding air storage plants, and in particular, plants using storage cavities constructed with nuclear explosives. This report summarizes the results of that study.

The objective of this study and a plant description will first be discussed. A brief comparison of underground costs using nuclear explosives versus conventional rock mining will then be drawn. Following this several pertinent factors affecting the design and operation of the air storage system will be discussed. These include:

1. Air Storage System Selection
2. Air Storage System Design
3. Current, and Projected, Characteristics and Operating Parameters of Conventional Gas Turbines and Their Relation to Air Storage Peaking Systems

A cost analysis will conclude the report.

STUDY OBJECTIVE

The objective of this study was to make a preliminary economic and technologic assessment of an air storage peaking power plant utilizing a modified industrial gas turbine and air storage cavities created with nuclear explosives. Technologic and economic conditions prevailing in the USA were the basis for the study.

PLANT DESCRIPTION

The plant considered is illustrated in Figure 1. The two primary elements are the modified gas turbine generating unit and the air storage system. The modified gas turbine generating unit consists of a compressor, a turbine, an electrical generator, a burner, and two couplings. The couplings allow the turbine and the compressor to be disconnected from the electrical generator. The air storage system consists of the underground cavities, the drilled and cased holes, the manifold, and the directional valve.

The plant functions in the following manner. During off-peak-power periods, the turbine is disconnected from the electrical generator. The electrical generator is used as a motor (taking power from the grid) to drive the compressor, which in turn pumps air into the cavities. During peak load periods, the turbine is coupled to the electrical generator and the compressor is disconnected. Compressed air from the cavities is

GAS TURBINE GENERATING UNIT

TYPICAL CHIMNEY ELEVATION

CHIMNEY PLAN ARRANGEMENT

FIGURE 1. Air Storage Peaking Power Plant

brought into the burner, heated, and then expanded in the turbine which drives the generator, thereby supplying peaking power to the grid.

The plant under consideration is rated at 174,000 kw and has a 5 hr generating capacity. Six cavities with a total volume of 8,000,000 yd³ are used for air storage. A 2-ft diam. (ID) drilled and cased hole and a 3-ft diam. (ID) manifold are used to transport air to and from each storage cavity. The nominal air storage pressure is 147 lbs/in². Pressure fluctuations during operation are $\pm 5\%$ of the nominal pressure.

In today's conventional gas turbine generating units about 2/3 of the turbine output is used to drive the compressor. In contrast, for the air storage peaking plant, total turbine output is available for generating electricity during the peaking period. The air storage plant then has a generating rating of about 3 times that for the same gas turbine components used in a conventional gas turbine plant. Today's largest industrial gas turbine units have a rating of about 58,000 kw. In the air storage system these same gas turbine components would have a rating of 174,000 kw. The capital cost in \$/kw of peaking capacity for the gas turbine equipment (excluding modification costs) in an air storage plant is, therefore, 1/3 that of a conventional unit.

NUCLEAR EXPLOSIVES VERSUS CONVENTIONAL ROCK MINING

Nuclear explosives were considered in contrast to conventional rock mining techniques because of the potential economic savings. Conventional rock mining costs are difficult to generalize since they depend on the following factors:

- a. Rock type and hardness
- b. Excavation depth
- c. Geographic location
- d. Mining method
- e. Labor rates
- f. Excavation size
- g. Rock support required.

Costs may vary from \$2 to \$47/yd³ of rock removed depending on the above factors.⁽⁶⁾ As an example, total underground cost, including piping, for the Swedish air storage peaking plant, was estimated at \$13.50/yd³ of storage volume based on Swedish conditions. Total storage volume was 180,000 yd³ at a depth of about 1200 ft. As another example of mining costs, total underground costs for a very large pumped hydro system were estimated at \$8.50/yd³, including piping.⁽⁴⁾ Rock removal costs were estimated at \$5.36/yd³ for 9,850,000 yd³ at a depth of 3200 ft. Cost estimates in this last example were based on conditions prevalent in the USA.

In contrast, a 100 kt explosive implanted at a minimum containment depth of 1500 ft would result in costs of \$0.60/yd³ including a 2 ft diam. cased hole for air transport. There are, however, other technical and economic factors which must be considered in addition to the cost/yd³ of storage volume, before the viability of this type of system can be established relative to air storage systems based on conventional rock mining or to other types of peaking systems. These factors will now be discussed in what follows together with a power cost breakdown.

AIR STORAGE SYSTEM SELECTION

The pressure in the air storage system rises as air is pumped into the cavern with the compressor. The pressure decreases as air is withdrawn to drive the turbine. The pressure fluctuation is inversely proportional to cavern volume. A large cavern volume which results in only small pressure fluctuations during operation was selected for the air storage system used in this study. The reason for the selection will be discussed briefly.

Three different types of air storage systems using cavities produced with nuclear explosives are possible (see Figure 2):

1. Small cavity volume with resulting large pressure fluctuations.
2. Small cavity volume with hydrostatic pressurization.
3. Large cavity volume with resulting small pressure fluctuations.

These are illustrated in Figure 2 and are discussed in turn.

TYPE 1 AIR STORAGE - SMALL VOLUME, LARGE PRESSURE FLUCTUATION

TYPE 2 AIR STORAGE - SMALL VOLUME, HYDROSTATIC PRESSURIZATION

TYPE 3 AIR STORAGE - LARGE VOLUME, SMALL PRESSURE FLUCTUATION

FIGURE 2. Types of Air Storage Systems

TYPE 1 STORAGE SYSTEM - SMALL VOLUME, LARGE PRESSURE FLUCTUATIONS

Large pressure fluctuations should be avoided if effective operation is to be achieved. Compressors and turbines operate most effectively at the design pressure ratio. Large departure from the design value could result in poor system efficiency. In addition, if the storage pressure drops continuously during the peaking period, then the available output of the turbine will be a continually decreasing fraction of the rated capacity of turbine. This is particularly undesirable since maximum demand may occur during the latter portion of the peaking duty period. Though actual cost estimates were not made on an air storage system of small storage volumes, with resulting large pressure fluctuations, the decrease in system efficiency would appear to offset the decrease in air storage system capital costs. This, coupled with the continually decreasing available output throughout the duration of the peaking duty period, discouraged further study of this type of air storage system.

TYPE 2 STORAGE SYSTEM - SMALL VOLUME, HYDROSTATIC PRESSURIZATION

The hydrostatic pressurization method allows the use of a small air storage volume, which would appear to offer low cost. However, additional complication and resulting expense is engendered by the hydrostatic pressurization system. First, a water storage reservoir is required and should be of about the same volume as the air cavity. Second, a very large diameter water conduit extending to the bottom of the air storage cavity is required. (This is a 20 ft diam. water conduit for the Swedish study.) The large diameter is necessary to minimize pressure drop losses associated with transporting water into and out of the air cavity. Third, the distance between the reservoir water surface and the cavity water surface must remain nearly constant to minimize pressure fluctuations. Cavities produced with nuclear explosives usually approximate rubble filled hemisphere-capped cylindrical chimneys with a height of the order of 4.5 times the chimney radius. This type of geometry is not conducive to maintaining a constant head. A reduction of 60% in cavity pressure over the duty period could be expected. Fourth, the cavity air pressure resulting from the head must match the pressure (i.e. pressure ratio) required by the gas

turbine components. The minimum head is that specified by the minimum implant depth criteria--to be discussed later. For a 100 kt explosive the minimum head is 660 lbs/in.² which corresponds to a pressure ratio of 45:1. This is not compatible with industrial gas turbine components currently manufactured in the USA which typically have a 10:1 pressure ratio. Maximum pressure ratios of 28:1 are forecast for the early 1980's.⁽⁷⁾ However, this will entail considerable development. In view of these factors it appears that the use of nuclear explosives is not applicable to the construction of underground cavities for hydrostatically pressurized systems.

TYPE 3 AIR STORAGE SYSTEM - LARGE VOLUME, SMALL PRESSURE FLUCTUATIONS

Nuclear explosives appear to be particularly applicable to air storage systems which have large volumes and tolerate small pressure fluctuations. Gas turbine components should tolerate a pressure fluctuation of $\pm 5\%$ of the design pressure without a serious decrease in performance. This approach does require 10 times the storage volume of a hydrostatically pressurized system. However, it has some important advantages. First, it eliminates problems and expense related to a hydrostatic pressurization system and allows siting in arid areas since no water is required for operation. Second, it permits operation beyond the design duty period by increasing the allowable pressure fluctuation. This is a very desirable feature since it provides a wide margin against unexpected peak demand periods which may continue for time periods beyond the design duty period. This characteristic is not available in pumped hydro storage, or hydrostatically pressurized air storage. Once the design capacity is used up due to unanticipated demand periods, these types of systems provide no power towards meeting the demand.

RADIOLOGICAL CONSIDERATIONS

After the initial shot, sufficient time will be allowed for the decay of short-lived radionuclides. Long-lived volatile radionuclides will be mixed with the air that is pumped into the storage chambers. During the peaking duty period this air is discharged through the turbine to the

atmosphere. Since the turbine exhaust gas is hot it will rise as a thermal plume and diffuse in the upper atmosphere. The site will be located some distance from any inhabited area if seismic effects are to be minimized. (For example, a 100 kt device may initiate plaster cracking at distances 4 miles from the site.)⁽⁸⁾ Radionuclide concentrations in the exhaust gases will decrease rapidly with accumulated operating time due to the continual dilution of cavity air with daily additions of new air and the removal of cavity air. These factors should provide adequate conditions for dilution of the radionuclides to well below acceptable levels. Initial dispersion of volatile radionuclides should be somewhat similar to that for natural gas stimulation projects.^(9,10,11) Consider the Wagon Wheel project (5-100 kt) which will have about the same total explosive yield as the air storage plant under consideration. The most significant residual radioactivities expected in the Wagon Wheel cavity are tritium, carbon-14, krypton-85, argon-37, and argon-39.⁽¹²⁾ In the immediate period following detonation, other gaseous nuclides are expected to be present, mainly isotopes of krypton, xenon and radioiodine. They should be considered if re-entry and operation are contemplated within 6 months of detonation. In the case of natural gas stimulation, the volatile radioactive elements pose the most serious problem as the refractory nuclides become trapped in the melt at the bottom of the cavities.⁽⁸⁾

In the Wagon Wheel project 2-1/2 billion standard cubic feet of gas⁽⁹⁾ will be flared over a period of one year. The resulting maximum radiation dose to the nearest local residents (10 miles from the detonation site) is estimated to be about 1% of the natural background radiation (130 mrem/year). For the air storage plant 2-1/2 billion standard cubic feet of air (resulting in one complete flush of the caverns) will be circulated through the caverns in about a 10 day period. During the first few days of operation of the air storage plant the daily dose rate via direct exposure routes would appear to be somewhat higher than in the case of the Wagon Wheel flaring operation. However, after the first few operating days, the daily dose via direct routes would decrease dramatically due to flushing of the caverns. Flushing of two or three cavity volumes of air should reduce the concentration of volatile radioactive elements in the discharge air by 95%.⁽⁸⁾

The yearly dose rate should, therefore, not be significantly higher than estimated for the Wagon Wheel project.

Further detailed analysis of this subject, including potential ground-water contamination problems, will be required to insure safe operation. However, the details are beyond the scope of this study and will not be taken up in this initial assessment.

AIR STORAGE SYSTEM DESIGN

The air storage system consists of the underground cavities (rubble filled chimneys), the drilled and cased holes for air transport, the manifold connecting the cavities to the gas turbine, and the directional valve which controls flow to and from the cavity. Important factors which must be considered in the design of the air storage system include:

1. Total Air Storage Volume Required
2. Size of Nuclear Explosives
3. Number of Nuclear Explosives, Implant Depth, and Rock Properties
4. Geological Formation
5. Diameter of Implant Hole
6. Diameter of Postshot Hole for Air Transport and Manifold Piping
7. Vertical or Horizontal Arrangement of Cavities

STORAGE VOLUME

The storage volume must be matched to the gas turbine components and the peaking duty period. The approach taken in this study was to use the parameters typical of today's largest industrial gas turbine generating units as a base for making technologic and economic calculations. (Calculations were also made using projected 1980 gas turbine technology.) The following parameters are somewhat typical of those found in the literature for today's gas turbines and are assumed for calculations based on 1973 gas turbine technology:^(7,17)

Conventional Gas Turbine Output	58,000 kw
Pressure Ratio = P_r	10:1
Turbine Inlet Temperature - T_h	1600°F = 2060°R
Compressor and Turbine Efficiencies - $\eta_c = \eta_t$	87%

The total underground volume is fixed by the mass flow through the gas turbine, the generating period, the temperature and pressure of the stored gas, and the allowable pressure fluctuation.

The pressure of the stored air is set by the pressure ratio required by the gas turbine. For today's technology this corresponds to $10 \times 14.7 = 147 \text{ lbs/in}^2$. The optimum allowable pressure fluctuation would depend on a trade off between off-design turbo-machinery performance and underground capital costs. For the purpose of this study the allowable pressure fluctuating was set at $\pm 5\%$ of the design pressure. This value is only a reasonable estimate of the optimum. Since underground costs are a large portion of the total capital costs, further study on the optimum allowable pressure fluctuation would be worthwhile.

The air storage temperature is primarily dependent on the temperature of the rubble in the chimney. The temperature of the rubble in a chimney a few months after a shot will probably be fairly uniform with the exception of the bottom part of the chimney. The bottom of the chimney may be several hundred degrees °C hotter. Natural convection of steam tends to equilibrate the temperature.

At the same time that temperature equilibration is proceeding in the chimney, the chimney is losing thermal energy to the surrounding rock of the earth via conduction. This is a very slow process due to the low thermal conductivity of the surrounding rock and the high heat capacitance of the chimney rubble. Cooling of the entire chimney to near preshot temperature may require several years, depending on the size of the yield, thermal properties of the rock, etc. Studies of the Wagon Wheel project indicate that the average temperature of the chimney rubble a short time after the shot could be on the order of 200-800°C.⁽¹²⁾ As pointed out in Reference 12 the temperature is strongly dependent on explosive spacing, energy distribution, and depth of implantation. For example, if we assume the use of five - 100 kt explosives in a single vertical hole at an average depth of 10,000 ft, a spacing of 6 times the cavity radius, and 60% of the explosives heat being dissipated in the chimney rubble then the estimated rubble temperature is 420°C. For the purpose of evaluating the effect on

plant costs of gas storage temperatures, two values were considered. In the first case the chimney was assumed to have cooled back to preshot temperature - 120°F was assumed. In the second case the chimney was assumed to be of the order of the compressor discharge temperature 660°F. This value is close to that expected for the Wagon Wheel project under the above described conditions.

In the first case the hot air from the compressor is cooled as it contacts the assumed cold rubble. Less storage volume is required in this case, but more fuel is required to heat the air to a given turbine inlet temperature.

In the second case, the hot air from the compressor is near the temperature of the chimney rubble, therefore, little heating or cooling of the gas occurs. (After a long period, on the order of years, the rubble will reach some equilibrium temperature such that the heat transfer from the compressor discharge air to the chimney rubble will equal the heat transfer from the chimney rubble to the surrounding rock.) This case will require more storage volume, but less fuel than the assumed cold rubble case. Our study indicated that the reduction in fuel costs for the second case does not offset the increased underground capital costs.

The mass flow, $\dot{m}$, can be determined from the following simplified relation for gas turbine shaft power under conventional operation:

Power (conventional) = Turbine output - Compressor input

$$= \dot{m} c_p T_h \left[n_\tau \left(1 - P_r^\gamma \right) - \frac{T_L}{T_h n_c} \left(P_r^\gamma - 1 \right) \right] \quad (1)$$

$$c_p = 0.24 \text{ Btu/lbm-}^\circ\text{F}$$

$$T_L = 80^\circ\text{F} = 540^\circ\text{R}$$

$$K = 1.4$$

$$\gamma = \frac{k-1}{k}$$

Knowing the mass flow we can calculate the required storage volume:

$$V(\text{storage}) = \frac{MR T_c}{R} \quad (2)$$

$$M = \dot{m} \times \Delta t \times F_p \quad (3)$$

$$R = 53.34 \frac{\text{ft-lbf}}{\text{lbm-}^\circ\text{R}}$$

Δt = duty period

F_p = ratio of air mass in storage/air mass cycled
each duty period

= 10 for $\pm 5\%$ pressure cycling

$$P = P_{\text{atmosphere}} \times P_r, P_a = 14.7 \text{ lb/in}^2$$

$$T_c \begin{cases} 120^\circ\text{F cold cavity} \\ 660^\circ\text{F hot cavity} \end{cases}$$

SIZE OF EXPLOSIVES

The maximum size of a nuclear explosive for an air storage system is limited by seismic effects. For an example of seismic effects, literature indicates a 100 kt explosive may initiate plastic cracking at distances less than 4 miles from the shot.⁽⁸⁾ It, therefore, appears that air storage peaking plants could be installed at a large number of sites if the explosive size is limited to 100 kt.

The cost per explosive is given approximately by:

$$C = 241,300 + 108,700 \log_{10} W^{(8)} \quad (4)$$

W = yield in kilotons

The cost per explosive is only slightly dependent on its size. Economic considerations, therefore, dictate that the largest size explosive within seismic limitations be used. A 100 kt explosive size was selected for this study since the resulting seismic effects appear to be tolerable at a large number of sites. Larger sizes could be considered for remote areas.

NUMBER OF EXPLOSIVES, IMPLANT DEPTH, AND ROCK PROPERTIES

The number of explosives required depends on the size of the explosive, the depth of implantation, the rock properties, and the total volume required. The void volume generated by each explosive depends on the yield, the depth, and the rock characteristics according to the following relation:

$$\text{Vol/exp} = \frac{4\pi}{3} R_c^3 = \frac{aw}{h^b} \text{ ft}^3 \quad (13) \quad (5)$$

R_c = Initial void radius - ft

k = Implant depth - ft

w = Yield in kt

The rock parameters a and b depend on grain density, water content, and porosity.

Rock that has low grain density, high water content, and high porosity will produce a larger void volume for a given yield and implant depth than rock which has inverse properties. For example, rock which has properties conducive to the formation of high void volume/kt, i.e.:

grain density = 2.40 g/cm^3

water content = $0.15 \text{ wt fr H}_2\text{O}$

porosity = 0.30 vol fr

results in values for a and b of:

$$a = 2.101 \times 10^5$$

$$b = 0.87$$

for $W = 100 \text{ kt}$, and $h = 1522 \text{ ft}$ (minimum implant depth)

$$\text{Vol/exp} = 35.8 \times 10^6 \text{ ft}^3$$

Whereas, rock that has properties not conducive to high void volume/kt, i.e.:

grain density = 2.80 g/cm^3

water content = $0 \text{ wt fr H}_2\text{O}$

porosity = 0 vol fr por

gives

$$a = 2.265 \times 10^5$$

$$b = 1.011$$

for $W = 100$ kt, and $h = 1522$ ft

$$\text{Vol/exp} = 13.7 \times 10^6 \text{ ft}^3$$

The point of this discussion on rock characteristics is that high density rock with low porosity and water content may require 2 to 3 times as many explosives (plus additional drilling) to obtain the same air storage volume as would low density rock with high porosity and water content.

Other major factors affecting the design, construction, and resulting cost of the underground storage is the minimum depth of emplacement. The depth must be adequate to contain the initial explosive and also prevent growth of the chimney to the surface. Cavities produced with nuclear explosives approximate rubble filled, hemispherical-capped cylindrical chimneys with a height on the order of 4.5 times the chimney radius. The chimney is produced in this manner. The initial explosive creates a void in the rock. Sometime after void growth stops, the rock above the void collapse into the void. The upward growth of the chimney continues until it bulks full, or until a structurally sound arch is formed. The initial void volume is equal to the void volume distributed throughout the chimney. It is this void volume which serves as the air storage for the system under consideration. The depth must also be adequate to prevent continuous fractures from penetrating the surface. Literature indicates that containment can be achieved if the depth is:

$$h \geq 328 W^{1/3} \quad (13) \quad * \quad (6)$$

Literature also indicates that chimney height is of the order of 4.5 times the initial cavity radius, and that fracture radius is of the same order. (13,14)

*Reference 13 gives two slightly different values for the minimum implant depth for containment - $h \geq 350 W^{1/3}$ ft (page 2), and $h \geq 100 W^{1/3}$ m = $328 W^{1/3}$ ft (page 33). The values given by equation (6) are used in this report for calculational purposes.

Drilling costs for bore diameters 12" and larger appear to be linearly related to depth.^(14,15) Economics discourages implant depths greater than the minimum for containment.

GEOLOGICAL FORMATION

A geological formation with very low permeability is required to reduce leakage from the air storage cavities to an insignificant value. As previously discussed the rock in the geological formation should have a low grain density and a high water content to obtain a high void volume per kiloton of explosive. A recently published report by the United States Geological Survey gives the relative permeability of various rock types.⁽¹⁶⁾ A shale rock formation appears to be a suitable type since it has low permeability, moderate grain density, contains moisture, and is widely found. Metamorphic rock and bedded salt formations may also prove satisfactory.

DIAMETER OF IMPLANT HOLE

The implant hole must have an inside diameter large enough to allow passage of the explosive. The 100 kt devices to be used in the Wagon Wheel natural gas stimulation project are to be implanted in a 10 3/4 in. ID bore hole.⁽⁹⁾ References 13 and 14 indicate that drilling costs above 12 in. increase more than proportionally with diameter. However, for the standard size oil and gas wells below 12 in. dia. no correlation between diameter and cost is apparent. Therefore, for this study, 12 in. was assumed to be the minimum implant hole diameter.

VERTICAL VERSUS HORIZONTAL CAVITY ARRANGEMENTS

Multiple explosives may be vertically spaced in a single implant hole, or spaced horizontally in separate implant holes at the same minimum implant depth. Vertically spaced explosives must be spaced at intervals which will result in interconnected chimneys. At the same time sufficient containment must be provided to insure void formation through the compression of the surrounding rock. Detonation of the top explosive would occur first, and then the next lowest, and so on. This would prevent the upward growth of a lower chimney into the zone of the

above undetonated explosive which might occur if the detonation order were reversed. A vertical spacing of $3 R_C$ was assumed in the costing, further study would be needed to establish that this is adequate. If the vertical spacing were increased to $6 R_C$ then reversing the order of detonation may be possible.

Horizontally spaced explosives must also be placed at large enough intervals which will provide adequate containment for void formation. A value of $4.5 R_C$ was assumed in the costing. Further study would be needed to establish that this is adequate.

Since the void volume generated by each explosive decreases with depth, more than twice as many explosives are required with multiple vertical placement than if the explosives were placed in separate holes in a horizontal arrangement. Since explosive costs are the major part of underground costs, the horizontal system is more economical. It was selected for final system costing. Other arrangements employing combined vertical and horizontal spacing are possible but were not considered in depth in this study.

DIAMETER OF AIR TRANSPORT HOLE AND MANIFOLD PIPING

After the decay of short-lived radionuclides, a post shot drill hole will be made to the roof of each chimney. This hole will be used to transport air to and from the rubble filled chimney (or cavity).

The pressure drop in the manifold and in the air transport hole is a strong function of the diameter of these components. For the pressure drop between the compressor and the cavity we have from the familiar relationship for pipe flow:

$$\Delta P_{in} = \frac{\dot{m}^2 16}{\rho_{in} g \pi^2} \left[\left(\frac{f L}{D^5} \right)_{\text{manifold}} + \left(\frac{f L}{D^5} \right)_{\text{air transport hole}} \right] \quad (7)$$

For pressure drop between the cavity and the turbine we have:

$$\Delta P_{out} = \frac{\dot{m}^2 16}{\rho_{out} g \pi^2} \left[\left(\frac{f L}{D^5} \right)_{\text{manifold}} + \left(\frac{f L}{D^5} \right)_{\text{air transport hole}} \right] \quad (8)$$

where,

L = hole or manifold length
 D = hole or manifold diameter
 f = friction factor
 ρ = air density
 $\dot{m}$ = mass flow rate

The effect of these pressure drops is an equivalent reduction in the efficiency of the compressor and turbine:

$$\eta_c(\text{total}) = \eta_c(\text{conventional}) \times \eta_c(\Delta P)$$

$$\eta_t(\text{total}) = \eta_t(\text{conventional}) \times \eta_t(\Delta P)$$

$$\eta_c(\Delta P) = \frac{\text{Compressor input--no } \Delta P}{\text{Compressor input--}\Delta P} = \frac{P_r^{\gamma-1}}{\left(P_r + \frac{\Delta P_{in}}{P_a}\right)^{\gamma} - 1} \quad (9)$$

$$\eta_t(\Delta P) = \frac{\text{Turbine output--}\Delta P}{\text{Turbine output--no } \Delta P} = \frac{1 - \left(P_r - \frac{\Delta P_{out}}{P_a}\right)^{\gamma}}{1 - \frac{1}{P_r^{\gamma}}} \quad (10)$$

These relations can be combined with the capital and variable costs for power (presented later) to obtain the optimum air transport hole and manifold diameters which result in minimum power costs. This will be discussed further in the section on power costs.

GAS TURBINE CONSIDERATIONS

A modified gas turbine generating unit is a primary element in the air storage plant. Currently, a typical industrial gas turbine generating unit in the USA consists of a compressor and turbine on a single shaft. Multiple combustion chambers are arranged symmetrically in an annular region near the compressor discharge and turbine inlet.

In the air storage plant the compressor and turbine function at different time periods and must, therefore, be on different shafts. To minimize mechanical coupling the generator should be located between the compressor and the turbine. The resulting modified gas turbine is illustrated in Figure 1. In addition to splitting the compressor and turbine shafting, the outer casing on the turbine and compressor would need to be split. These modifications would not require major development work and should not increase the cost of the gas turbine by more than 10%. (This estimate is based on component cost breakdown information in Reference 7.)

Industrial gas turbines currently operate at the following typical conditions:^(7,17)

Pressure ratio	= 10:1
Compressor and Turbine Efficiencies	= 85-90%
Turbine Inlet Temperature	= 1600-2000°F
Thermal Efficiency (Based on HHV of Fuel)	= 20-27%

Advances in gas turbine technology will result in higher pressure ratios, higher turbine inlet temperatures, and a moderate increase in compressor and turbine efficiencies. Overall thermal efficiency will increase significantly as well as specific output.

At this point in the discussion of current and projected gas turbine characteristics, we must investigate the potential of optimizing gas turbine operating parameters for the type of air storage system under consideration. First, we must examine the effect of each parameter on

system performance, and second, we must consider where development beyond that proposed for conventional gas turbines may be economically beneficial.

TURBINE INLET TEMPERATURE

Increasing the turbine inlet temperature will increase the specific output of the air storage plant turbine and increase overall system efficiency. However, as turbine inlet temperature is increased air density is reduced and the size of the turbine and burner flow areas must be increased to maintain the same mass flow. Higher temperature materials must also be used in the turbine and burner. Changes in the compressor and air storage system are not required; however, the cost/kw of output charged to the compressor and air storage system are reduced due to increased turbine output.

In conventional gas turbines the optimum turbine inlet temperature for a given time frame is set primarily by a trade off between increased turbine costs and increased output and efficiency. By early 1980, turbine inlet temperatures for conventional gas turbine generating units are forecast to be as high as 2600°F.⁽⁷⁾ The optimum turbine inlet temperature for air storage plants in any particular time frame may possibly be higher than it is for conventional gas turbine systems. Additional study would be required to verify this.

COMPRESSOR AND TURBINE EFFICIENCIES

Higher compressor and turbine efficiencies result in higher turbine output and lower required compressor input. These factors drive capital, operation and maintenance (O&M), fuel and off-peak-power costs (in mills/kw-hr) down. Considerable effort has been and is currently being made to improve compressor and turbine efficiencies of conventional units. Compressor and turbine efficiencies of 92% are forecast for the early 1980's.⁽⁷⁾ Increases beyond this point are expected to be small. The incentive for additional development to improve compressor and turbine efficiencies in behalf of air storage systems does not appear to be warranted.

PRESSURE RATIO

For a given load factor, conventional gas turbine generating units (with fixed turbine inlet temperature and fixed compressor and turbine efficiencies) have an optimum pressure ratio for minimum power costs. This optimum pressure ratio lies somewhere between the pressure ratio corresponding to maximum specific output and the pressure ratio corresponding to maximum efficiency. See Figure 3. As turbine inlet temperature is increased through materials research, corresponding increases in pressure ratio must be made to obtain high thermal efficiency. Pressure ratio values for the early 1980's for industrial gas turbine generating units are expected to be between 15:1 and 28:1 depending on the load factor.⁽⁷⁾ Values of 15:1 would be used for load factors of 20%. Whereas values of 28:1 would be used for load factors of 70% in order to minimize power costs.

For the air storage plant increasing the pressure ratio will result in: (a) higher specific turbine output, and (b) higher specific compressor input. These factors drive fuel and O&M costs down. Off-peak-power costs rise since increased compressor input more than offsets increased turbine output. At higher pressure ratios, less air mass is required for a fixed total output, and the air is stored at higher pressure. As a result storage volume is reduced. Air transport hole diameter is reduced since decreased mass flow rates and increased density give a smaller diameter for a fixed pressure drop. The result is lower air storage system costs.

On the other hand, increasing the pressure ratio requires more stages and thicker casing for the compressor and turbine. Higher temperature materials, or intercooling, will be required in the compressor. These factors result in increased capital costs of the turbo-machinery which may or may not be offset by the decrease in air storage system capital costs, and the decrease in fuel and O&M costs.

Further study to optimize the pressure ratio for an air storage plant for minimum power cost in a given time frame is needed--but beyond the scope of this study. However, simultaneous changes in all gas turbine operating parameters are going to occur in the next decade and

FIGURE 3. Conventional Gas Turbine
Performance Vs. Pressure Ratio

cost estimates of the resulting gas turbine generating units are available.⁽⁷⁾ Some understanding of the effect of this simultaneous improvement can be obtained by costing an air storage plant on the basis of costs and operating parameters for these advanced gas turbine generating units. Comparisons to systems based on current gas turbine technology can then be made and the effect of improved technology can be evaluated. This will be done as part of the cost analysis which is the next item of discussion.

POWER COSTS

Air storage plant power costs are composed of capital charges, operation and maintenance charges (O&M), fuel costs, and off-peak-power costs (OPP).

$$\text{Power Cost} = \text{Capital} + \text{O\&M} + \text{Fuel} + \text{OPP} \quad (11)$$

These costs are discussed in detail for a plant based on current gas turbine technology and a 5 hr duty period. Rock properties which result in large void volumes for a given yield are assumed. The chimney rubble temperature is assumed to be 120°F and to correspond to air storage temperature.

Summarized power costs for other potential operating conditions such as early 1980 gas turbine technology, longer duty periods, different rock properties, and high air storage temperature are also considered.

CAPITAL COSTS

Capital costs include those associated with the gas turbine generating unit and those associated with the air storage system. Gas turbine generating unit costs include the cost of the conventional gas turbine, modification costs, and the costs of the generator. Air storage system costs include explosive costs, implant hole costs, postshot air transport hole costs, and manifold costs. (All hole costs are based on cased holes.) Land costs and seismic damage costs were not considered in this study. Fixed charges of 15% were assumed. A load factor of 20.8% (5 hr/day at full load) was assumed.

For the gas turbine generating unit we have:

Conventional Gas Turbine Costs ^(18,19)	\$77.6/kw
Modification Costs (Assumed 10% of G.T. costs)	<u>7.8/kw</u>
Total	\$85.4/kw

In today's conventional gas turbine generating units about 2/3 of the turbine output is required to drive the compressor.

$$\text{Power (Conventional)} = \text{Turbine Output} - \text{Compressor Input}$$

In the air storage plant, total turbine output is available for generating electricity during the peaking period.

$$\text{Power (Air Storage Plant)} = \text{Turbine Output}$$

The uprated capacity of the air storage plant can be evaluated in terms of the conventional plant as follows:

$$\begin{aligned} & \text{Power (Air Storage)} \\ &= \text{Power (Conventional)} \times \frac{\text{Turbine Output}}{\text{Turbine Output} - \text{Compressor Input}} \\ &= \text{Power (Conventional)} \times \frac{n_{\tau} (1 - \text{Pr}^{-\gamma})}{n_{\tau} (1 - \text{Pr}^{-\gamma}) - \frac{T_L}{T_h n_c} (\text{Pr}^{\gamma} - 1)} \\ &= \text{Power (Conventional)} \times \text{Uprated Capacity Factor.} \end{aligned}$$

For 1973 gas turbine technology, we have:

$$\text{Power (Air Storage Plant)} = 3.01 \times \text{Power (Conventional)}$$

For the air storage plant the capital cost/kw for gas turbine components is thus reduced proportionately by the uprated capacity factor. For the air storage plant we then have:

Air Storage Plant Gas Turbine Costs	\$28.4/kw
Generator Costs ⁽⁷⁾	<u>10.0/kw</u>
Total	\$38.4/kw

Here the generator costs remain the same in \$/kw as for the conventional plant.

For the air storage system we have:

Explosives (6-100 kt)		\$15.8/kw
Drilling and Piping		
Implant Hole Costs ^(14,15)	\$ 6.6/kw	
Postshot Air Transport Hole Costs ^(14,15)	4.0/kw	
Manifold (Assumed \$30/ft Installed)	<u>0.9/kw</u>	
Subtotal	\$11.5/kw	<u>11.5/kw</u>
	Total	\$27.3/kw

Fixed capital charges for the air storage plant were assumed to be 15% per annum. Capital charges for the air storage plant are therefore:

$$\begin{aligned}
 \text{Capital Charges (mills/kw-hr)} &= \frac{\text{Capital Costs in \$/kw} \times 0.15 \times 10^3}{5 \text{ hr/day} \times 365 \text{ days/yr}} \\
 &= \text{G.T. Generating Unit} + \text{Explosives} + \text{Drilling and Piping} \\
 &= \quad 3.16 \quad + \quad 1.30 \quad + \quad 0.95
 \end{aligned}$$

OPERATING AND MAINTENANCE COSTS

Operating and maintenance costs were estimated on the basis of O&M costs for projected base loaded gas turbine generating plants.⁽⁷⁾ These cost estimates were corrected for the decreased load factor and uprated capacity of the air storage plant. A 20.8% load factor (corresponds to a full load, 5 hr duty period) was assumed for the air storage plant. Making the corrections for the air storage plant then we have:

$$\begin{aligned}
 \text{O\&M Costs} &= 0.7 \times \text{Load Factor Correction} \times \text{Uprated Capacity Factor} \quad (13) \\
 &= 0.7 \times \frac{0.70}{0.208} \times 3.01 \\
 &= 0.71 \text{ mills/kw-hr}
 \end{aligned}$$

FUEL COSTS

Gas turbine fuels include gaseous fuels such as natural gas, butane, and propane, and liquid fuels such as distillate and residual oils. Residual oils are limited to low turbine inlet temperatures due to ash deposition, etc. Prices for gaseous and liquid fuels vary with geographical location. Prices in general will increase with time. Though cost analysis could have been based on any of these fuels, natural gas with a higher heating value of 1000 Btu/ft³ was assumed for this study. A price of 30¢/10⁶ Btu was also assumed. Since fuel costs represent only 20% of the total power production costs significant changes in the fuel cost could occur without altering power costs a great deal.

The fuel cost is somewhat dependent on air storage discharge temperature--as are underground storage capital costs. The higher the air storage temperature the lower the fuel costs. For this particular case a storage temperature of 120°F was assumed. For fuel cost then we have:

$$\text{Fuel Cost} = \frac{\text{Heat Input}}{\text{Turbine Output}} \times \text{Fuel Cost} \quad (14)$$

$$\begin{aligned} \text{Fuel Cost} &= \frac{T_h - T_c}{n_T T_h (1 - P_r^{-\gamma})} \times \frac{300}{10^6} \text{ mills/Btu} \times 3413 \text{ Btu/kw-hr} \quad (15) \\ &= 1.75 \text{ mills/kw-hr} \end{aligned}$$

OFF-PEAK-POWER COST

Off-peak-power is required to drive the compressor during the off-peak period. The cost to the air storage plant for this off-peak-power should be approximately equal to the fuel cost for the base load plant supplying the power. This may be of the order of 2 to 4 mills/kw-hr depending on whether the plant is nuclear or fossil fueled, the time frame, etc. Off-peak-power for this case was taken to be 2 mills/kw-hr. This must be multiplied by the ratio of power consumed by the compressor to power produced by the turbine to obtain the portion of total power costs attributed to off-peak-power requirements:

$$\text{OPP Costs} = 2 \text{ mills/kw hr} \times \frac{\text{Compressor Input}}{\text{Turbine Output}} = 2 \times \frac{\frac{T_L}{n_c} [P_r^{\gamma}-1]}{T_h n_\tau (1-P_r^{-\gamma})} \quad (16)$$

$$= 2 \times 0.67 = 1.335 \text{ mills/kw-hr.}$$

COST CORRECTIONS DUE TO AIR TRANSPORT PRESSURE DROP

Pressure drop in the manifold and air transport hole reduce the turbine and compressor performance as described in Equations 7, 8, 9, and 10. This loss in performance can be reduced by increasing the manifold and air transport hole diameters. However, this is done at increased capital cost of the manifold and air transport hole. The trade off for minimum power costs occurs at a manifold diameter of 3 ft and an air transport hole diameter of 2 ft.

The costs given thus far do not include the effect of decreased compressor and turbine performance. For the case under consideration we have $\eta_T(\Delta P) = 0.988$ and $\eta_C(\Delta P) = 0.961$. Making the corrections we have:

[illegible]

SUMMARIZED POWER COSTS FOR POTENTIAL OPERATING CONDITIONS

The preceding detailed cost estimate was based on the following conditions:

- a. 1973 Gas Turbine Technology
- b. Rock Properties with large void volume/kt
- c. 5 hr peaking duty period
- d. 120°F air storage temperature - cold rubble
- e. 2 mills/kw-hr for OPP.

Other conditions are possible. Using the above as a base the following were considered and are summarized in Table 1:

1. 8 hr peaking duty cycle
2. Low void volume/kt rock properties
3. 660°F air storage temperature - hot rubble - corresponds to compressor discharge temperature
4. 1980 Projected Gas Turbine Technology
5. 4 mills/kw-hr for OPP.

Table 1 indicates that large variations in power cost can result depending upon the conditions. A cost comparison to other peaking system is required to evaluate the economic viability of the air storage system.

COMPARISON OF PEAKING POWER SYSTEMS

A comparison of various peaking system power cost is given in Table 2.

The air storage peaking plant based on current gas turbine technology, and what might be considered the best air storage temperature and rock conditions considered thus far, has the potential of producing peaking power at significant savings over other systems. An exception to this is pumped hydro when natural conditions are conducive to low capital costs. In this case, the power costs are about the same.

On the other hand, combined poor rock conditions and high air storage temperatures would result in power costs of 19.08 mills/kw-hr. The high costs result from excessively large storage volumes. These combined conditions would eliminate from consideration the air storage system based on current technology.

If we assume 1980 gas turbine technology, the air storage system is clearly economically competitive--even under the worst of rock conditions and air storage temperature, where power costs approach 9.22 mills/kw-hr.

A comparison must also be drawn again between nuclear explosives and conventional rock mining. As previously discussed, 10 times as much storage volume is required when nuclear explosives are used as compared to

TABLE 1. Estimated Air Storage Plant Power Costs Under Various Conditions mills/kw-hr

Conditions	Gas Turbine* Gen. Unit	Air* Storage	O & M	Fuel	OPP	Total
1. Base: 1973 G.T. Technology, 120°F storage temperature, high void volume/kt rock properties, 5 hr duty cycle, 2 mills/kw-hr for OPP	3.20	2.28	0.72	1.77	1.41	9.38
2. Base + 8 hr duty cycle	2.00	2.28	0.45	1.77	1.41	7.91
3. Base + low void volume/kt rock properties	3.20	5.96	0.72	1.77	1.41	13.06
4. Base + 660°F air storage temperature	3.20	4.40	0.72	1.12	1.41	10.85
5. Base + OPP 4 mills/kw-hr	3.20	2.28	0.72	1.77	2.82	10.79
6. Base + 3 + 4	3.20	11.50	0.72	1.12	1.42	19.08
7. Base + 1980 G.T. Technology	2.98	0.48	1.09	1.47	1.58	7.60
8. Base + 3 + 4 + 7	2.98	2.42	1.09	1.15	1.58	9.22

*Note: 15% Fixed Annual Charges Assumed

TABLE 2. Estimated Power Costs for Various Peaking Systems - mills/kw-hr

Type	Size-mw	\$/kw	Cap*	O & M	Fuel 30¢/10 ⁶ Btu	OPP	Total
Pumped Hydro ⁽⁴⁾	7.2-600 (current) 122-1000 (und. const.) 194-2000 (und. study)	75-125	6.16-10.27	0.55		3.00	9.71-13.82
Gas Turbines	58 (1973 Technology) ^(18,19) 250 (1980 Technology) ⁽⁷⁾	77.6 66.5	6.33 5.49	1.7- 2.35 1.7- 2.35	3.93 2.86		11.96-12.68 10.05-10.70
Steam Peaking ⁽⁴⁾	135-400	105	8.63	2.19	3.75		14.57
Air Storage							
Base	175/unit	65.7	5.48	0.72	1.77	1.41	9.38
Base + 1980 G.T. Technology	542/unit	42.2	3.46	1.09	1.47	1.58	7.60

*Fixed charges 15%/annum

conventional rock mining since hydrostatic pressurization is not practical. On the other hand, conventional rock mining is more expensive in terms of $\$/\text{yd}^3$ of storage volume. If the cost for the conventional rock mined storage (including piping, reservoir, etc.) exceeds $\$6/\text{yd}^3$ of volume, then the use of nuclear explosives may offer potential savings. (Cost estimate for similar type systems have been on the order $\$8.50 - \13.50 yd^3 using conventional rock mining.)

It must be kept in mind that the cost estimates presented herein, are preliminary and further refinement is necessary. Factors which have been briefly considered but which need further scrutiny include:

1. Annual fixed charge rates to be applied to competing types of peaking systems
2. Fuel costs
3. Off-peak-power costs
4. Allowable pressure fluctuation
5. Air storage temperature
6. Expected rock properties
7. Safety costs
8. Allowable explosive yield
9. Expected load factor
10. Gas turbine technology forecasts
11. Development costs for increasing pressure ratio and possibly turbine inlet temperature specifically for air storage plants.

CONCLUSIONS

1. The air storage peaking plant based on currently available gas turbine generating unit components, air storage temperatures near 120°F, and rock properties which yield high void volume per kt, has the potential of producing peaking power at significant savings over other systems.
2. High air storage temperatures, combined with rock properties which yield low void volume per kt, can eliminate from consideration air storage systems based on current gas turbine technology. These combined effects result in excessive costs for the underground storage chambers.
3. Air storage systems based on 1980 gas turbine technology are clearly competitive to other systems - even under the worst rock conditions and high storage temperatures.

RECOMMENDATIONS

The capital cost of the underground air storage system is a critical factor which determines the general economic viability of the air storage peaking plant. Future work should, therefore, be directed towards a more accurate definition of underground storage costs. To more accurately define underground storage costs, the following factors must be thoroughly considered and defined in detail:

1. Air storage temperature.
2. Potential sites and associated rock properties.
3. Allowable storage pressure fluctuation in terms of off-design performance of gas turbine components.
4. Costs of increasing the pressure ratio and turbine inlet temperature of gas turbine components at a faster pace than will normally occur for conventional gas turbines.
5. Safety costs.
6. Allowable explosive yield at potential sites.

Once the general viability of the air storage system is established through detailed definition of the above, thorough consideration must be given to the following when comparisons are made to other peaking systems for a given geographical location:

1. Fuel costs
2. Off-peak power costs
3. Load factor
4. Fixed charge rates.

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