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THE DESIGN OPTIMIZATION OF AQUIFER RESERVOIR-BASED COMPRESSED AIR ENERGY STORAGE SYSTEMS

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THE DESIGN OPTIMIZATION OF AQUIFER RESERVOIR-BASED COMPRESSED AIR ENERGY STORAGE SYSTEMS

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ABSTRACT

The application of a general Compressed Air Energy Storage (CAES) power system design optimization methodology to the class of CAES plants having aquifer air storage reservoirs is discussed. The resulting procedure incorporates performance and economic models for the aquifer reservoir, wells, piping, and air compression system. Its use allows identification of designs which minimize the subsystem power generation cost (mills/kWh), while satisfying constraints related to the geology, equipment, and utility load curve. The design specification resulting from the optimization procedure includes: land area to be purchased, well depth, number of wells, well spacing, wellbore diameter, main pipeline diameter, required compressor system power and discharge pressure, and required compression time durations for each day of the week. A capital and operating cost summary for the optimum design is a final output of the procedure. This paper reviews the models and constraints incorporated in the optimization procedure. Although the basic framework is well-developed, some refinements or additions to the modeling may be necessary to improve the results; these possibilities are discussed. Results of case studies are included in the paper in order to illustrate the power and potential economic impact of the techniques described, to demonstrate some of the economic tradeoffs which occur in the optimal design of aquifer reservoir-based CAES systems, and to show the influence of certain cost parameters.

INTRODUCTION

A major portion of the Department of Energy research program on Compressed Air Energy Storage (CAES) is devoted to addressing air reservoir concerns. In the case of constant-pressure (hard rock) caverns, it is quite easy to design a reservoir which satisfies the planned operating cycle of the CAES plant, once the turbine system air supply requirements have been specified. It is then straightforward to include the effect of cavern costs in economic studies of turbomachinery options (e.g., see Ref. 1). The situation is somewhat more complicated in the case of constant-volume (usually salt cavity) reservoirs. For these reservoirs, the peak storage pressure (related to the amount of cushion air) must be selected, which involves finding the economic balance between air compression and cavern volume costs. The relative design simplicity of hard rock and salt cavity reservoirs has resulted in a DOE-sponsored research emphasis on the long-term stability or reliability of the reservoirs undergoing CAES plant operating conditions.

When aquifers are considered for CAES reservoir application, the number of design parameters to be selected is much larger and, in addition, there are many constraints imposed by the operating cycle, the interaction with aboveground machinery, and the geological characteristics. These factors give a great incentive to the careful exploration of aquifer system design options, so that the economic benefit of the plant can be maximized while simultaneously insuring its long-term capability to meet the plant operational criteria. The primary goal of the work reported here has been to develop an appropriate, comprehensive, means for performing these design studies. The performance, economic and design optimization considerations which form the bases of the design procedure are described and illustrated with example case study results in subsequent sections.

PHILOSOPHY

Because of the complexity of an aquifer reservoir-based CAES system, both in terms of subsystem interactions and design constraints, it was decided to orient the formulation of the design procedure toward the utilization of generalized, computer-oriented techniques for solving nonlinear, constrained optimization problems.[2] With this approach, a basic framework for system design can be developed so that new improvements in the technical or economic models can be easily incorporated. Implicitly, the choice of basing the design procedure on modern optimization techniques reflects a recognition of the confusion and inadequacy which could result from applying the more traditional "parameter study" approach to a problem of this magnitude.

SYSTEM CONSIDERATIONS

In principle, and probably in practice, the design optimization of an entire CAES system could be handled as one large problem, especially if the models employed for individual system components were not too detailed. However, consideration of a general formulation led to the development of an advantageous decoupling strategy which enables separate optimization of particular subsystems without compromising the optimal system design. Each of these suboptimizations is, of course, simpler to perform that that of the full problem.

In broad terms, a CAES power system comprises the following: the air compression train (compressors, intercoolers, aftercooler); compressed air piping; air storage reservoir (any type); power generation train (e.g., turbines, combustors, recuperator); reversible motor/generator and the utility grid. Although the utility grid is not physically part of the CAES plant, this interaction should be considered in designing the plant, since the design (cost) of the plant can influence utility usage (operating cycle). Conversely, the utility load cycle affects the plant design (i.e., a coupling exists). For the purpose of design optimization the overall system can be decomposed into three subsystems (see Fig. 1). The first subsystem (subsystem 1) comprises the air compression train, the main piping and air distribution system and the air storage reservoir.

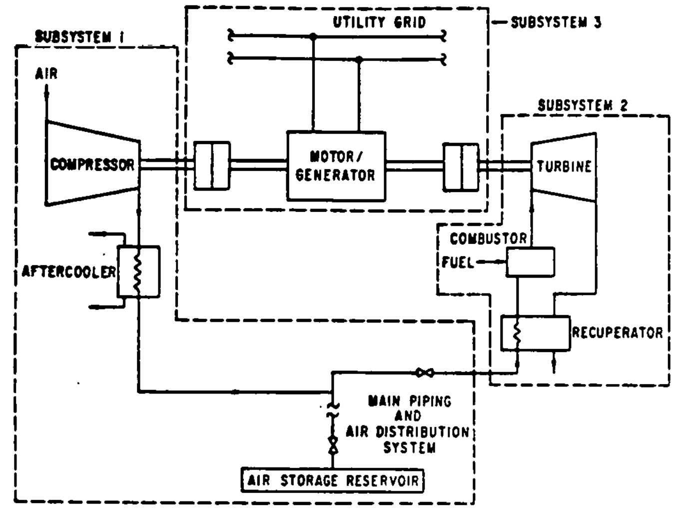

Fig. 1. Typical CAES Power System

Subsystem 2 is the power generation train. The motor/generator and the utility grid are incorporated in the third group (subsystem 3). It is important to note that this particular decomposition is general, in the sense that it is not dependent upon the internal design of any particular subsystem. Furthermore, it minimizes the number of coupling variables. That is, the interactions of subsystems 1 and 2 with subsystem 3 are dependent on only one coupling "variable" -- the utility load cycle. The interactions between subsystems 1 and 2 (the ones of principle concern to the plant designer) are dependent on only three coupling variables -- the inlet pressure to the power generation train (p_{t_i}), the specific air mass flow rate ($\dot{m}'$) and the utility load cycle.

The criterion for optimum design is chosen to be the total normalized cost (C) of the system (i.e., cost per unit of electricity generated by the CAES power plant). This total cost is the sum of the individual subsystem normalized operating costs.* The costs have to be minimized subject to various performance and technical constraints. The implication for CAES plant design is that, for a given utility load cycle, a suboptimization of subsystem 1 would provide the minimum subsystem operating cost (C_1^0) and values for the corresponding subsystem design variables, as a function of the coupling variables -- p_{t_i} and $\dot{m}'$. Similar optimization for subsystem 2 would yield

*Typically the normalized operating costs include fuel costs, maintenance, charge rate on capital investment, etc.

C_2^0 (the minimum operating cost of subsystem 2) and its optimum design, as a function of the coupling variables only. Finally, the sum of C_1^0 and C_2^0 can be minimized by inspection to determine the optimum values of the coupling variables, the minimum plant cost (C*) and the optimal plant design. The process can obviously be expanded (in principle) to include variations in the utility load cycle and consideration of the resulting economic benefits or penalties to the utility. A noteworthy corollary of the approach described is that changes in the design options considered (e.g., turbines vs. piston expanders) in one subsystem do not invalidate the optimization results for the other subsystem. The remainder of this paper is confined to consideration of the design of a particular variety of subsystem 1 -- one with an aquifer reservoir.

AQUIFER RESERVOIR TECHNICAL CONSIDERATIONS

The design of aquifer reservoirs for CAES requires integration with the characteristics of the aboveground machinery, piping, and the utility load cycle. The design also depends greatly upon site-specific geological properties like porosity, discovery pressure, permeability and threshold pressure.[3,4] Some of these *in situ* properties enter into the flow performance; others impose design constraints. Complications are introduced by way of distributed flow resistance, formation heterogeneities and possible two-phase flow of water and air. Due to the complexities, however, aquifer reservoirs appear to offer a significant potential for economic optimization.

For an underground porous formation to be suitable for storing compressed air, it should have certain structural features. Suitable aquifers are usually in the approximate shape of an inverted saucer. The top consists of a tight porous caprock, saturated with water. The interfacial property of the air-water system in these tight pores does not permit the flow of air. Thus, the dome shape will prevent any lateral or vertical migration of compressed air. The compressed air is contained in the pores of the rock between the caprock and the bottom layer of water and/or rock. In aquifers, the adjacent water moves under an applied pressure gradient and therefore requires careful monitoring to ensure zero net movement over a period of time.

For the purpose of analysis, it helps to make a distinciton between edge-water and bottom-water reservoirs. Edge-water reservoirs, shown in Fig. 2, are characterized by relatively thin formations, a caprock of appreciable dip, an underlying impermeable layer, and water driven to the edge of the field during bubble development.

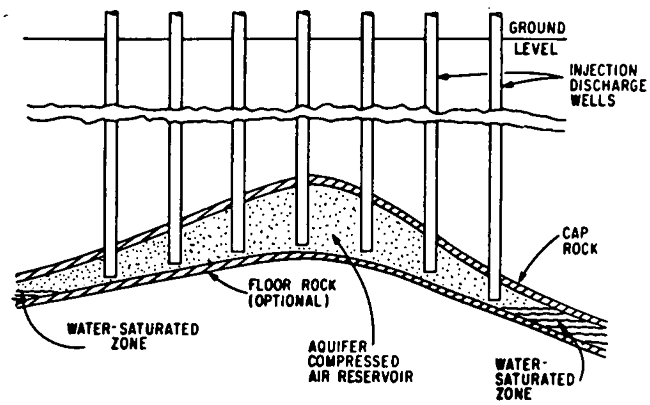

Fig. 2. Edge-Water CAES Aquifer Reservoir

In bottom-water reservoirs, depicted in Fig. 3, a water-air interface lies in a nearly horizontal plane beneath the air bubble. This commonly occurs in thick formations. A characteristic unique to bottom-water reservoirs is the phenomenon of water coning. Because the bottom-water reservoirs involve more design variables and constraints, they have received the greatest attention in the present optimization study.

AQUIFER-RELATED DESIGN CONSTRAINTS

As related to CAES systems, potential constraints imposed by the aquifer characteristics have been discussed in Refs. 3 and 4. These constraints were largely identified from experience in natural gas storage. The DOE-funded work in progress on aquifer reservoir stability may result in identification of additional ones. The constraints presently appearing to be important for inclusion in the CAES design procedures are as follows.

Air Bubble Size. After growing the air bubble to the desired equilibrium size, further growth or shrinkage due to the daily variations in pressure is to be nullified. This concern is reflected in two related constraints. First, the total mass of air stored during a weekly cycle should equal the total mass removed. Second, for

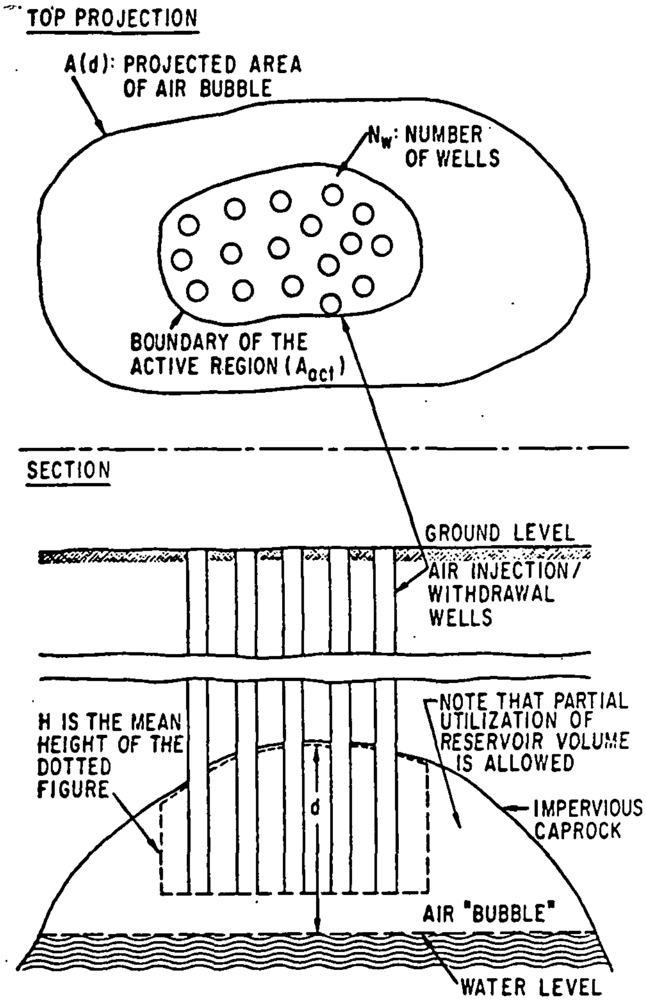

Fig. 3. Bottom-Water CAES Aquifer Reservoir

long-term constancy of bubble size, a pressure schedule having the average weekly pressure (corresponding to the mean mass of air in the bubble during the week) equal to the aquifer discovery pressure should be adopted.

Charging Pressure. In operating CAES plants, no apparent advantage results from using high injection pressures; actually, there are economic benefits of injecting air at the minimum possible pressure compatible with the reservoir dynamics and power availability. However, during air bubble development, a high pressure will reduce the development time. An upper limit on charging pressure is imposed to avoid exceeding either the caprock threshold pressure or the overburden pressure.

Aquifer Geometry. It is obvious that the reservoir design and storage capacity must be compatible with the site-specific geometry of the formation. Contour maps for the site enable the information needed for optimization to be determined. This information includes the total bubble volume as a function of bubble thickness (measured at the apex of the dome) and the spill point (maximum bubble thickness for which the air will remain trapped by the caprock). The corresponding constraints are that the area occupied by the well-field must not exceed the projected bubble area and the bubble size must not exceed the spill point volume.

Water Coning. The problem of water coning in bottom-water reservoirs means that, for given reservoir conditions and well penetration depth, a critical flow rate of air exists above which air cannot be withdrawn from the reservoir without simultaneous production of water. The critical flow rate is extremely sensitive to *in situ* reservoir heterogeneities. It is known that the presence of an impermeable barrier like a shale streak below the well would drastically inhibit bottom-water from coning into the well. The phenomenon of water coning has been studied extensively in the past under the assumption of steady state flow, but an order of magnitude estimation for CAES applications (short discharge time) indicates that a non-steady analysis is required to adequately determine the maximum well penetration that permits withdrawal of compressed air without co-production of water. Little attention has been given to this situation in the literature. Therefore, the coning height is presently treated as a parameter in the design procedure. The intention is to calculate the cost and performance sensitivity of the aquifer system to this parameter. This will help establish the priority to be assigned to the study of transient coning.

Well Spacing. It can be observed[5] by considering the dynamics of flow in porous media that, for a given charging or discharging time, a critical distance exists around each well beyond which only a negligible amount of compressed air storage can occur. This gives rise to an economic constraint on maximum well spacing (i.e., greater spacings would be wasteful of land and bubble volume). The critical spacing can be calculated from a diffusion time formula.[3,5]

AQUIFER FLOW MODELING

Due to the design requirements imposed by the system coupling variables (turbine inlet pressure and mass flow rate) and the need to select a proper pressure ratio for the air compressor train, a prediction of the formation pressure drop is needed in the design optimization procedure. Based on an extensive study of the modeling requirements for flow in porous radial disc geometry (as applied to CAES applications in edge-water aquifers),[5] it can be reasonably expected that a simple quasi-steady model will suffice. To allow consideration of bottom-water reservoirs (having a coning constraint), as well as to insure that potential economic benefits of partially-penetrating (i.e., shallower) wells can be examined by the optimization procedure, a more general, two-dimensional, version of the quasi-steady model[2] is employed in the present study. In order to easily use the formation pressure drop equation (i.e., to employ a single "typical well" model), the active part of the actual dome-shaped reservoir has to be represented by an equivalent cylinder having the same projected area and a height equal to the ratio of actual storage volume to projected area. This information is determined from contour maps.

The amount of mass stored or removed during a given charge or generation process is used, together with the void volume of the active well-field within the bubble, to determine the change in mean formation pressure occurring during that process. Combining this information with the quasi-steady formation pressure drop prediction enables the maximum and minimum wellbore pressures occurring during the week to be found. These values, in turn, are needed in assessing the compatibility between the reservoir design and the aboveground equipment.

The chief uncertainty in the flow modeling just described is that it assumes values for the effective permeability and porosity of the porous medium are known. These values are influenced not only by heterogeneities in the rock, but also by the distribution of water throughout the formation following bubble development and subsequent dryout (to the extent it occurs). Although moisture effects have been considered,[3] more work is required to resolve the issues. As a reasonable measure, for design study purposes, the following simplifications are used. First, to account for the reduction of storage space because of moisture remaining after bubble development, a modified porosity has to be defined. It is recommended that, until more accurate information becomes available, the dry porosity value, <u>reduced</u> by the connate water saturation,[4] be used in all calculations. Second, since, in a radial geometry, the pressure losses are concentrated around the wellbore, which should be relatively dry, it seems justifiable to use the <u>dry</u> permeability values in estimating the pressure drop in the reservoir.

OPTIMAL DESIGN OF A CAES SUBSYSTEM WITH AQUIFER RESERVOIR

The decomposition concept described earlier suggests that the aquifer reservoir, compressed air piping, and air compression train should be designed concurrently as a subsystem. This grouping has minimal interaction with the rest of the CAES system. It should be realized that any attempt to design and optimize only part of this subsystem (namely, the aquifer well-field alone) would be less satisfactory and, possibly, misleading. The resulting "solution" would be dependent on assumed values of parameters such as piping pressure drops and would not directly allow the compression costs to impact the reservoir design.

Site-specific reservoir design studies for CAES have been discussed in previous literature. For example, a conceptual design of a complete CAES plant using the Brookville aquifer as the reservoir was conducted by General Electric.[6] The design was based on more or less state-of-the-art equipment and was used to test some general conclusions concerning technical and economic feasibility of compressed air storage. Also, Katz and Lady[4] have analyzed (and partially optimized) an aquifer and a reef system to illustrate a design philosophy for CAES plants using underground porous media. The general techniques resulting from the present project should aid in conducting optimal design studies for CAES systems in the future.

<u>SUBSYSTEM PERFORMANCE MODELING AND DESIGN CONSTRAINTS</u>

The performance modeling and design constraints associated with the aquifer were discussed in an earlier section. These aspects have received the greatest attention because they are complex and reservoir costs are dominant in subsystem 1. Rather simplified compressor train and piping system performance models are used in the present subsystem 1 design procedure. However, the incorporation of more detailed models would not alter its basic structure.

The design considerations are best illustrated by reviewing a typical step in the iterative search for the optimum CAES subsystem design. The typical design step includes compression train design, based on flow rate and pressure drop calculations for a charging process, and checking of the available turbine inlet pressure, based on pressure drop calculations for a power generation process.

First, the compressor train mass flow rate is calculated from the known turbine flow rate and ratio of weekly power generation to storage time. This calculation incorporates the non-growth constraint for the air bubble and also assumes (for simplicity) that the mass flow rate during every charging period is the same. Next, the required compressor train discharge pressure is calculated by adding the pressure drops in the wells and compressed air piping to the maximum wellbore bottom pressure, predicted with the aquifer model. The maximum wellbore pressure depends on the weekly mass charging/discharging cycle, the wellbore diameter, depth of well penetration, well spacing, and number of wells. From knowledge of the compressor train discharge pressure and flow rate, and specification of the pressure ratio across the low-pressure compressor* (either 11:1 or 16:1), the total compression power is calculated from available data.[3,5,7]

The pressure difference from well-head to well-bottom reflects friction and gravity effects using standard relationships.[3,4] The piping system friction pressure drop is patterned after the simplifications employed by Katz.[4] It is assumed that the majority of the pressure drop in the surface piping system occurs in the main pipeline and that an equivalent pipe length (L) can be defined to account for pressure drops in the feed, cross-feed and branch pipelines. The most significant design variable of the piping system is then the diameter of this main pipeline. Standard relationships are used in these calculations.[3] A 2% additional pressure drop in the aftercooler is added.

After the pressure drop analysis of the compression process, some similar pressure drop calculations are done for the power generation process occurring at the time of the week for which the mass stored (bubble pressure) is minimum. This procedure enables the determination of the minimum pressure <u>available</u> to the power generation train for the design being considered. For a design to be acceptable, this pressure must be at least as high as the <u>specified</u> inlet pressure.

In the compressor design stage described above, the total charging time was used; it influenced the predicted charging flow rate and power. It should be noted that this charging time duration and power level must be checked for compatibility with the specified utility load cycle. An idealized utility load cycle is shown in Fig. 4, together with the corresponding reservoir air storage cycle.

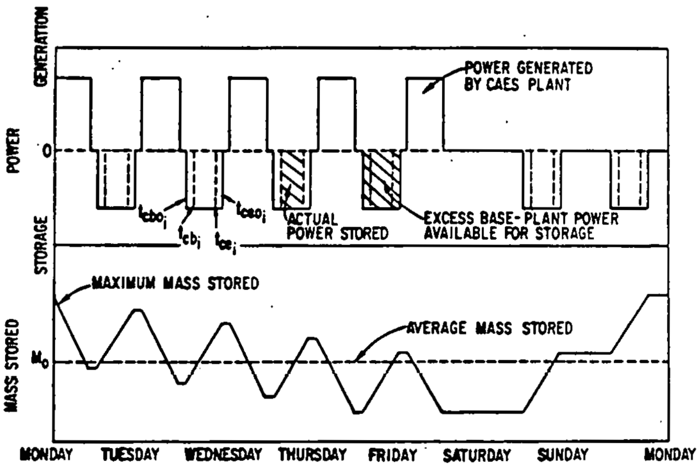

Fig. 4. Idealized Weekly Utility Load and Air Storage Cycles

The power <u>generation</u> level and time schedule is considered invariant, reflecting the power demand for which the CAES plant is to be designed. The excess power level for storage and its daily available time durations, however, have maximum values but these may not be entirely needed by the CAES plant which is being designed. Since the compressor power and the time variation in air storage over the week can both influence the subsystem costs, the tradeoffs between the two* allowed by the present optimization procedure can lead to potential operating cost reduction.

*The compressor train is modeled as comprising a low-pressure compressor, a booster compressor, and appropriate intercoolers and aftercooler.

*The beginning and ending time for each charging process and the compression power (assumed uniform for simplicity) are all considered as design variables, subject to the maximum value constraints imposed by the utility.

SUBSYSTEM ECONOMICS: THE OBJECTIVE FUNCTION

At every stage in the optimization process, the trial design being considered has an associated set of costs. To put the costs on a common basis, it was decided to minimize the total operating cost (per unit of power generated) attributable to subsystem 1. In the terminology of optimization theory, this operating cost is the objective function to be minimized. It comprises the annual carrying charge on capital, subsystem operating and maintenance (O&M) costs, and the cost of compression energy (electricity) derived from the base plant off-peak power. The specific capital costs included are:

(1) Main piping and distribution system - dependent on piping design and number of wells.

(2) Wells - dependent on number, depth, and diameter.

(3) Land - for simplicity, assumed proportional to projected area of air bubble.

(4) Compressor train - based on data from Ref. 7.

(5) Bubble development - dependent on equilibrium bubble volume (air compression cost).

The O&M cost is assumed proportional to the capital charge cost. Further details on the cost calculations and data are given in Refs. 2 and 3. The design variables influencing the various cost components are depicted in Table 1.

Table 1. Subsystem 1 Cost Factors

Design Variables	Cost Items: Wells	Land	Piping	Compressor	Bubble Development	Air Compression
Utility Load Cycle				X		X
Wellbore Diameter	X			X		X
Well Penetration	X			X		X
Bubble Thickness		X		X	X	X
Number of Wells	X		X	X		X
Well Spacing				X		X
Main Pipeline Diameter			X	X		X
L.P. Compressor Pressure				X		X

OPTIMIZATION PROCESS

A detailed discussion of the nonlinear programming (optimization) algorithms, or their computer code implementations (OPT[8] and BIAS[9]), which were employed in this study, will not be given here. In essence, these generalized procedures interact with computer subroutine representations of the subsystem performance and cost models, and the constraint definitions, in order to find that combination of design variables which minimizes the objective function and satisfies all the design constraints. During the course of the search for the optimum, many (e.g., hundreds) of trial designs are considered. The computer codes used work only on the continuous design variables. Discrete variables (those restricted to only a few allowed values, such as pipe diameters) must be examined "manually" by repeated application of the computer code. In the present formulation, the number of wells is approximated as a continuous variable, because it is typically a large number (e.g., a few hundred). The present CAES design optimization procedure results in the specification of the following independent variables: air bubble size, number of wells, well depth, wellbore diameter, well spacing, compression (charging) time duration for each day, compression ratio of the low-pressure (L.P.) compressor and main piping diameter. Much additional information can subsequently be derived from these results (e.g., booster compressor pressure ratio, land area to be purchased, etc.).

ECONOMIC TRADEOFFS IN DESIGN

The number of design variables (related to the flexibility of the model) requires the investigation of many tradeoffs during optimization. Although some of these tradeoffs are perhaps obscured by the "automatic" nature of the optimization, the formulation of the procedure and operational experience have led to the identification of several tradeoffs.

(1) *Active Bubble vs. Total Bubble Size.* Little incentive exists to sinking wells near the outer periphery of the reservoir. For a given bubble thickness at the apex of the dome, as the active land area increases, the average well thickness decreases (see Fig. 3) so that the performance per well suffers and the number of wells increases. However, fewer, deeper, wells concentrated near the center of the bubble results in development of a largely

inactive bubble and in greater cost per well.

(2) *Well Penetration*. Greater penetration of wells into the bubble reduces the number of wells, but increases the cost per well.

(3) *Well Spacing*. Closely spaced wells have less pressure drop (compression cost) but also less storage volume associated with each well.

(4) *Bubble Thickness*. Greater thickness permits deeper wells (fewer needed) but requires more surrounding land (projected area of bubble).

(5) *Compression Time*. Use of all the charging time available minimizes the capital cost of the compressor train (lower flow rate). Use of reduced time (higher flow rate) can alter the shape of the reservoir mass storage cycle, reducing the maximum pressure swing. This could reduce the number of wells needed to meet the turbine inlet pressure requirements.

EXAMPLE APPLICATIONS

The CAES subsystem 1 design optimization procedure described in the preceding sections has been successfully implemented. Results of applying it are presented in this section for illustration purposes, to examine the potential economic impacts that can be achieved with aquifer reservoir subsystem optimization, and to examine the effects of certain cost parameters.

Originally, it was planned to apply the new procedure to the design of a 600 MW plant at Brookville, Illinois, so that the optimized design could be compared with the G.E. design.[6] In preparing to do this, however, it was noted that the G.E. design appears to violate the spill point constraint for the Brookville aquifer site. That is, the storage volume encompassed by the G.E. Brookville reservoir design exceeds that available above the spill point, as determined from contour maps of the aquifer layer. In the Brookville study, the actual site-specific properties (porosity, permeability, average aquifer thickness) were used, but the reservoir was approximated as a constant thickness circular disc without water-related constraints. Application of the procedure developed in the present study, which attemps to account for geometrical limitations more correctly, led to a design with about 700 wells; 308 wells were recommended in the G.E. report[6] using the less restrictive aquifer geometry assumption.

The major testing of the capabilities of the design optimization procedure has been for the example of a hypothetical 600 MW CAES plant using the Media, Illinois, Galesville aquifer as the reservoir. Contour maps and "material properties" for this aquifer were taken from Ref. 4. The geometrical information on storage volume and projected bubble area as a function of bubble thickness, based on the contour maps, is tabulated in Ref. 3. Other pertinent parameter values used in the study are given in Table 2.

Table 2. Galesville Study Parameters

Aquifer Discovery Pressure	840 psia
Effective Porosity	14.3%
Closure (top structure to spill point)	110 ft
Average Horizontal Sand Permeability	448 md
Average Vertical Sand Permeability	354 md
Specific Flow Rate	10.4 lb_m/kWh
Turbine System Inlet Pressure	750 psia
Utility Cycle:	
Power Generation	600 MW
Power Generation Time	5 days, 10 hrs/day
Max. Compression Power	590 MW
Max. Compression Time	6 days, 10 hrs/day (excludes Friday)
Storage Temperature	150°F
Base Plant Electricity Cost	15 mills/kWh
Land Cost	$1200/acre
Other Cost and Subsystem Parameters	see Ref. 3

As a starting point, a feasible (but nonoptimal) design for the Galesville plant was developed intuitively, although this is not essential for the implementation of the optimization procedure using the OPT[8] or BIAS[9] algorithms. Table 3 compares the initial intuitive design with two optimized designs. The first one of these is the result of the formulation described in previous sections. The second design was obtained by employing a further simplification in which the charging time variables were held constant. In all these cases, the discrete design variables were held fixed at the values: main pipeline diameter (48 in.), wellbore diameter (7 in.), L.P. compressor pressure ratio (11:1).

Table 3. Sample Galesville Study Results

	Initial Design	Optimized Design	Optimized Fixed Storage Time Design
Aquifer Reservoir Specifications			
Surface area to be bought (acres)	5895	2777	2944
Active well-field area (acres)	2755	2038	2944
Air bubble thickness (ft)	105.0	79.9	81.7
Well depth (ft)	1385	1369	1380
Well spacing (ft)	467	530	533
Number of wells	700	402	575
System Pressures, Flow Rates and Powers			
Minimum available turbine system inlet pressure (psi)	775.5	750.0	750.0
Total storage process time (hrs)	59.4	51.4	60.0
Air flow rate during storage processes (lb_m/sec)	1459	1686	1444
Compressor power required (MW)	385	449	384
Compressor discharge pressure (psi)	850.3	879.3	874.6
System Costs			
Land cost ($, millions)	8.843	4.165	4.417
Bubble development cost ($, millions)	6.818	2.580	2.779
Well construction cost ($, millions)	73.379	41.915	60.190
Low pressure compressor cost ($, millions)	4.642	4.996	4.619
Booster compressor cost ($, millions)	4.455	4.897	4.511
TOTAL CAPITAL COST ($, millions)	101.59	62.00	79.97
REDUCTION IN CAPITAL COST (%)	-	39.0	21.3
BASE LOAD ELECTRICITY COST (mills/kWh)	11.45	11.54	11.53
TOTAL SUBSYSTEM OPERATING COST (mills/kWh)	24.25	19.36	21.60
REDUCTION IN OPERATING COST (%)	-	20.2	10.9

There are many interesting observations to be made from the results in Table 3. Both of the optimum designs reduce the number of wells, average well depth and bubble size, indicating that the starting point was a case of overdesign. This conclusion can also be drawn from a comparison of available turbine system inlet pressures in the three designs. Thus, a carefully formulated constrained optimization problem has allowed a reduction in "safety factors" required in an intuitive design process.

The optimization also underlines the compromise necessary between compression power requirements and capital costs of the reservoir system. Higher compressor power and cost are tradeoffs for lower land, bubble development, and well construction costs. In the first optimum design, the weekly reservoir pressure variation is reduced by an even distribution of air storage over the entire cycle. This is accomplished by reducing the weekend storage process durations. On the other hand, the simplified optimization, with fixed storage times, uses a larger active reservoir volume and reduced reservoir formation pressure drop (larger number of wells) to decrease the cyclic pressure fluctuation. A noteworthy feature of the optimum design is partial utilization of the air bubble. This is caused by the high cost of constructing additional wells in the outer region of the bubble, where they yield only minimal benefit due to the tapering of the aquifer formation.

The most important results are the reductions achieved in the subsystem 1 costs. The optimization procedure described herein yielded a 39% lower capital cost and 20% smaller operating cost, compared to the initial design! Restricting the storage processes to fixed values caused these improvements to be only half as much. Although substantial design improvements have been made, further cost reductions are expected as the optimization algorithms are fine tuned and the models improved.

Further optimization runs for the Galesville problem have been made, using different starting point designs, to determine whether the "global" optimum has been found. The best of these solutions has an operating cost of only 17.8 mills/kWh, a reduction of 8% from the optimum value given in Table 3. This design has only 252 wells, an active area of 1294 acres, a bubble thickness of 91.6 ft., and a 53 hr. charging time. Interestingly, the fixed charging time (60 hr.) version of this solution is very similar in design and cost.

When a CAES plant using the Media Galesville aquifer was investigated by Katz and Lady,[4] they concluded "... use of 100 input/output wells seem reasonable for full development (600 MW)." This number, not based on detailed optimization, is considerably less than found in the present study (252). The discrepency may be partially due to the imposition of the diffusion time-related constraint on well spacing in the optimization procedure. Whether that constraint is conservative or the assumptions of the previous investigators overestimates the reservoir flow capability under CAES cycling conditions remains to be determined.

Examination of the various Galesville optimization runs, and those done for the Brookville site, shows that the optimum wells penetrate nearly to the bottom of the bubble, often being limited by the coning constraint. Increasing the coning distance parameter from 1 ft to 5 ft increases the operating cost by about 1 mill/kWh, indicating that the coning problem should be studied further.

For the Galesville problem, the effect of wellbore and main pipeline diameters on optimum design operating cost are shown in Figs. 5 and 6, respectively. The main pipe size has little effect.

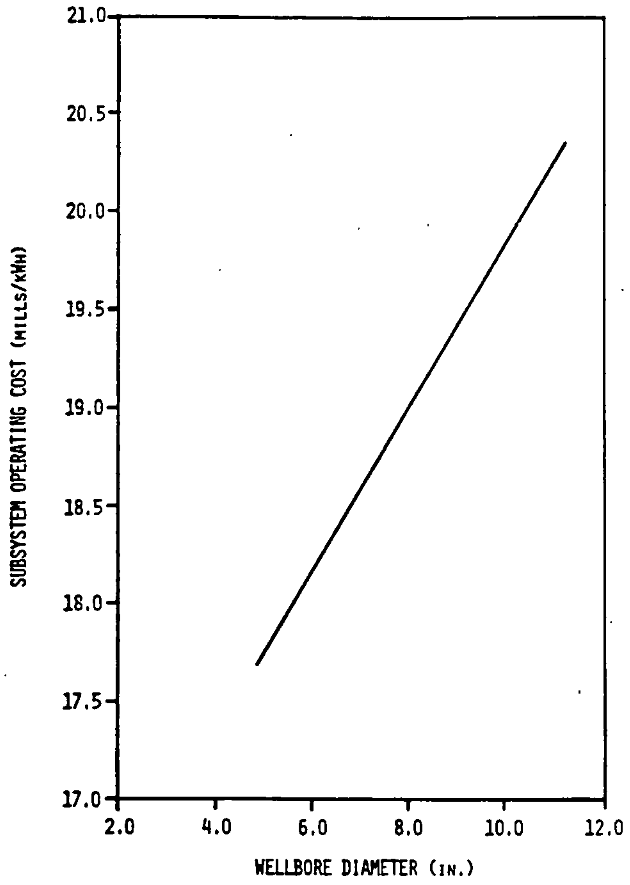

Fig. 5. Effect of Wellbore Diameter in Galesville Problem

The effect of certain cost parameters on the optimum Galesville subsystem 1 operating cost has also been investigated (see Figs. 7-9). It was found that the optimum design variables did not change as these costs were varied, thus explaining the linear relationships in the figures. Although this observation may not be of general validity, it would be comforting to know that a CAES design would remain optimum if the cost of base-plant electricity were to increase in the future!

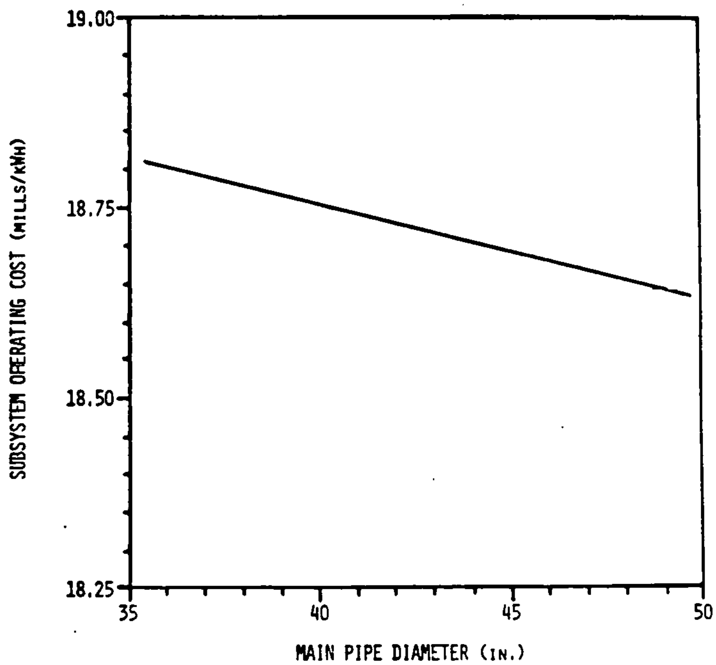

Fig. 6. Effect of Main Pipe Diameter in Galesville Problem

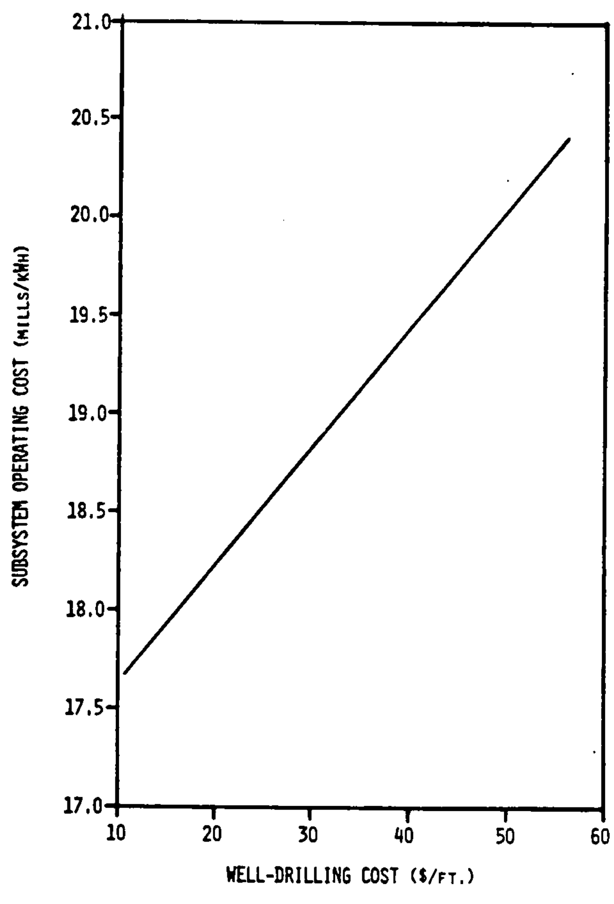

Fig. 7. Effect of Well-Drilling Cost-Galesville.

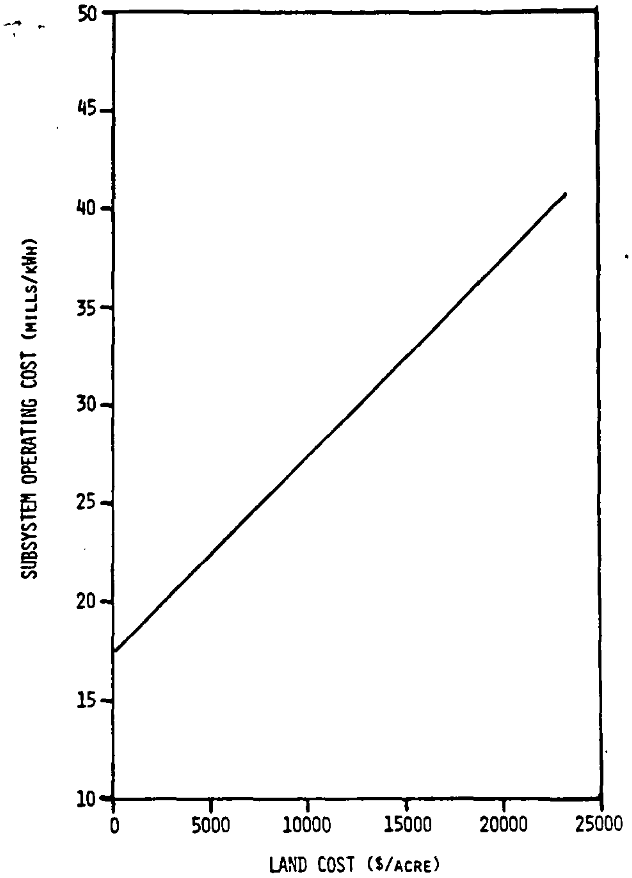

Fig. 8. Effect of Land Cost - Galesville

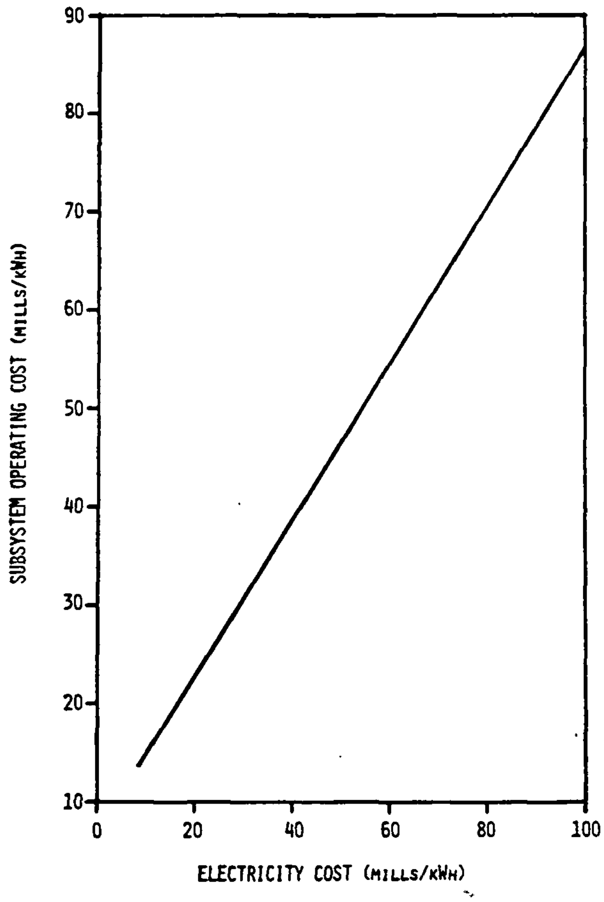

Fig. 9. Effect of Base Plant Electricity - Galesville

CONCLUDING REMARKS

The design procedure described in this paper appears to be the most complete method available for designing aquifer reservoir-based CAES plants. Limited comparisons with published results using more simplified methods of analysis suggests a possible inadequacy in those methods. Further work is recommended to resolve these issues.

The design optimization procedure is general in its structure, but its current computer implementation is somewhat restricted (e.g., bottom-water reservoirs, equal compression power for each charge process, etc.). It is also based on a somewhat idealized aquifer model and on particular judgements on important constraints. However, extensions and refinements can be readily incorporated as required.

Utilization of the design optimization procedure can be valuable, when carefully applied. It can:

- result in actual capital and operating cost savings in plant design,
- give insight into the economic trade-offs among design variables, and
- assess the influence of uncertainties in cost data.

Furthermore, if combined with a similar optimization model for the turbine system, a complete CAES plant design optimization could be performed.

Some additional information on the work presented is available in Refs. 2 and 3. A final report is in preparation which will provide full documentation, including listings of the computer subroutines embodying the optimization-oriented CAES model.

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