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An Assessment of Energy Storage Systems Suitable for Use by Electric Utilities

AN ASSESSMENT OF ENERGY STORAGE SYSTEMS SUITABLE FOR USE BY ELECTRIC UTILITIES

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Prepared by

Public Service Electric and Gas Company
Research and Development Department
Newark, New Jersey 07101

Prepared for

Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

and the

Energy Research and Development Administration
Office of Energy Conservation
Washington, DC 20545

Project Manager
Dr. Fritz Kalhammer

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ABSTRACT

This volume provides an expanded treatment of the material on conventional and underground pumped hydro found in Volume II of this report.

Hydro pumped storage is a commercial reality. Many plants have been built and their costs and characteristics are well known. Nevertheless, there is a need for further research and study, particularly with respect to underground pumped storage. The possibility of using excavated caverns or abandoned mines as the lower reservoir in a pumped storage system opens up opportunities for use of higher heads and possibly larger capacities. It also extends the area in which hydro pumped storage might be economically developed, and at the same time has environmental advantages.

This report describes the current state of development for both conventional and underground pumped hydro and characterizes for each typical, or expected, unit sizes, head, efficiency, charge/discharge ratio, reliability and availability, storage capacity, turnaround time, life, and siting potential.

Principal findings are that:

- Hydro pumped storage is a well developed, mature technology
- Where suitable sites are available for two surface reservoirs, no technical obstacles exist to impede implementation
- Underground reservoirs may extend the areas where hydro pumped storage can be used
- Further development of high head equipment will be desirable for use in high head underground plants

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The draft report was submitted for review to several utilities, consultants and other experts in the field of pumped storage, and the resulting suggestions and corrections were most useful. Particular thanks are due Acres American Incorporated, Harza Engineering Company, and the Hydro Turbine Division of Allis-Chalmers; but this acknowledgement should in no way imply their agreement with or approval of material contained in the report.

E. S. Loane
Principal Investigator

CONTENTS

CONTENTS CONTINUED

CONTENTS CONTINUED

FOREWORD

This is the third volume of the final report on "Assessment of Energy Storage Systems Suitable for Use by Electric Utilities." This third volume is a separate topical report on hydro pumped storage and was prepared as part of a subtask by the GPU Service Corporation under subcontract to Public Service Electric and Gas Company.

The outline and coverage of this report were intended to provide input to the main study (see Volumes 1 and 2) and present data and discussion in a form to permit comparison with other energy storage technologies. Prepared during the first part of 1975 and based on data available then, it has not been updated.

As all of the information contained within this volume could not be incorporated into the main report and was not generally available in the published literature, it was deemed appropriate to publish this subtask report.

- Public Service Electric and Gas Company

1. INTRODUCTION

Hydro pumped storage is distinguished from all other energy storage methods suitable for utility application in that it has already reached a mature state of development. Plants have been built and their costs and characteristics are known; many more are planned. The literature covering the technical, economic and environmental aspects of pumped storage is extensive.(1)(2)(3)

Nevertheless, the use of pumped storage in the United States has been limited. More storage could now be used to advantage; and expected future loads, generation mixes and fuel costs point to an expanded role for possibly several energy storage methods. Consequently, further improvements in design and in construction methods and extention of the range of suitable plant sites would be of value to the electric utilities and to their customers.

There is need for further research and study, particularly with respect to underground pumped storage. The possibility of using excavated caverns as the lower reservoir in a pumped storage system opens up opportunities for use of higher heads and possibly larger capacities. It also extends the area in which hydro pumped storage might be economically developed, and at the same time it has environmental advantage. Although no plants using underground storage have been built, their costs and characteristics can be predicted (with such reliability as is inherent in most cost estimates) on the basis of existing plants and of excavation costs for other purposes.

1.1 DESCRIPTION AND PRESENT STATUS OF DEVELOPMENT

In a hydro pumped storage system, energy is stored by pumping water from a lower to a higher elevation. The energy is recovered for utility use by passing the water from the higher to the lower elevation through a hydro turbine driving an electric generator. The two operations may be accomplished by using separate pumps and turbines, which may be connected to separate electrical machines or which may be connected to a single generator/motor. Pumping and generation can also be accomplished with a reversible pump/turbine connected to a generator/motor. It was the development of the reversible unit, along with favorable economic conditions, that contributed to the accelerated interest and development of pumped storage in this country in the 1960's. The few older plants in the United States and many more abroad had been developed with separate pumps and turbines prior to that time.

The reservoirs needed for the pumped storage operation may be natural bodies of water, reservoirs of existing hydro plants or of water storage systems, specially constructed surface reservoirs, an underground cavern, or combinations of these several storage possibilities. The pumping-generating plant is connected to the two reservoirs by appropriate waterways; these may be entirely underground or partially on the surface. The powerhouse itself may be either on the surface or underground; and underground construction has sometimes been found economically and environmentally desirable, even where the reservoirs are on the surface.

All hydro pumped storage plants in the United States, except those built by Federal agencies, have been licensed by the Federal Power Commission. At the end of 1974, its records show the status of pumped storage development in the United States to be as follows:

	Number of Plants	Reversible Cap. 10^6 kW
In operation, Dec. 31, 1974	26	8.8
Under construction	10	5.0
Planned, as evidenced by application to FPC for project license or by receipt of preliminary permit	18	19.8
Total (excluding duplications)	51	33.6

The capacity in service at the end of 1974 represents less than 2% of the total utility generating capacity; but even this is a significant development, considering the geographical limitations of this storage method and the limited role to date of energy storage in the service of utility loads.

Most of the pumped storage capacity now in service can be classified as "pure" pumped storage, i.e., units or plants built only for the storage of off-peak energy and the delivery to utility systems of energy from the same plant during on-peak periods. However, several constructed plants have additional purposes, including the development of conventional hydroelectric output from natural flow into the upper storage reservoir, storage of water primarily for use in downstream hydroelectric plants, storage for irrigation or potable water supply, and the pumping and subsequent generation incident to the diversion of water for irrigation or municipal use. In fact, wherever there is need to store water or to move it from one place to another, there may be an opportunity for storage of hydro energy.

Plants have been built in the United States in sizes from a few megawatts to more than 1000 MW; plants under study range to more than 2000 MW. Developed heads have ranged from less than 100 feet to more than 1200 feet; and even higher heads are to be utilized in some of the planned plants. In general, the plants with the smaller sizes or lower heads have been special purpose plants. With perhaps a few exceptions. the modern "pure" pumped storage plants have involved unit capacities of about 100 MW, or more, and heads above 300 feet.

The necessity of storing relatively large volumes of water in two reservoirs, separated by several hundred feet of head, but not too far apart in distance, requires topography that is not everywhere available. Consequently, the developed and planned pumped storages are confined to certain sections of the country. However, the absence of pumped storage plants in certain areas is not necessarily indicative of unfavorable topography, rather it may indicate either the absence of economic need for a peaking service or the supply of this service by conventional hydro plants. It is estimated that hydro pumped storage, using above-ground reservoirs, could be built, if needed and if economically justified, to serve the peaking requirements of the systems supplying about 70% of the total electric load in the United Stated.

The possibility of using underground reservoirs extends the geographical area in which pumped storage might be developed and also extends the range of heads that might be utilized. Within limits, the over-all cost of a plant using underground storage will decrease as the head is increased. Therefore, since the head for which the usual reversible unit might be built is limited, the optimum development of underground pumped storage may involve some different concepts, including the use of two plants in series, separate pump and turbine units (as used abroad for higher heads), or multistage reversible units.

1.2 ALTERNATIVE IMPLEMENTATIONS TO BE ANALYZED

There is but a single basic method of hydro energy storage, and any differences in implementation are the result of differences in site conditions, utility system load conditions, economic factors, and the possibilities for multipurpose development. However, for purposes of analysis and discussion it will be convenient to consider two concepts:

(1) Conventional hydro pumped storage, using two above-ground reservoirs (but possibly including an underground powerhouse); and

(2) Underground pumped storage, with one reservoir located in an excavated cavern.

It is furthermore proposed that analysis and discussion be limited to "pure" pumped storages in unit sizes above about 100 MW and heads above 300 feet. The existing and potential pumped storages thus eliminated from further consideration are those that depend on use of the plant facilities for other special purposes and those smaller, low-head plants which will generally not be economic for utility applications. This elimination is not a recommendation against the use of such plants for energy storage, but rather a practical recognition of the difficulty of predicting their costs or characteristics without reference to specific sites and specific applications. On the other hand, the two classes of plants that will be considered can be analyzed, discussed, and evaluated in a general manner. Even so, it is still necessary to recognize the effects of size and head, as well as generalized site conditions, on the per-unit costs of pumped storage plants.

With respect to the conventional pumped storage, consideration will be given only to the use of reversible pump/turbine units, such as have been used in the larger existing plants. This limits the head on these plants, with the present development of such units, to less than 2000 feet. For underground pumped storage, consideration will be given to all available methods of developing even higher heads.

The discussions of pumped storage in the following Sections 2 and 3 have been organized in a form designed to facilitate comparisons among all energy storage systems.

REFERENCES

(1) Bibliography on Pumped Storage to 1975, Hydro Electric Power Subcommittee of the IEEE Power Generation Committee Paper F76 007-5, Winter Meeting, New York, New York, 1976.

(2) Walter A. Garvey and Gabor M. Karadi, "A Bibliography of Pumped Storage Development," Pumped Storage Development and Its Environmental Effects, edited by Gabor M. Karadi, Raymond J. Krizek and Sandor C. Csallany, American Water Resources Association, pp.557-572.

(3) J. S. Schlimmelbusch, June 1971, "Pumped Storage, A Bibliography (1961-1970)," Bonneville Power Administration Library, Portland, Oregon.

2. CONVENTIONAL HYDRO PUMPED STORAGE

In the case of hydro pumped storage with above-ground reservoirs, there is an adequate body of information with respect to existing and potential developments, technical characteristics and costs. This information, as it relates to plants in the United States, is reported and discussed in a series of appendices which cover:

Appendix A -	Existing and Planned Pumped Storage Projects
Appendix B -	Availability of Future Pumped Storage Sites
Appendix C -	Pumped Storage - Technical Characteristics
Appendix D -	Pumped Storage - Construction Costs
Appendix E -	Pumped Storage - Operation and Maintenance Expenses

The reported experience has been confined to plants in the United States, not only because of the more readily available data (generally in reports to the Federal Power Commission), but also because it is believed that some of the costs and characteristics of plants built abroad will not be applicable to United States conditions. This is because of differences in site conditions, utility system loads, fuel availability and cost, and in construction practices.

Because many characteristics and costs can be most conveniently expressed on a per-unit basis (i.e., per unit of plant capacity), it is necessary to make some preliminary comments on the operation and rating of pumped storage plants.

During the generating portion of the operating cycle, the lower reservoir is filled and the upper reservoir is emptied. The difference in water surface elevation between the two reservoirs, or gross head, is decreased. The change in head may cover a wide range, and differences in head of 10 to 20% are not uncommon. As the head decreases, so does the available plant capacity. Unless there are hydraulic or electrical limitations that prevent the use of the full turbine output at higher heads, the percentage change in output is even greater than the change in head. (The relationship of both generating capacity and pumping load to head is shown in Appendix C, Figure C-3.) This results from the fact that the rate of water use, at full gate opening, also decreases as the head decreases. There is therefore need to provide for some consistency in the basis for rating the plant capacity.

Reports to the Federal Power Commission will usually show the generating capacities available at both maximum and minimum heads. However, the nominal capacity of the plant, for publicity purposes or for inclusion in various listings of plant capacity, may be reported by the owner as the maximum or the minimum or somewhere in between. Some plant owners have followed the conservative practice of rating the plant capacity at minimum head; and where this is evident, such rating has been accepted for the purpose of analyzing costs and characteristics. Where the nominal rating is evidently based on a higher head, it has been ignored in this report; and for consistency in comparison among the existing plants, a rating has been adopted which gives 80% weight to the minimum head and 20% weight to the maximum head. This arbitrary average rating assures that the rated capacity will be available for more than 80% of a daily operating cycle, and where operation is on a weekly cycle, for an even greater percentage of time. Thus the plant capacities used in this analysis differ from those reported for other purposes.

During the generating portion of the cycle, the output of the plant may be controlled at some level below the available output. It will most often be the intent to operate at or near the most efficient load point, which is a load less than the available plant capacity at all heads. If desired, it would be possible to operate continuously at or close to the rated capacity, but with some sacrifice in efficiency. Departures from efficient loading may be required for area load regulation and to provide maximum available capacity under heavy load conditions or during shortages of other generation.

During pumping, the lower reservoir is emptied and the upper reservoir is filled; the gross head is increased. This results in a change in input, but generally there is a small decrease in pumping load as the head increases. This is the result of the much larger water quantity that can be pumped at minimum head as compared to that at maximum head. The input to the unit is not ordinarily under the control of the operator, for once the unit has been started as a pump, it is operated at or close to its most efficient gate opening. Because the input, or pumping load, is whatever it must be as the head varies, the average of the reported loads at maximum and minimum heads has been used for purposes of comparison to the rated output of the plant in the generating mode of operation.

Because of the opposite effects of head on the water quantities used during generation and on the quantities that can be pumped, it is possible, by selection of the pump/turbine unit design, to favor either one or the other. This permits a selection to be made of the ratio of pumping load to generating capacity, which will be discussed later as an important characteristic of any storage method.

2.1 CHARACTERISTICS

Both technical characteristics and construction costs have been based on the experience or expectations of the 11 selected plants listed in Table 1, which are believed to be generally representative of future pumped storage projects. The selection of these plants is discussed in Appendix A. Several of their characteristics are investigated in Appendix C, and for these, only summary conclusions are reported below.

Table 1 SELECTED PUMPED STORAGE PROJECTS FOR WHICH CHARACTERISTICS AND COSTS HAVE BEEN ANALYZED

Plant Name	Initial Operation	Plant Capacity MW(a)	Average Head Feet(b)
Taum Sauk	1963	350	809
Yards Creek	1965	330	723
Muddy Run	1967	855	386
Cabin Creek	1967	280	1159
Seneca (Kinzua)	1970	380	741
Northfield	1972	1000	772
Blenheim-Gilboa	1973	1030	1099
Ludington	1973	1675	328
Jocassee	1973	628	310
Bear Swamp	1974	540	725
Raccoon Mountain	1975(c)	1370	968

Notes:

(a) Capacity may differ from amount reported by owner or by FPC in order to provide consistency in the basis of rating.

(b) Average of reported maximum and minimum heads.

(c) Initial operation has been delayed to 1978 by unanticipated construction difficulties.

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2.1.1 Size and Head

The unit size suitable for utility application will generally be larger than 100 MW; in fact, the reported planned units are generally larger than 200 MW. Smaller units have, of course, been built, and may continue to find application in special situations.

The reversible unit of maximum physical size thus far constructed is the relatively low-head unit for Ludington; the maximum capacity unit, for Raccoon Mountain, is 383 MW. Since conventional hydroelectric units have been built in even larger sizes, it is likely that still larger pumped storage units may be planned for future plants. Although larger sizes tend toward lower per-unit ($/kW) costs, there are structural and mechanical reasons, as well as operational and possibly economic reasons, for continued use of units of moderate size. Because of the diverse site and system conditions that influence the selection of an optimum size, speculation as to the future maximum size is not likely to be productive, rather the removal of limitations on large sizes is a subject for research and development.

Plant size can be any multiple of unit size, and generally per-unit costs will decrease with increase in the plant capacity. From two to eight units have been installed in the selected group of plants; and the largest one in service contains six units for a total of 1675 MW. Total plant size is frequently limited by the available reservoir capacity; and if this is not the limitation, it will usually be the size that fits the utility system needs, including possibly those of its neighbors.

The heads that have been found economical for development, in the absence of special conditions, have been above 300 feet. The maximum head utilized by a reversible unit in the United States is now 1200 feet; but plants are planned that will utilize more than 1600 feet. (A plant in Japan is now operating with a head of 1640 feet.) The practical limit for a single-stage reversible unit is probably an even higher head, and there is some opinion that such units can be operated successfully at more than 2500 feet of head. For still higher heads, and particularly for underground plants, it will be necessary to consider multistage units, units in series, or separate pumps and turbines.

The development of reversible units for higher heads is probably the major needed research and development activity related to hydro pumped storage.

2.1.2 Efficiency

Demonstrated over-all efficiencies have increased from 66% to 75%; several projected efficiencies, not yet demonstrated, are reported to be still higher. The improved efficiencies have resulted from improvements in pump/turbine design and from more liberal design of water passages to reduce energy losses and increase plant capacity. This results from system economic conditions that justify the higher expense of larger penstocks and lower water velocities.

Because over-all efficiency is the product of the separate pump, motor, generator, transformer (used twice), turbine, and waterway (used twice) efficiencies, and because each efficiency is at or close to its practical limit, there appears to be little prospect for an over-all theoretical efficiency as high as 80%. Furthermore, in actual operation best efficiency cannot be attained because of variations in loading, starts and stops, requirements for station service, and minor losses due to leakage and evaporation. It appears therefore that 75% may be a practical upper limit of operating efficiency, and the more likely efficiency may be as low as the 70% demonstrated by several plants.

If efficiency is to be represented by a range, this range should be 70 to 75%. For a single value, use 72%. Note that these efficiencies do not cover transmission losses incurred during delivery to or from the pumped storage plant, but can be assumed to cover the step-up transformer losses.

2.1.3 Charge/Discharge Ratios

This particular ratio is measured by the relation of power input (average pumping load in MW) to power output (rated capacity in MW); and the selected plants (with one exception) show a range in this ratio of 1.0 to 1.3. The importance of the ratio is in its effect on available generating time. For example, if the ratio of pumping load to rated capacity is 1.25 and the over-all efficiency is 72%, then the duration of generation available from one hour of pumping will be 0.9 hours (= 1.25 x 0.72).

These ratios are within the control of the plant designer and the higher values of these ratios are obtainable only at some cost. Where the lower ratios have been used, it appears that less value has been placed on additional daily generating hours. However, it appears to be generally and economically advantageous, particularly where long durations of daily generation are required, to increase the available generating time by increase in these ratios in preference to, or in addition to an increase in reservoir storage. Of course, the optimum design for any particular site will depend on reservoir costs and other site related conditions.

There appear to be practical limits to these ratios. The lower limit for the charge/discharge ratio might be 1, which means that the pumping load is equal to the rated generating capacity; this might be considered a balanced electrical design. A practical upper limit is reached when the ratio equals about 1.35 to 1.4, indicating that the average motor load is well in excess of the rated generating capacity, but that the rate of water pumping is about equal to the rate of water use. The reason for higher cost is therefore evident, for in addition to the larger electrical equipment, it is also necessary to have a somewhat larger hydraulic unit to produce these higher ratios. Conversion efficiencies are slightly lower for the higher charge/discharge ratios.

It is suggested that the charge/discharge ratio, as measured by electrical input and output, be considered to be within the range of 1 to 1.4. Consequently, the available duration of generation from one hour of pumping will be within the range of 0.72 to 1.0, based on the suggested average efficiency of 72%.

2.1.4 Reliability and Availability

Based on limited experience, and discounting very unfavorable experience during a few early years of operation of several pumped storage plants, it appears that the following factors may reasonably represent the reliability and average availability of future pumped storage units:

(a)	Forced outage rate	4%
(b)	Average annual maintenance, scheduled outages and incidental unplanned outages	5 weeks/yr.
(c)	Average availability (47/52 x 0.96)	87%

The factors (a) and (b) are equal or close to those used by the Mid Atlantic Area Council area for planning purposes, and are based on the operation of three pumped storage plants within this area. The factor (c) is derived from (a) and (b), but is independently confirmed by the operating availability of pumped storage as reported by the EEI Prime Movers Committee(1).

There is substantial opinion that pumped storage units can, and eventually will show higher reliability and availability than is suggested above. Since conventional hydro units have an average forced outage rate below 1% and a maintenance time more like two or three weeks per year, there is room for improvement in the pumped storage factors. On the other hand, there is no doubt that pumped storage units are subject to more severe strains than conventional hydro units and have more opportunities for breakdowns.

Reliability of any energy storage system is also affected by the adequacy, or inadequacy of its limited energy to "firm up" its capacity on the system load curve. Any unreliability that may result from energy limitations decreases as the storage, in terms of generating hours, is increased.

Some explanation of the above stated forced outage rates, both for pumped storage units and for conventional hydro units, is required, since they are higher than those reported by the EEI Prime Movers Committee. The explanation lies in the forced outage rate definition, which is not well suited to the determination of such rates for peaking units. Because this definition relates forced outage time to exposed time (operating time plus forced outage time), the rates are very high for units that deliberately have only limited operating time. For peaking units a lower and more significant rate is obtained if the forced outage time is reduced to the outage time occurring during the period of demand for the operation of the unit.

The need for this adjustment of the forced outage rate was recognized soon after the first outage data were published for combustion turbines(2). The subject has also been discussed in an IEEE paper(3), which recommends a formula to be used in the adjustment of the forced outage rate. The adjusted rate is then roughly that which would result were both outages and operating time measured in whole days, with its status being determined by its condition at the time of daily peak load. When forced outage data were first recorded and analyzed nearly 40 years ago, the records were kept on this daily basis.

If the adjustment formula is applied to the 1974 EEI data for pumped storage units, the reported 12.97% forced outage rate is reduced to 5.27%. This adjusted rate can be further discounted, based on the fact that the EEI data contain a large proportion of experience for immature units, i.e., units that have had high outage rates while design and construction deficiencies were being corrected.

The EEI rate for "operating availability," which is equal to available hours (whether or not operated) divided by period hours, needs no substantial adjustment. If forced outages are random as to the times they occur on any day, this ratio is again roughly equivalent to a count of the days that the unit is available divided by the days in the year.

The stated forced outage rate of less than 1% for conventional hydro units is not based on the very limited EEI data, but is based on two reports, from much larger samples of hydro units, showing respectively rates of about 0.5%(4) and 0.7%(5).

2.1.5 Extent and Duration of Energy Storage

The energy storages at the existing selected plants (with one exception) are sufficient for about 6 to 24 hours of generation at rated capacity. For a daily cycle of operation, 8 to 10 hours of storage appears to be sufficient; any greater storage will necessarily be operated on a weekly cycle. The Jocassee plant has a storage equivalent to 94 hours in order to take advantage of natural flow into the upper reservoir and to permit its use for other purposes.

For future plants, the amount of storage measured in hours of available generation is a variable to be determined by system load conditions and economics.

Once the water has been pumped into the upper reservoir of a pumped storage plant, it can be maintained as a stored energy resource for a relatively long time. Losses from leakage and evaporation are small and may even be offset by rainfall and local runoff. Under unfavorable conditions, these losses are likely to be less than 5% per month, assuming there is some reason for the storage to be unused for such a long period.

Also, when the storage is used, almost all of it can be used--only enough must be retained to fill the water passages and maintain the normal minimum head on the plant.

2.1.6 Turn-around Time

A pumped storage plant, unlike some other storage devices, cannot pass quickly from the pumping to the generating mode, or vice versa. A definite time interval is required, because of mechanical and hydraulic inertias, for decelerating the unit in one direction, for switching and proper operation of auxiliaries, and for acceleration in the opposite direction. Also because of limitations in control facilities or in the mechanical and electrical arrangement of the plant, it will frequently not be possible to "turn-around" more than one unit at a time, or possibly two units if the total number is as many as six or eight.

Typical turn-around and starting times are:

from pumping to full load generation..	2 to 20 minutes
from generation to pumping............	5 to 40 minutes
from shutdown to full load generation.	1 to 5 minutes
from shutdown to pumping..............	3 to 30 minutes

These times might be applied, in series, to each unit in a plant. Under normal conditions, the successive operation of each unit may not be a real disadvantage, since changes in system load could require even longer intervals between the initial operation of each unit.

2.1.7 Load Regulating Ability

A pumped storage plant can follow load to a limited extent, but generally the effect on efficiency and on maintenance requirements will be considered prohibitive. Nevertheless, under some conditions the advantages outweigh the penalties of such operation. At least one and possibly two of the selected plants do operate as load regulating units and the effect of this operation shows up in very low over-all efficiencies.

Of course, some gross load regulation is accomplished by the starting and stopping of the units, either as pumps or generators; but this is no more or less than can be accomplished by the starting and stopping of other energy storage systems. Because of its quick starting ability, a pumped storage unit at standstill may, in some systems, be counted as operating reserve, in the same manner as is combustion turbine capacity.

For purposes of this investigation, it is suggested that hydro pumped storage be considered to provide load regulating service only in unusual situations, with no regulation being consistent with the use of the above suggested efficiency range.

2.1.8 Useful Life

Hydro units and plants are inherently long-lived property. Many hydro plants are already 50 years old and some plants that are 70 years old are still operating with original equipment. Massive structures, such as dams, dikes and tunnels seem to have an almost indefinite life if adequately maintained, and there is little difference in these as between hydro and pumped storage plants.

Although pumped storage units are subject to more severe service requirements than are conventional hydro units because of reversals in direction of operation and more frequent starts and stops, maintenance and interim replacements of breaker parts, generator windings, bearings, etc. should give the pumped storage plant equipment a comparably long life.

For accounting purposes, a number of pumped storage plant owners are using an average life of 70 years as compared to 80 years for hydro. Reports filed with the Federal Power Commission show a range from about 50 to 75 years for pumped storage. For tax purposes, IRS allows a life of 50 years for all hydro property.

For economic comparisons, the difference between 50 and 70 years is of little significance, and the shorter life is therefore recommended for the purposes of this investigation.

2.1.9 Other Characteristics

There are several other characteristics of storage systems in general that are either not applicable to hydro pumped storage or that can only be considered in qualitative terms. Among the former are storage density and temperature range. Among the latter are the following:

Maintainability - good, as evidenced by a reasonably low cost per kW per year.

Simplicity - also good, but only relative to the complexity of a modern fossil or nuclear plant.

Ease of expansion - poor, unless substantial expenditures are made in advance for larger reservoirs and for ultimate expansion of the plant.

Compatibility with existing power generation - complete, as evidenced by existing operations.

2.2 COSTS

2.2.1 Basis of Estimates

Because of the status of pumped storage development, estimates of costs for both construction and operation can be based on experience.

Construction cost data are available for 11 plants of the size and head that are considered typical of future utility applications. Representative operating experience is available for a smaller number of plants. The cost data are available in Federal Power Commission publications(6), in reports to the Federal Power Commission, and from communications from the plant owners.

The individual plant cost data are reported and analyzed in two appendices; only summary data on a per-unit basis ($/kW or $/kWh) are reported below. All costs have been adjusted to January 1, 1974 cost levels.

2.2.2 Determinants of Plant Costs

Pumped storage plant costs are heavily dependent on the topography and geology of the available sites and the requirements of the utility load that is to be served. Only a small part of the total cost is controlled by the designer on the basis of economic trade-offs.

The site determines the head, the maximum size of the reservoirs, the character and length of the required water passages, and the character (surface or underground) and cost of the powerhouse structures. System load requirements (and system energy costs) determine the capacity that can be served by the available reservoir size. The available head and the size of the units and of the plant in turn are the principal determinants of the per-unit costs of the plant, exclusive of the reservoirs. Within a reasonable range of conditions, the per-unit cost of this balance of plant decreases with increases in both size and head; and while reservoir cost might also be expected to decrease with increase in head, this is not always the case. Of all components of plant costs, those for the storage reservoirs vary most widely, for they depend directly on the topography and geology of the site and on the possibility of using existing lakes or reservoirs for one or both storages.

The designer of the plant controls its cost to a small extent. Costs are, of course, affected by the reliability, maintainability, and permanence that are built into the plant and by amenities that are provided in connection with it. Important economic decisions are involved in the selection of the pump/turbine and the connected generator/motor, for as noted in 2.1.3, costs are affected by the charge/discharge ratio. For example, to vary the ratio as earlier suggested from 1 to 1.4 might add about $12/kW to the plant costs. (This increase, however, may be more apparent than real, for if the plant capacity is limited in system operation by available energy, rather than by the physical limit of turbine output, the cost per effective kW may be actually reduced by the increase in pumping capacity.) Another economic decision relates to the size of the waterways and the resulting water velocities, which in turn affect the friction losses and penstock overpressures.

Considering site differences and other variables, it is not surprising that there is more than a two to one variation, even after reduction to comparable conditions, among the per-unit costs of the plants that have been built and which are here analyzed. When reservoir costs are removed from the total costs, most of the balance of plant costs can be explained by differences in size and head. Nevertheless, there still remains some variation that is probably explainable only in terms of specific local conditions.

Because of these conditions, no parametric analysis of actual costs has been attempted and for the purpose of this investigation ranges of costs have been suggested. These ranges do not cover either the lowest or the highest cost facilities, but are believed to be representative of the cost conditions (as of January 1, 1974) that might be experienced for future pumped storage plants.

2.2.3 Construction Costs

In view of the above discussion, it is desirable that reservoir costs be considered apart from the balance of the plant costs. This is also desirable for subsequent economic analysis, for reservoir costs are closely equivalent to energy storage costs that should be expressed in terms of \$/kWh, while the balance of the plant costs are essentially capacity or power related and are to be expressed in terms of \$/kW. Plant substation costs (not ordinarily included in pumped storage plant accounts) are separately stated (in \$/kW) for comparability to the costs for interfaces between other storage systems and utility system transmission.

It is proposed that pumped storage plant construction costs as of January 1, 1974 be represented by the following ranges:

energy storage	\$2 to 10/kWh
balance of plant	\$100 to 150/kW
plant substation	\$5 to 10/kW

2.2.4 Operating and Maintenance Costs

These costs have been found to be relatively small. They also vary from plant to plant; but if extreme values are ignored, the variation is not likely to be a significant factor in any economic analysis. It is proposed that these costs, at January 1, 1974 wage and price levels, be represented by the following range of costs or preferably by a single annual rate:

Operation and maintenance	\$1.40 to \$1.80/kW/year
or	\$1.60/kW/year

It is expected that future expenses, except for escalation in wage rates, should be even lower for two reasons. For the larger plants, operating expenses per kW should be lower, because essentially the same manpower is required for a small as for a larger plant. For all plants, the maintenance expenses should be lower after correction of design and construction deficiencies during the early years of operation. However, there is little evidence of these trends in the presently available data.

2.2.5 Other Costs

Other costs for pumped storage plants include those accounted for as fixed charges which are related to the investment in plant, and certain fees. For all non-federal plants to date, these fees include the license fee payable to the Federal Power Commission (about $0.10 per kW per year); and for those plants that make use of an existing reservoir or of other facilities, there will usually be a payment required for such use. Such payments are reported as an operating expense, but have been excluded from the basis of the above estimates, for it is difficult to generalize as to the appropriate rates.

Because of the expected long life, salvage values or costs of removal are not significant and are ordinarily covered by the annual charge for depreciation. Start-up costs, as related to initial plant operation, e.g., initial fill of the upper reservoir by pumping, testing, training, etc. are included in construction costs. Start-up costs, as related to daily starts, are covered either by the over-all plant efficiency (water losses require more pumping) or by O&M expenses. Costs for recreational facilities, environmental requirements, or other amenities are considered to be covered by the above proposed construction costs or by annual expenses.

2.3 SAFETY AND ENVIRONMENTAL CONCERNS

2.3.1 Safety

Because of the status of pumped storage development, the safety problems are known and adequate protections against structural failures and adverse occurrences have been developed. The principal problem areas are as follows:

(a) Safety during construction - closely regulated by various state and federal agencies.

(b) Dam safety - subject to state and federal requirements for design, construction and periodic inspection.

(c) Powerhouse flooding, particularly for an underground powerhouse - flooding has occurred and protection is obtained only by conservative design, special unwatering arrangements and care in operation.

(d) Water surface fluctuation - rapidly varying water surface elevations may be a hazard, if reservoirs are open to public use.

(e) Operating hazards, usual to work near high-voltage equipment, moving mechanical equipment, and water - safe practices are enforced by the owner and various state and federal agencies.

None of the above safety problems are a reason for not building or operating a pumped storage plant. All the costs of adequate protection against them are included in the above recommended cost ranges.

2.3.2 Environmental Concerns

Because of environmental objections, some proposed pumped storages have been long delayed and some may never be built. These projects have attracted the major attention, so far as the general public is concerned. On the other hand, a number of plants have been built or are under construction; and others are planned to meet the evident need for this type of capacity. At least some of these have already met the environmental test. Many more sites are suitable for development and the environmental acceptability of these must be weighed as each one is presented for licensing to the Federal Power Commission (or other approval applicable to federal projects).

An environmental impact report is now required as a part of every Federal Power Commission license application. Although these environmental assessments require consideration of energy conservation, load flattening, and the possibility of no plant as an alternative to the proposed pumped storage, in the context of this investigation of alternative energy storage methods, the no-plant alternative need not be considered.

The environmental impact of a proposed pumped storage must be considered relative to the impact of other plants that can provide the same service; these should be both pumped storages and other types of generating capacity. Consequently, it doesn't necessarily follow, because development of a pumped storage site has certain adverse environmental impacts, that the site is environmentally unacceptable. Rather its acceptability must be measured in relation to other sites, to other types of capacity and to the benefits of the proposed development. Such comparative assessments are impossible and inappropriate in this report.

Because of the diverse conditions existing at sites suitable for pumped storage development, it is difficult to generalize as to the importance of various environmental impacts and as to methods and costs of minimizing adverse effects. It is possible, however, to list the environmental factors, the basis of objections made to pumped storage, the possibilities of minimizing or eliminating some objectionable conditions, the positive benefits of pumped storage, and (in the next section) some research needs.

The environmental factors that would be involved in a comparative assessment of sites were outlined and discussed in the 1973 report on "An Environmental Reconnaissance of Alternative Pumped Storage Sites in New England"(7). It is there stated that:

> "A comprehensive outline of environmental factors was first drawn up showing . . . the elements of the environment which would be affected by pumped storage projects. . . . Ideas for this outline were obtained from many similar outlines used in other studies and environmental evaluation systems . . . . The outline, in its final form, is shown below.

"I. WATER RESOURCES DISRUPTION

- A. Hydrology
    - 1. Surface Water
        - a. Drainage
        - b. Stream Flow
        - c. Evaporation
    - 2. Groundwater
- B. Quality
    - 1. Surface Water
        - a. Sediment
        - b. Turbidity
        - c. Dissolved oxygen
        - d. Temperature
    - 2. Groundwater
- C. Plants and Animals
    - 1. Plants
        - a. Habitat
        - b. Unique flora
    - 2. Animals
        - a. Resident
        - b. Migratory
        - c. Rare and endangered species
- D. Wetlands

"II. LAND RESOURCES DISRUPTION

- A. Plants
    - 1. Habitat
    - 2. Unique flora
    - 3. Timberlands (ecological impact)
- B. Animals

1. Rare and endangered species
2. Resident species
3. Migratory species

C. Aesthetics

1. Scenic land forms
2. Unique physical features
3. Land and vegetative patterns
4. Water

"III. SOCIAL RESOURCES DISRUPTION

A. Private Developments

1. Residences (including vacation homes)
2. Farms
3. Commercial
4. Industrial
5. Timberlands

B. Public Developments

1. Utilities
2. Transportation
    a. Highways and roads
    b. Railroads
3. Facilities
    a. Schools
    b. Cemeteries
    c. Other
4. Public Plans
    a. Regional, state and local plans
    b. National and state forests and parks
5. Other
    a. Archaeological sites
    b. Historical sites

C. Recreation

1. Water Related
    a. Swimming
    b. Boating
    c. Fishing
2. Land Related
    a. Hunting
    b. Hiking and camping
    c. Other"

A listing of problem areas, which are the basis for objections often made to pumped storage, puts some of the environmental factors in a different context. Some of the objections can be overcome at reasonable cost, some cannot.

(a) Use of land areas for reservoirs, otherwise to be used for agriculture, recreation or left as wilderness. Because of the relatively small reservoirs and the nature of the sites, the displacement of population is generally not a major factor.

(b) Use of land for required transmission.

(c) Use of land for construction purposes.

(d) Temporary noise, dust, traffic, people problems, etc. during construction.

(e) Aesthetic objections to structures, such as dikes, transmission towers, and penstocks.

(f) Displacement of wildlife and damage to fish.

(g) Aesthetic and safety objections to fluctuating water surfaces.

(h) Effects of exposed reservoir areas on water temperatures.

(i) Possibly increased energy use due to cycle efficiency.

(j) Relative irreversibility of the effects of the project.

There is not much that can be done about some of these problems beyond selection of the site for which these impacts are small. For example, there will always be objections on the basis of land use, and overcoming objections from one segment of the population only leads to objections from others with different interests. Also the irreversibility of the effects of the project, if there are irreversible effects, must be given whatever weight is appropriate.

Some of the undesirable conditions experienced during construction can probably be minimized by better planning, scheduling, screening, paving, etc., all at some small additional costs.

Some of the aesthetic objections can be overcome by planting or screening the outside slopes of dikes and downstream slopes of dams, by placing waterways and powerhouse underground (usually an economic decision, if site conditions are favorable), and by careful routing of transmission lines to minimize their impact. The aesthetic and safety objection to fluctuating water surface elevations may be minimized by use of low auxiliary dams to maintain the water elevation in shallow arms of the reservoir which, even if completely exposed by drawdown, would contribute little to storage capacity. The resulting small ponds are then better suited to recreation uses. This involves some additional costs, which usually are small (at Muddy Run such an auxiliary dam represented less than 1% of the project costs). Aesthetic objections also tend to be countered by adequate provisions for recreation, including a visitors' center, suitable landscaping and other amenities.

Damage to fish is a site-related factor and the extent of the problem is quite different for a plant on a major river or natural lake as contrasted to one developed on a very small drainage area. Where there was a prior existing major water body, it is desirable that fish be kept from passing through the plant or that it be conclusively demonstrated that such passage is not seriously harmful. For a plant on a very small drainage, however, the pre-plant fish may have been nonexistent. Consequently, although some fish may here be damaged by plant operation, there is likely to be a net increase in the fish population. Further work is needed on various aspects of the fish problem, as noted in the next section.

If the various environmental objections can be overcome and the plant can be built, then the costs of various necessary features can be assumed to be included either in the previously estimated construction cost or in the annual expenses.

The alleged increased energy use due to cycle efficiency is often an unjustified objection to pumped storage. A pumped storage supplied with pumping energy from incremental loading of efficient base-load units, i.e., units that would otherwise be only partially loaded during off-peak hours, produces its energy at a heat rate of about 12,000 to 14,000 Btu/kWh. This is the range of heat rates for combustion turbines that could supply the same amount and quality of peaking service. It is also the same or an even better range of performance than can be expected from fossil-fired cycling units, either older units adapted to this service or new units designed for the service. In cycling service such units have much higher heat rates than are usually mentioned as a basis of their design.

The argument favorable to pumped storage that can be based on heat rate is further reenforced by consideration of the types of fuel utilized by pumped storage and saved by its operation. In general, a more abundant fuel will be substituted for one that is scarce or more costly. This, of course, is one of the major positive advantages of pumped storage.

Other direct benefits of pumped storage, additional to the benefits and economies in its power supply use, may include substantial contributions to recreation and, in some cases, other incidental uses of the stored water.

Recreational uses include camping, picnicking, fishing, hiking, and where auxiliary ponds are provided, boating and swimming.

Substantial additional uses of the stored water for other purposes may, of course, result in the plant's being considered no longer as a "pure" pumped storage; but some such uses can be obtained without material increase in size or cost of the pumped storage facilities and without interference with their intended operations. Perhaps the most likely such use is in water supply, where diversion is required from one watershed to another, or some storage is required at a higher elevation. Generally, the water quantities involved in such diversion or storage are far smaller than those involved in the power operations. Another potential water supply use is the delivery of make-up for a closed cooling system of an associated thermal plant. Also, where the pumped storage is located on a relatively small drainage area, the plant operation can increase the quantity and quality (except for temperature) of low flows by releases from storage, these being generally required by the license or by state permits. Under the same site conditions, the storage may provide some flood control benefits.

Even the addition of heat to the water, resulting from the dissipation of the losses involved in the operating cycle, may not be all bad, for this may assure some open water for waterfowl use during the winter season.

It is obvious that the benefits as well as the adverse environmental impacts are site-related and can be evaluated only for specific conditions. The New England report had this to say on the subject:

> "Early in the evaluation procedure the Task Force was confronted with the question of the amount of attention that should be paid to ways of mitigating, or ameliorating, environmental damage at any site, and to the new, socially valuable, outcomes that the project might be made to produce. Every water resource project, including pumped storage projects, destroys some things, modifies others, and creates still others that are new. It is normally possible, when trying to conceive in the mind's eye of the way that a particular site would be affected, to think of a very large number of small design and operating variations that would change the amount of environmental impact at and near the site. Of course in order to evaluate a given site it is necessary to have some general idea of the range of project design variations that could be made at that site. At the same time, however, it is important to avoid overemphasizing this part of the evaluation procedure. If care is not exercised here, a great deal of energy and speculation can be devoted to thinking of ways that projects 'might' be altered to avoid this or that environmental impact, or to produce this or that new recreation or other experience for people. It is then easy to begin making, perhaps unconsciously, trade-offs between the environmental

damange that would occur and the newly produced attributes of the project. While this analysis is certainly needed when full-scale studies are undertaken of individual sites, it can be a hindrance to evaluations designed to identify the best set of candidate sites solely from the standpoint of environmental impact.

"The approach taken in this study, therefore, was to concentrate on the detrimental implications of each site. This is not meant to suggest that all effects will necessarily be detrimental or that there exist no ways to offset detrimental effects to some extent. . . ."

2.4 RESEARCH AND DEVELOPMENT OPPORTUNITIES

There are limited but important opportunities for research and development related to hydro pumped storage, including investigations of several basic problems that have wider application. These opportunities are:

1. Extension of head range for reversible pump/turbine units.
2. Investigation of metal fatigue in water with particular reference to the removal of structural and mechanical limitations on larger unit sizes.
3. Reduction of tunnel and other underground excavation costs.
4. Development of fish repulsion devices to keep fish away from intakes.
5. Further investigations (different types and different head ranges) of effect on fish of fluctuating water surfaces and of passage through plant.
6. Analysis of thermal effects of hydraulic losses and of extended reservoir areas on downstream releases in small streams.

REFERENCES

(1) EEI Prime Movers Committee, "Report on Equipment Availability for the Ten-Year Period, 1964-1973," EEI Publication No. 74-57, December 1974.

REFERENCES CONTINUED

(2) P. F. Albrecht, W. D. Marsh and F. H. Kindl, "Gas Turbines Require Different Outage Criteria," Electrical World, April 27, 1970, pp. 38-40.

(3) Report of the IEEE Task Group on Models for Peaking Service Units, "A Four-State Model for Estimation of Outage Risk for Units in Peaking Service," IEEE Transactions, Vol. 91/ 1972, January-June 1972, pp. 618-627.

(4) AIEE Committee Report, "Outage Rates of Steam Turbines and Boilers and of Hydro Units," AIEE Transactions, Vol. 68, Part I, 1949, pp. 450-457.

(5) Hilton U. Brown III, Lawrence A. Dean and Alfred R. Caprez, "Forced Generation Outage Investigations for the Northwest Power Pool," AIEE Transactions, Vol. 79, Part III, 1960, pp. 689-698.

(6) Federal Power Commission Annual Supplements, "Hydroelectric Plant Construction Cost and Annual Production Expenses," Fifteenth Annual Supplement, 1971.

(7) New England River Basin Commission, Power and Environment Committee, "An Environmental Reconnaissance of Alternative Pumped Storage Sites in New England," July 1973.

3. UNDERGROUND PUMPED STORAGE

Underground pumped storage, with one reservoir located in an excavated cavern, differs from conventional pumped storage using two surface reservoirs in a number of respects:

1. Because there are now no constructed plants, all costs must be estimated. However, because all components of an underground pumped storage have been constructed for other purposes, there is a good basis for such estimates.
2. Because there is a powerful economic incentive to use higher heads and thus reduce per-unit costs, particularly the costs of the excavated reservoir, single-stage reversible pump/turbine design will be pushed beyond the limits of present experience to perhaps heads of 2500 feet, or alternative unit and plant arrangements will be utilized to develop heads of 3000 to 5000 feet.
3. Because plant location depends primarily on the availability of suitable underground conditions, and to a less extent on surface conditions, the area in which hydro pumped storage may be constructed is extended. (See Appendix F.) Particularly important is the possible availability of sites closer to load centers and to sources of pumping energy.
4. Because of these differences, underground pumped storage probably involves additional safety problems, fewer environmental problems, and a greater need for research and development.

Except as suggested above, much of the discussion of conventional pumped storage is equally applicable to underground pumped storage and need not be repeated. Consequently, the similarities and differences need only brief comment in the discussion of characteristics and costs. Additional background materials, including the support for the recommended ranges of construction costs, are more fully discussed in the following appendices:

Appendix F - Sites for Underground Pumped Storage
Appendix G - Underground Construction Costs
Appendix H - Combined Hydro and Air Storage

3.1 CHARACTERISTICS

3.1.1 Size and Head

The unit size suitable for underground plants and for utility application will generally keep pace with reversible unit size for conventional pumped storage plants. However, because of higher heads, units of the same capacity will be smaller in physical size and of heavier construction.

There may be reasons, peculiar to underground pumped storage, for limiting the maximum size of unit for a particular application. For example, construction access to the underground powerhouse may place a physical limit on size. Also, where plants are constructed in series to utilize higher heads, the outage of a unit in one plant will require an outage in the other. System load requirements and reliability of operation may recommend that the individual unit size be limited, because of this double effect on system capacity. Also, staged construction of the lower reservoir over a long period of years may suggest the use of smaller units suitable to the successive increases in reservoir capacity.

None of these reasons for smaller unit size is a reason for smaller total plant size. In fact, to overcome certain high fixed costs of going underground, an economic plant size will usually be more than 1000 MW. Total plant size will be limited either by system requirements or by the size of storage available in the upper surface reservoir.

Because head is no longer limited by the topography of the site and because costs generally decrease with an increase in head, within a reasonable range, underground pumped storage will tend to utilize the highest practicable and economical heads. The use of higher heads will depend on:

1. The extension of the head range of single-stage reversible units.

2. The use of single-stage reversible units located in two plants in series, with a small intermediate reservoir, as a buffer between them, located at the draft tube exits of the upper plant.

3. The use of multistage reversible units, such as have been recently built abroad in moderate sizes. It is reported that designs have been developed for a unit of 150 MW capacity at 3000 feet of head.

4. The use of separate high-head turbines and multistage pumps. The separate turbine and pump would be connected to a single generator/motor in such fashion that the pump could be disconnected during turbine operation, this being a configuration that has been used extensively abroad.

3.1.2 Efficiency

The previously suggested range of 70-75% appears to be attainable. Relatively shorter water passages (length per unit of head) and smaller percentage variations in head may tend to increase efficiencies, but other unknowns may work in the opposite direction. For example, there is some expert opinion that the pump/turbine efficiency will decrease somewhat with an increase in head beyond the limits of present practices (see Figure G-3). Efficiencies may also differ, depending on the means employed to utilize the higher heads.

3.1.3 Charge/Discharge Ratios

This ratio, as measured by electrical input and output, can again be considered to be within the range of 1 to 1.4. Within this range, the selected value should be reasonably related to the energy storage capacity. If the storage is made relatively small, say 6 kWh per kW, because of high excavation costs for the lower reservoir and because this storage meets the needs of the system load curve, there is no need for a high ratio, since this smaller storage can be filled in an 8- to 10-hour pumping period. However, if the storage is as much or more than the equivalent of 8 hours of generation and such generation is required by the system load curve, then a higher ratio is desirable in order to permit as much use of the storage on a daily basis as is possible.

3.1.4 Reliability and Availability

There is no reason to modify the previously made estimates, although the first few plants in the early years of operation are likely to have less than the expected availability.

3.1.5 Extent and Duration of Energy Storage

High costs of excavation are likely to limit most underground plants to a storage suitable for operation on a daily basis, i.e., 8 to 10 kWh per kW.

Loss of energy from storage will not be significantly different, since the upper reservoir, from which such losses must take place, is still exposed to both leakage and evaporation. Minor losses may result from leakage into the lower reservoir, since such leakage must be pumped out.

3.1.6 Turn-around Time

No estimates are available that are different from the experienced times for other pumped storage, except that, if separate turbines and pumps are utilized, the turn-around time can be substantially reduced, because the direction of unit rotation need not be reversed.

3.1.7 Load Regulating Ability, Useful Life, and Other Characteristics

No changes are required in the previous discussion.

3.2 COSTS

3.2.1 Basis of Estimates

Estimates of costs have been prepared for several underground pumped storage plants, including estimates for various pump/turbine arrangements and reservoir construction procedures. One such proposed plant has reached the Federal Power Commission license application stage. Estimates for this plant have been compared to a completely independent estimate for another underground pumped storage and to the most nearly comparable estimates for a conventional pumped storage with an underground powerhouse. For the balance of plant, i.e., total plant excluding reservoirs and substations, the comparisons show the estimates to be reasonable.

Very little additional cost information is available in the published material, but what is available supports the conclusion that the balance of underground plant cost should be in the same range as the balance for a conventional plant.(1)

In connection with these plant cost estimates, an extensive investigation was made of underground excavation costs. This covered the actual excavation experience for underground hydro plants, including both tunnels and powerhouse caverns, also cavern excavation incident to quarry and mine operations, as well as the experience and opinions of several recognized experts.

3.2.2 Determinants of Plant Costs

The principal determinants of costs, as for conventional pumped storage, are the available head and size of units. However, unlike other pumped storage, head is not determined by the topography of the available sites, rather it is determined by the depth of competent rock that can encompass the lower reservoir (or reservoirs, if two plants are built in series to utilize a high head), the limitations of the available hydraulic equipment, and perhaps by economic limitations. As to the last factor, more work remains to be done.

Over a range of heads less than an optimum, total plant costs will decrease with increased depth, although this is not true of all components of plant cost. For example, there will probably be a step increase in costs at the head for which a single-stage reversible pump turbine can no longer be operated, and again at twice this head. Other costs, such as access shafts, high-voltage cable, ventilation, and certain components of construction costs obviously increase with depth. On the other hand, the size of the lower reservoir for a given energy storage decreases directly with depth; and because of the relatively high cost of excavation, this decrease more than offsets other increases over a fairly wide range of heads.

As indication of the importance of excavation, cost estimates have been made for proposed projects in which excavation represents more than 50% of the total project cost. For other projects where excavation may be accomplished under particularly favorable cost conditions, its estimated cost may be as low as 20% of the total project. Most of this excavation is, of course, in the reservoir cavern, where both volume and total cost decrease with depth. Other excavation for the powerhouse cavern and water passages may or may not decrease with depth, depending on the extent that their cross sections also decrease.

The underground reservoir involves not only a large volume of excavated material, but also a possibly long construction time with the accumulation of large interest charges for funds used during construction. These conditions suggest several steps to minimize over-all project costs including, (a) sale of excavated rock for concrete aggregate or fill, (b) provision of duplicate hoist shafts to permit more rapid excavation, (c) extended work schedules to permit greater use of hoists and other equipment, and (d) construction of the cavern in several physically separated sections, so that power facilities can be placed in service in successive stages. The optimum construction procedures and schedules will very likely depend on local conditions, including the expected labor costs and productivity as well as the type of rock to be excavated and its marketability.

In view of the local variability of these conditions, estimates have been made for <u>net</u> costs of reservoir excavation varying from about $3 to $10 per cubic yard (at approximate 1/1/74 cost levels), before addition of necessary allowances for overheads, contingencies and interest during construction.

There could also be variations in the estimated costs for the balance of plant, depending on head and type of unit. To develop the maximum head possible at minimum cost with units that are presently available, conservative design would probably dictate the use of single-stage reversible pump/turbines installed in two plants in series. This would permit the development of a total head of about 3500 feet and the use of unit sizes (if not otherwise limited) of about 300 MW. Although plant designs and cost estimates have been made on this basis, and such estimates are related to proven plant components, the use of plants in series is not necessarily the optimum design for the future. Two plants in series involve costs and operational problems that could be avoided, if the same head were developed in a single plant.

If single-stage reversible units are developed, as expected, for heads of up to 2500 feet (and particularly if underground excavation costs are favorable, thus reducing the incentive to use the maximum possible head), there may be little or no economic advantage to the use of two plants in series. Also, if further development of multistage reversible units permits the construction of larger units for higher heads and gives reasonable expectation of good reliability and low cost, then such units are also likely to be preferred to two plants in series. Depending on the optimism of the designer, an underground pumped storage that is being planned today for operation in the late 80's, may reflect in its plans either of these possibilities. No estimate of potential savings in costs has been attempted, but for the purpose of this investigation, the possibilities of savings are useful in indicating the direction of and need for further reversible unit development.

Absent other differences from conventional pumped storage plants, particularly those with an underground powerhouse, it might be expected the balance of plant cost for an underground storage plant would be in the lower range of the costs previously proposed, this being in recognition of the high heads and larger capacities that are desirable for underground construction. Partially offsetting this tendency is the added cost of safety features necessary to protect against flooding and high back pressures. Also tending toward higher underground costs are the required longer construction periods and consequent higher interest costs.

Based on review of the available information in Appendix G, it is concluded that the balance of plant can be constructed at costs (before allowances) in the same range as those proposed for a conventional pumped storage; but that the necessary allowance for contingencies and the higher interest cost result in higher total estimates for the underground plant. The resulting range of balance of plant costs can cover differences in head, size of units and type of units and more specific estimates are not justified for the purposes of this study.

Plant substations should not be essentially different in cost because they are underground; but there may be an additional cost, to be accounted for as transmission cost, for the long runs of high-voltage cable connecting the transformers to a surface switching station. For the purpose of the reported estimates, these costs are included in the substation.

3.2.3 Construction Costs

It is proposed that underground pumped storage plant costs as of 1/1/74 be represented by the following ranges:

energy storage	\$3 to \$12/kWh
balance of plant	\$120 to \$160/kW
plant substation	\$10 to \$15/kW

3.2.4 Operating and Maintenance Costs

There is no reason to believe these annual expenses will be materially different from the experienced small expenses for conventional pumped storage. The possibly higher costs for work underground may be offset by the larger size of plant. It is suggested that the estimate be a single rate of $1.60/kW/year.

3.2.5 Other Costs

These should be the same as for conventional pumped storage. Of course, there need be no rental payment for use of the lower reservoir; but it is possible that such a payment could be required for use of an existing facility as the upper reservoir.

3.3 SAFETY AND ENVIRONMENTAL CONCERNS

3.3.1 Safety

Safety problems will be increased because of the underground construction and operation. Assuming proper design of the underground reservoir system, there is no inherently greater risk of flooding the underground powerhouse than there would be for a structure with surface reservoirs. However, flooding has far more serious consequences in terms of long durations of plant shutdown, because there is no place to which water can drain, and pumping to unwater the plant may take a long time. This is a possibility that should be recognized in the design of the plant and some means of minimizing the impact of flooding have been considered. It is assumed that the costs of adequate protection are included in the recommended cost ranges.

Another condition peculiar to underground storage is the possibility, because of a mistake in operation, to subject the underground storage cavern to the full hydrostatic head of the project. This is not a problem for the cavern, but it is a serious matter with respect to all structures and equipment that would normally be subject only to the back pressure associated with normal water surface elevations in the cavern. The plant design must either allow for this condition or make its occurrence impossible. In either case, a substantial additional cost may be involved, but it is assumed that this also is covered by the recommended cost ranges.

The other safety problems of conventional pumped storage operation remain, although some may be reduced in extent by the use of one rather than two surface reservoirs.

3.3.2 Environmental Concerns

Reduction of adverse environmental effects is a strong, favorable factor, for nearly all those possible adverse effects previously mentioned for conventional pumped storage with two surface reservoirs are reduced when one reservoir is underground. Two new factors may need be considered. One is the disposal of excavated rock, assuming it cannot be sold as rapidly as it is produced, or cannot be fully utilized in dams or dikes required for the surface reservoir. The other is the introduction of relatively more heat into the water and a resulting higher equilibrium temperature for the hydraulic system, because of higher heads and smaller storage. This may increase the temperature of water discharged from the surface reservoir; and if the discharge is to a small stream, this may be objectionable or unlawful. The heating is due to the fact that system losses, approximately 40% of the daily generation, may have to be carried away, to a large extent, by the water returned each day to the surface reservoir.

3.4 RESEARCH AND DEVELOPMENT OPPORTUNITIES

The previously suggested list of opportunities for conventional pumped storage needs to be extended. Several additional items are evident from the above discussion; and others are explained only in the Appendices, to which references are made in the following list:

1. Development of multistage reversible pump/turbines.
2. Combined compressed air and water storage systems (see App. H).
3. Optimization of construction procedures.
4. Inventory of areas suited to underground pumped storage and air storage in excavated caverns (see App. F).
5. Studies of rock mechanics and of locked-in stresses as they affect limiting depths and location of suitable sites (see App. F).
6. Optimization of head-cost relationships.
7. Heat balance and temperature effects, both underground and in surface reservoirs.

REFERENCE

(1) J. G. Warnock and D. C. Willett, "Underground Reservoirs for High-Head Pumped-Storage Stations," Water Power, March 1973, pp. 81-87.

Appendix A

EXISTING AND PLANNED PUMPED STORAGE PROJECTS

Table A-1 lists the existing and planned pumped storage projects in the United States, based primarily on information published or assembled by the Federal Power Commission. The list is divided into three parts, as follows:

Part A - plants in operation at the end of 1974.

Part B - plants under construction, including the additional reversible unit capacity to be installed in plants already in operation.

Part C - planned projects, as evidenced by issuance of a Federal Power Commission license or preliminary permit, by the filing of a license application, or by other authorization.

The list shows the plant name, location, owner, capacity, head and year of initial operation of the reversible capacity. Capacities and heads are based on unit design data reported by the Federal Power Commission, and these will differ slightly from capacities and heads used elsewhere in this report in the analysis of characteristics and costs.

In summary, this list shows the present status of pumped storage capacity in the United States to be:

	Number of plants	Reversible cap. 10^6 kW
In operation, Dec. 31, 1974	26	8.8
Under construction	10	5.0
Planned (as defined above)	18	19.8
Total (excl. duplications)	51	33.6

In addition, there are many proposed projects or projects under consideration, the number depending on the source of the information. These projects and the availability of additional sites are discussed in Appendix B.

Data for some of the existing pumped storage plants will not be useful in the prediction of characteristics and costs for future pumped storage projects. Some of the existing plants are too small, operate at too low a head, or serve various purposes additional to the pumped storage of energy. Figures A-1 and A-2 are useful in the selection of those existing plants for which the characteristics and cost data are likely to be representative of future projects.

Table A-1 PUMPED STORAGE PROJECTS IN THE UNITED STATES

Plant Name	State	Owner	Reversible Cap.,MW Plant	Reversible Cap.,MW Units	Head feet	Initial Operation	Notes
A		In operation, Dec. 31, 1974					
Rocky River	Conn.	Conn.Light & Power Co.	7	3.5	230	1929	a,b,c
Buchanan	Texas	Lower Colo.R.Auth.	11	11	120	1950	a
Flatiron	Colo.	Bureau of Reclamation	8.5	8.5	292	1954	a,b
Hiwassee	N.Car.	TVA	60	60	190	1956	a, c
Lewiston	N.Y.	Power Auth.State of N.Y.	240	20	85	1961	b
Taum Sauk	Mo.	Union Electric Co.	408	204	820	1963	d
Smith Mt.	Va.	Appalachian Power Co.	132	66	180	1965	a
Senator Wash	Calif.	Bureau of Reclamation	7	7	74	1965	
Yards Creek	N.J.	Jersey Central P&L Co. and Public Service E&G Co.	339	113	760	1965	d
Muddy Run	Pa.	Philadelphia Electric Co.	800	100	411	1967	c,d
Cabin Creek	Colo.	Public Service Co. of Colo.	300	150	1226	1967	d
Salina	Okla.	Grand R. Dam Auth.	260	43	235	1968	c
Oroville	Calif.	State of California	293	98	615	1968	a
Thermalito	Calif.	State of California	82	27	95	1968	a
San Luis	Calif.	Bureau of Reclamation	424	53	323	1968	b
O'Neil	Calif.	Bureau of Reclamation	25	25	197	1968	b
Seneca	Pa.	Pennsylvania Electric Co. and Cleveland Elect.Illum. Co.	360	180	813	1970	c,d
Mormon Flat	Ariz.	Salt River A.I.& P.Dist.	50	50	122	1971	a
DeGray	Ark.	Corps of Engineers	28	28	188	1971	a
Horse Mesa	Ariz.	Salt River A.I.& P.Dist.	100	100	259	1972	a
Northfield	Mass.	Northeast Utilities	1000	250	820	1972	c,d
Blenheim-Gilboa	N.Y.	Power Auth.State of N.Y.	1000	250	1100	1973	d
Ludington	Mich.	Consumers Power Co. and Detroit Edison Co.	1872	312	330	1973	c,d
Jocassee	S.Car.	Duke Power Co.	304	152	310	1973	
Grand Coulee	Wash.	Bureau of Reclamation	100	50	299	1974	c
Bear Swamp	Mass.	New England Power Co.	600	300	730	1974	d
Total - Part A			8810				
B		Under Construction, Including Additional Capacity in Existing Plants					
Jocassee	S.Car.	Duke Power Co.	304	152	310	1975	d
Carters	Ga.	Corps of Engineers	250	125	384	1975	a
Raccoon Mountain	Tenn.	TVA	1530	383	1000	1978	c,d,e
Mt.Elbert	Colo.	Bureau of Reclamation	100	100	464	1976	b
Castaic	Calif.	Los Angeles Dept. of W&P	1200	200	1048	1976	a,b
Salina	Okla.	Grand R. Dam Auth.	260	43	235	1977	
Harry S. Truman	Mo.	Corps of Engineers	160	26	79	1977	c
Wallace	Ga.	Georgia Power Co.	216	54	95	1977	a, c
Fairfield	S.Car.	S.Carolina E&G Co.	480	60	150	1977	c
Montezuma	Ariz.	Arizona Power Auth.	500	125	1660	1978	
Total - Part B			5000				

Table A-1 PUMPED STORAGE PROJECTS IN THE UNITED STATES (cont.)

Plant Name	State	Owner	Reversible Cap.,MW Plant	Reversible Cap.,MW Units	Head feet	Initial Operation	Notes
C	Planned, as Evidenced by FPC License or Preliminary Permit, License Application, or Other Authorization						
Grand Coulee	Wash.	Bureau of Reclamation	200	50	299		c
Cornwall	N.Y.	Consolidated Edison Co.	2000	250	1050		c
Davis	W.Va.	Allegheny Power System	1000	250	864		
Stony Creek	Pa.	Pennsylvania P&L Co. and Metropolitan Edison Co.	1500	250	1000		
Blue Ridge	Va.	Appalachian Power Co.	1600	200	232		
Havasu	Ariz.	Arizona Power Auth.	1000	250	1000		
Antilon Lake	Wash.	Chelan Co. P.U. Dist.	1000	250	1290		c
Poor Mt.	Va.	Virginia E&P Co.	1500	-	890		
Bath County	Va.	Virginia E&P Co.	1500	-	1050		
Canaan Mt.	Mass.	Northeast Utilities	1000	-	900		
Green River	N.Car.	EPIC, Inc.	500	250	1000		
Breakabeen	N.Y.	Power Auth.State of N.Y.	1000	250	1035		
Rocky Mt.	Ga.	Georgia Power Co.	675	225	652		
Browns Canyon	Wash.	PUD No. 1 Douglas Co.	1000	-	2388		c
Jackson County	N.Car.	Carolina P&L Co.	1000	250	1398		
Helms	Calif.	Pacific G&E Co.	1050	350	1500		c
Bad Creek	S.Car.	Duke Power Co.	1000	250	1200		c
Kittatinny Mt.	N.J.	Jersey Central P&L Co. and Public Service E&G Co.	1300	260	1120		
Total - Part C			19825				

NOTES:

Listing of pumped storage plants is based on information published or assembled by FPC, supplemented for a few plants by information from other sources.

Listed capacities and heads are based generally on reported unit design data and will differ slightly from capacities and heads used elsewhere in this report in the analysis of costs.

a. Reversible units installed in same plant as conventional hydro capacity.

b. Plant used for special purposes, including downstream flow regulation, irrigation or water supply pumping.

c. Plant utilizes existing reservoir or natural body of water.

d. Plant data to be used in analysis of pumped storage characteristics and costs.

e. Originally scheduled for initial operation in 1975; delay caused by unanticipated construction difficulties.

Part C - The plants listed in this section, as well as their sizes and heads are less certain than those listed in Parts A and B. Several of the planned plants have been abandoned or indefinitely postponed, while other plants might be added to this list on the basis of preliminary permits pending at December 31, 1974. With such known changes, the total of Part C would show an increase in planned capacity of several thousand MW.

In both diagrams, each pumped storage project is identified by its unit capacity and head as reported in Table A-1. Figure A-1 shows the capacities and heads of the plants that are in operation or under construction; Figure A-2 shows the same data (where known) for planned projects.

Comparison of the two diagrams shows that, whereas the existing plants exhibit a wide range of unit sizes and heads, the planned projects are concentrated around a unit size of 250 MW and heads above 1000 feet. Larger units are possible and may be proposed, but the more moderate sizes will continue to have advantages in operation. It is, of course, possible that units with smaller capacities and lower heads will be utilized in future plants, particularly after the more favorable sites are utilized or where the development serves additional purposes.

Because there are an insufficient number of existing plants in the narrow size and head ranges indicated by Figure A-2, characteristics and cost data have been analyzed for those existing plants that have units at or above 100 MW and heads at or above 300 feet. These limits are shown on Figure A-1. In the area above and to the right of the dotted lines are located the principal "pure" pumped storage units, and it is this area that is believed to be typical of future projects. By "pure" pumped storage is meant those projects built primarily to store off-peak energy and to deliver it during on-peak periods. Many existing plants have additional purposes including development of conventional hydroelectric power, storage for use in downstream plants, storage for irrigation or water supply, or diversion of water from one watershed to another. Most of the special purpose or multipurpose plants are in the lower head and lower capacity range.

Of the 15 plants plotted in the higher-capacity, higher-head range of Figure A-1, 12 are considered to be "pure" pumped storage (or essentially so) and thus useful in the analysis of future pumped storage characteristics and costs. Eleven of these plants are listed in Table A-2, Montezuma being excluded because of the expected date for its completion. Note that the capacities and heads listed here are different from those recorded in Table A-1. These changes are necessary in order to provide some consistency among the data for the several plants.

Reports to the Federal Power Commission will usually show the generating capacity available at both maximum and minimum heads. However, the nominal capacity of the plant, for publicity purposes or for inclusion in various listings of plant capacity, may be reported by the owner as the maximum or the minimum of somewhere in between. Some plant owners have followed the conservative practice of rating the plant capacity at minimum head; and where this is evident, such rating has been accepted for the purpose of analyzing costs and characteristics. Where the nominal rating is evidently based on a higher head, it has been ignored; and for consistency in comparison among the existing plants, a rating has been adopted which gives 80% weight to the minimum head and 20%

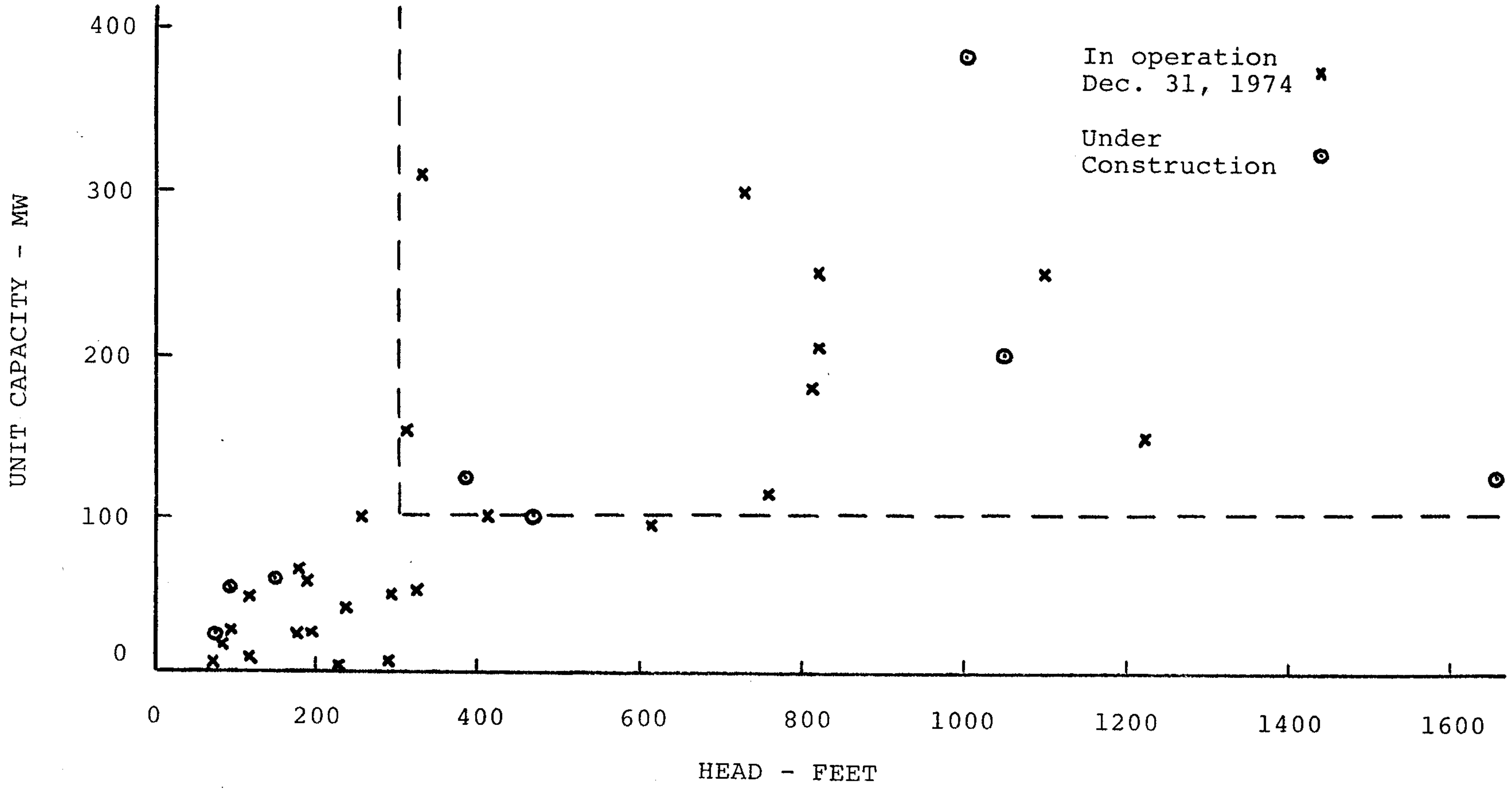


Figure A-1 UNIT CAPACITY AND HEAD OF PUMPED STORAGE PROJECTS IN THE U.S.

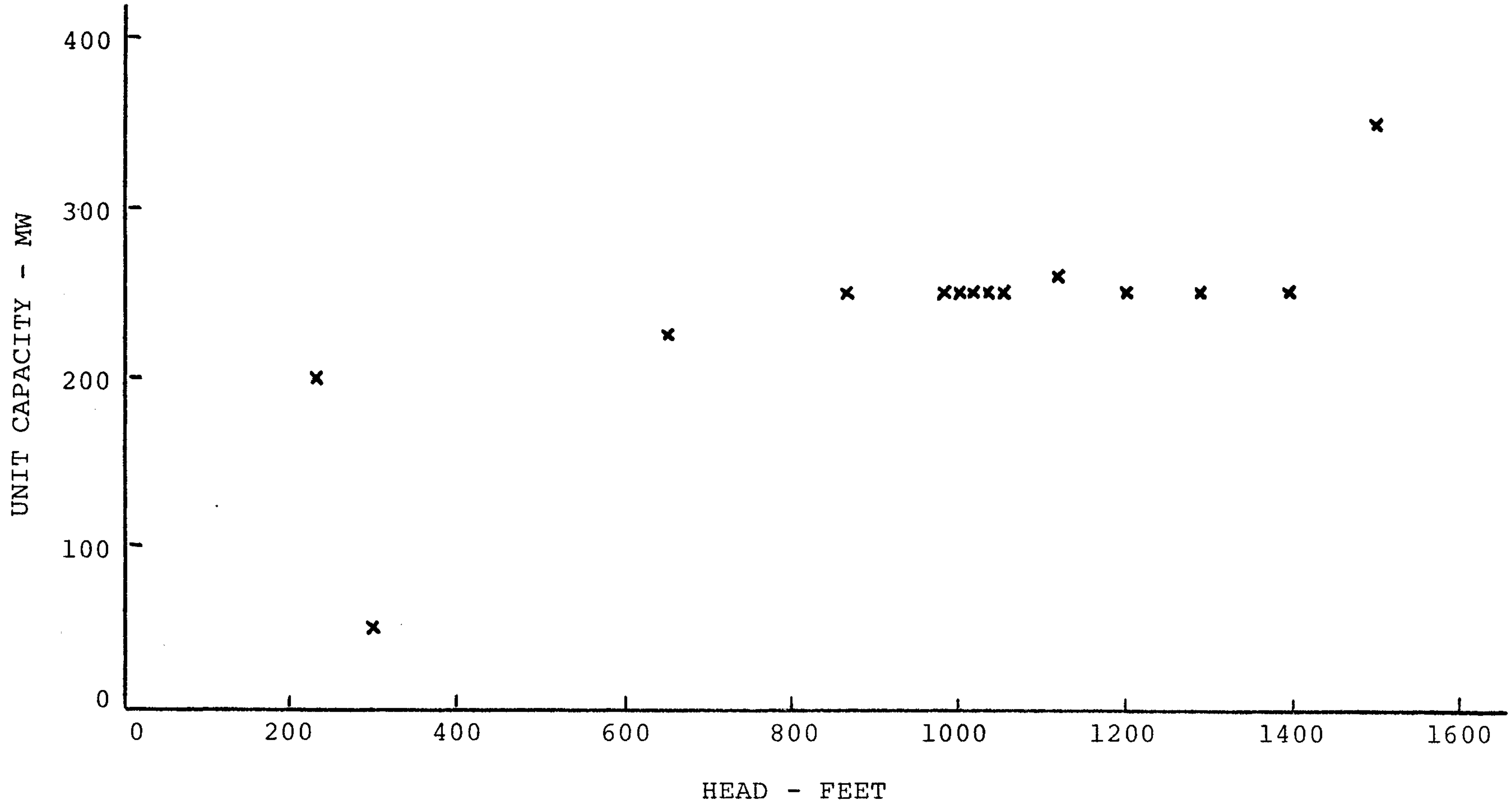


Figure A-2 UNIT CAPACITY AND HEAD OF PLANNED PUMPED STORAGE PROJECTS

Table A-2 SELECTED PUMPED STORAGE PROJECTS FOR WHICH CHARACTERISTICS AND COSTS HAVE BEEN ANALYZED

Plant Name	Initial Operation	Plant Capacity MW[(a)]	Average Head feet[(b)]
Taum Sauk	1963	350	809
Yards Creek	1965	330	723
Muddy Run	1967	855	386
Cabin Creek	1967	280	1159
Seneca (Kinzua)	1970	380	741
Northfield	1972	1000	772
Blenheim-Gilboa	1973	1030	1099
Ludington	1973	1675	328
Jocassee	1973	628	310
Bear Swamp	1974	540	725
Raccoon Mountain	1975(c)	1370	968

Notes:

(a) Capacity may differ from amount reported by owner or by FPC in order to provide consistency in the basis of rating.

(b) Average of reported maximum and minimum heads.

(c) Initial operation has been delayed to 1978 by unanticipated construction difficulties.

weight to the maximum head. This arbitrary average rating assures that rated capacity will be available for more than 80% of a daily operating cycle, and where operation is on a weekly cycle, for an even greater percentage of time. Thus the plant capacities used in this analysis differ from those reported for other purposes.

The heads shown in Table A-2 are the average for each plant of its reported maximum and minimum head.

Appendix B

AVAILABILITY OF FUTURE PUMPED STORAGE SITES

The development of future pumped storages, utilizing surface reservoirs, depends on the availability of suitable sites. Suitable sites must have the required topographic and geological characteristics, must not obviously involve the dislocation of substantial existing uses of the site, and must be reasonably close to the area in which the pumped storage capacity is to be utilized. These physical characteristics are fairly readily identifiable, and many site surveys have been based on these several factors as revealed by maps and field reconnaissance. Suitable sites also depend on their environmental acceptability, which is a more difficult factor to assess; probably few site surveys have given it the recognition that it requires.

Pumped Storage Sites in New England

A comprehensive survey of pumped storage sites, with consideration of their environmental acceptability, has been made by the New England River Basins Commission. Its report on "An Environmental Reconnaissance of Alternative Pumped Storage Sites in New England" was published in July 1973(1).

A total of 52 sites were examined in this report; based only on size criteria, 21 of these were eliminated from further consideration. Of the remaining 31 sites, 17 were considered to have obvious and unacceptable environmental impacts, leaving 14 sites with suitable characteristics for pumped storage development. These 14 sites have a maximum potential capacity in excess of 38,000 MW, based on 8 hours of storage. (A utility appraisal of the same sites results in a total installed capacity approximately half as large - a still considerable potential.) The 14 sites were further examined and classified as follows; but as to this classification it is stated that it "is not meant to imply that the sites in the least impact category should be the only ones considered in more detail":

4 plants having the least amount of on-site environmental impact	7,100 MW
8 plants involving an intermediate amount of environmental impact	24,700
2 plants involving the greatest amount of environmental impact	6,600

Although the report considers at length the "Environmental Implications of Alternative Peaking Power Technologies," it deliberately expresses no conclusions as to whether pumped storage is or is not the preferred option for New England.

Estimates of Projected and Potential Pumped Storages

Several estimates of projected and potential pumped storages on a nationwide basis have been published; these include the following three items:

1. In May 1974, the Federal Power Commission issued a "Staff Report on the Role of Hydro-electric Developments in the Nation's Power Supply."(2) This report includes estimates of projected conventional hydro and of projected pumped storage capacity. As to pumped storage, a summary of Table 6 shows:

In operation, May 1974	-	8,119 MW
Under construction, May 1974	-	6,253
Project for Development by 1983	-	13,103
Other Sites Possible of Development by 1993	-	13,715
Total		41,190

Of this total, about 7000 MW is additional to the plants listed in Appendix A.

2. In October 1974, Ebasco published a list of pumped storage projects(3), including categories designated as "Authorized or Proposed" and "Under Consideration." The listed plants in these categories, that are additional to those already listed in Appendix A, resulted in the following totals:

Proposed (additional to App.A)	-	7,837	to	9,337	MW
Under consideration	-	25,519	to	34,319	
Total		33,356	to	43,656	MW

It is reasonable to believe that the listed projects have had at least some environmental review, and that a large number will ultimately be found to be environmentally acceptable.

3. In August 1974, Mr. J. J. Stout, Chief, Division of Licensed Projects, FPC, presented a paper on "Potential Pumped Storage Projects that Would Use Existing Reservoirs."(4) In Table 3, he lists 27 such projects that provide a total capacity of 60,065 MW; and concerning this Table, he makes the following statement:

"The Commission's staff has made reconnaissance-type studies for at least five times the number

> of potential projects using existing facilities as are shown in Table 3. The projects selected for the table are those considered to be among the more favorable from the standpoint of physical characteristics and possible environmental impacts. Consideration was also given to probable costs, although this type of information is inconclusive in the absence of geologic and other data requiring extensive investigations."

In the above three references, the plants listed for future development in New England are respectively 2000, 7950 and 5480 MW. These listed amounts should be compared with the earlier reported estimate of 14 sites in New England with a total capacity in excess of 19,000 MW.

A map published by Ebasco(3) locates the 104 sites included in its list (item 2 above) and is here identified as Figure B-1. Reproduction of the map in black and white does not distinguish the ownership of the projects, as does the original colored map. This is not important, for the purpose is to show the areas in which pumped storages have been built or are proposed for construction. However, the absence of plants in certain areas does not mean that plants could not be built there, if needed. In some cases, at least, it simply means that the peak portion of the load is already adequately served by conventional hydro resources.

Regional Estimates of Potential Pumped Storages

In addition to the New England study, reported above, several other investigations of potential pumped storages have been made on a regional basis. Several of these have been published, the results of a few others are available from unpublished sources, and it is likely that there are many more such investigations that are necessarily unreported.

Pacific Northwest - In January 1972, the North Pacific Division Corps of Engineers prepared a report on "Pumped Storage Potential of the Pacific Northwest."(5) Part 1 of this report covered an inventory of sites in western Washington and Oregon and the Columbia River Basin below Pasco. In the "Summary" of the 1972 report, it is stated:

> "Pumped-storage, as a source of supplemental peaking capacity, holds great promise in the Pacific Northwest. As indicated by this survey, 242 sites exist in western Washington, western Oregon, and along the Columbia River below Pasco, Washington, each with the capability of furnishing at least 1,000 megawatts of capacity on a daily-weekly operating cycle. These sites represent a total capacity potential of more than 650,000 megawatts.

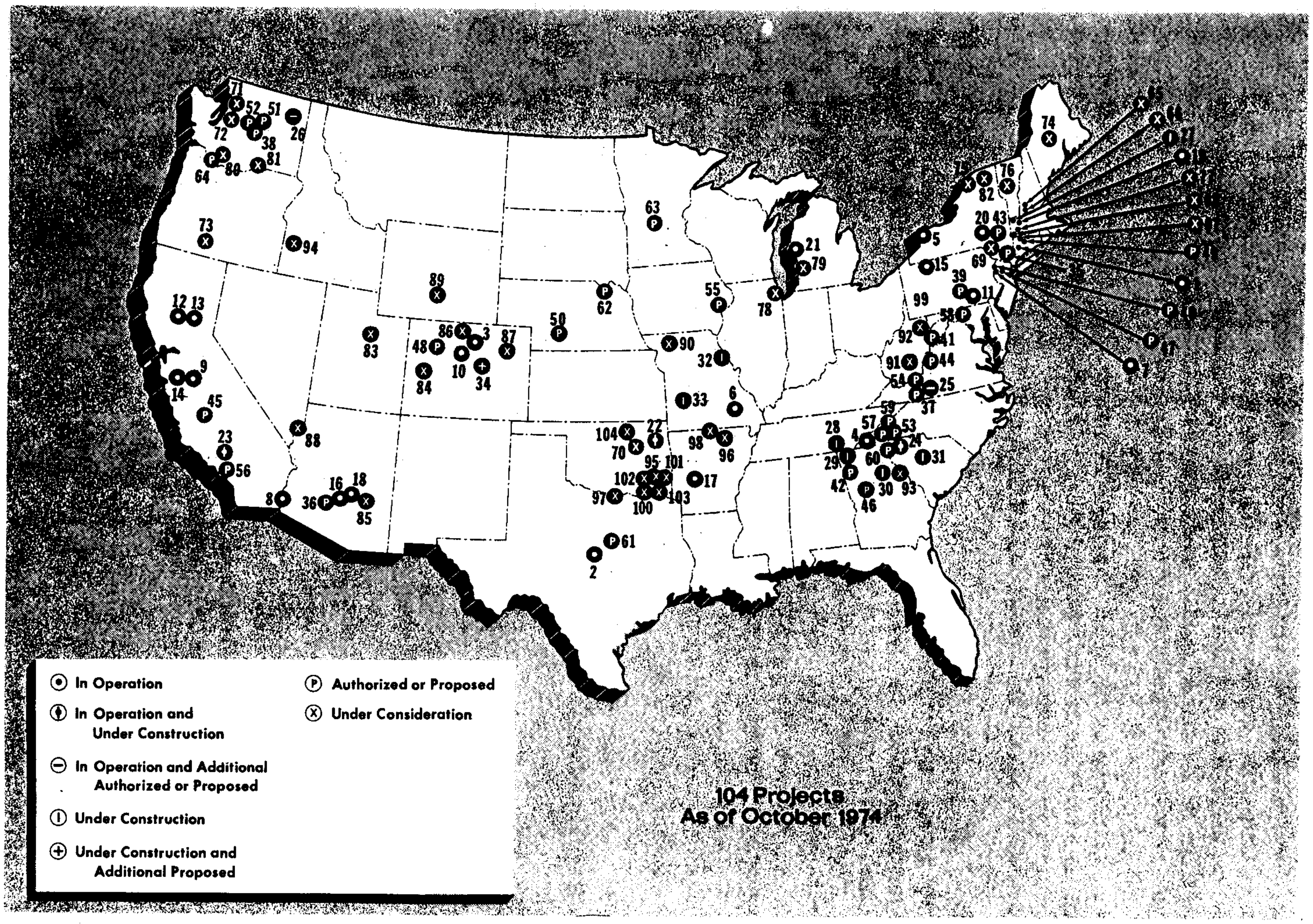


Figure B-1 HYDRO PUMPED STORAGE PLANTS IN THE U.S.

Source: "1974 Business and Economic Charts," prepared by Ebasco Services Incorporated, Business and Economic Research Department. Data Sources: FPC, U.S. Department of the Interior, Other Publications.

> "The region is blessed with an abundance of sites with investment costs, based on a 14-hour equivalent full-load operating requirement, in the range of $100 to $130 per kilowatt (1971 basis) . . .
>
> "From a purely economic standpoint, pumped-storage development would be timed to follow the completion of the present program of adding conventional units at existing hydro plants. However, for practical reasons, several pumped-storage plants may be constructed ahead of this schedule. It is quite possible that some conventional hydro will be delayed so that pumped-storage can be added to the system sometime between 1978 and 1995.
>
> "This study shows the total potential for pumped-storage development with full realization that further study will exclude many sites from future development. After detailed studies are made, many sites included in this inventory may eventually be found to be environmentally unacceptable. In any event, pumped-storage potential exceeds the need beyond the most liberal estimates of regional growth."

<u>Pacific Southwest</u> - The Federal Power Commission has published a report (1975) on "Potential Pumped Storage Projects in the Pacific Southwest,"(6) and the following statement is from the "Summary" of this report:

> "About 400 possible pumped storage sites were identified from United States Geological Survey quadrangle maps covering the States of California, Arizona, Utah, and Nevada. Of this total, about 245 sites, or over 60 percent, were eliminated because they did not meet the site selection criteria . . .
>
> "The remaining 155 sites would have an ultimate installed capacity of 341,100 megawatts, distributed by States as follows:

	No. of Sites	Ultimate Installed Capacity (MW)
California	56	144,200
Arizona	22	36,900
Nevada	20	44,400
Utah	57	115,600
Total	155	341,100"

The site selection criteria did not include environmental effects, but they did provide for elimination of sites located in special designated areas such as national or state parks, wilderness or primitive areas, and wild or scenic river reaches.

Because of the large number of available sites and their potentially large capacities, it is necessary to find only that relatively few are environmentally acceptable in order to meet the peaking capacity needs of the area.

Susquehanna River Basin - In 1963 a study was made of potential pumped storage sites in the Susquehanna River Basin in New York and Pennsylvania, a relatively small area of about 27,000 square miles. The results of the study have not been published.

The study started with an initial list of 326 sites, which was first reduced to 60 and then to 25 on the basis of map studies and preliminary estimates of cost. These 25 sites were then studied in further detail, after field reconnaissance, and the cost of estimates were revised. Finally, a list of 15 sites that met certain cost and other criteria were recommended for further investigation.

The criteria did not include environmental effects; but the selection did take into account the possible involvement of state lands and parks and required relocations of various kinds. All the recommended projects were on very small drainage areas (5 to 80 square miles), thus eliminating the problems associated with use of a major stream. It is believed that at least some of the sites would be found to be environmentally acceptable.

A preliminary permit has been issued by the Federal Power Commission for study of one of the projects, Stony Creek, which is included among the planned projects listed in Appendix A. The capacity presently contemplated at this site is nearly double that assigned to it in the 1963 study.

Excluding this one planned project, the capacity of the remaining 14 sites was estimated to be about 10,400 MW. It is likely that a current survey would show an even larger potential capacity; and development of only a small part of this capacity would meet the needs of the area.

Vicinity of Washington, D.C. - Mr. E. T. Cox, Executive Vice President of Potomac Electric Power Company (PEPCo), presented a paper in August 1974 on "Pumped Storage Generation, Factors to be Considered."(7) In it he referred to studies of available pumped storage sites in an area 80 to 120 miles west and northwest of Washington in parts of Maryland, Virginia and West Virginia. An initial list of 100 potential sites was reduced to 19, and a field survey of these was conducted as the basis of cost estimates, assessment of construction problems and transmission routes, and the evaluation of environmental impact. In the end, there were 10 acceptable sites, each of which had a potential capacity in excess of 2000 MW. However, these sites were not close to the PEPCo service area, and construction at these sites would have an undesirable environmental impact due to the need for (long) transmission lines. Therefore, in 1972, the company began an investigation of nearby areas suitable for underground pumped storage.

Availability of Pumped Storage Capacity

The availability of many suitable pumped storage sites is well established in certain areas, and the extent of their availability can be reasonably inferred in other areas from general information as to topography and the location of existing and proposed pumped storages as well as conventional hydro plants. The environmental acceptability of the sites is less certain.

Environmental factors are considered elsewhere in this report and it is necessary to mention here only that environmental acceptability must be measured in relative rather than in absolute terms. There is some opinion that pumped storage, properly located, generally has less adverse impact than any of the other usual forms of generation.

In spite of the obvious uncertainties, an attempt has been made to estimate the extent to which suitable and acceptable pumped storage capacity could be made available, if needed and if economically justified, to meet the peaking capacity needs of various regions and of the entire United States. This estimate is shown in Table B-1 and is related to the period at the end of this century.

The first column of Table B-1 lists by regions the installed generating capacities at the end of 1974. This is a preliminary list, copied from the "1975 Annual Statistical Report" of ELECTRICAL WORLD.(8) This Report also shows installed capacities by states and by type of capacity; furthermore, it lists planned additions by regions and by types. These additional data were useful in development of the estimates that are here described, but they need not be recorded here. The listed 1974 capacities by regions have been used for two purposes:

1. They provide a weighting factor that permits an estimate of the nationwide average availability of pumped storage to meet peaking capacity requirements.

2. They serve as indication of future peaking requirements, which were here assumed to be about half the amount of the present installed capacity. This is based on future installations three or four times as large as the present installations, with peaking capacity being 10 to 15% of the expanded total.

The second column is an estimate of the probable availability of suitable and acceptable sites for pumped storage that could provide capacity to meet the requirements of the region, assuming pumped storage were needed to the extent of about half the amount of

Table B-1 ESTIMATED AVAILABILITY OF PUMPED STORAGE SITES

	Installed Cap. 12-31-74 10^6 kW(a)	Availability of Pumped Storage Sites - %(b)
New England	18.5	100
Middle Atlantic	66.1	60 - 80
East North Central	86.7	40 - 60
West North Central	34.6	40 - 60
South Atlantic	86.3	60 - 80
East South Central	42.1	80 - 100
West South Central	59.7	20 - 40
Mountain	24.7	100
Pacific	54.0	100
Alaska & Hawaii	1.8	40 - 60
Total Capacity	474.5	
Weighted Average Availability		60 - 75%

(a) Used as a factor for weighting estimated availability; also 50% of these amounts are assumed to approximate the future peaking capacity requirements of the region.

(b) Estimate of the probable portion of the peaking capacity requirements that could be provided by pumped storage, if such capacity were needed and economically justified, at the end of the century.

capacity in the first column and assuming it were found economical to install it. Admittedly, in such estimates the physical availability of the sites can be forecast with greater certainty than their environmental acceptability. However, there are certain regions, New England for example, in which it appears likely that 100% of the peaking capacity needs could be met, if desired, by installation of pumped storage. There are some areas, such as Florida, where the availability of pumped storage (at least with surface reservoirs) will be practically zero. For other areas, the percentage availability can only be guessed within wide limits, as indicated by the ranges shown for several regions.

Over-all, the availability of pumped storage is estimated to be from 60 to 75% of the future peaking capacity needs of the United States at the end of this century. This is not an estimate that this much pumped storage will either be needed or be installed.

REFERENCES

(1) New England River Basin Commission, Power and Environment Committee, "An Environmental Reconnaissance of Alternative Pumped Storage Sites in New England," July 1973.

(2) Federal Power Commission, News Release No. 20393, June 13, 1974, "Staff Report on the Role of Hydroelectric Developments in the Nation's Power Supply," May 1974.

(3) Ebasco, "1974 Business and Economic Charts."

(4) James J. Stout, "Potential Pumped Storage Projects That Would Use Existing Reservoirs," ASCE Engineering Foundation Conference Publication, "Pumped Storage," August 18-23, 1974, pp. 221-252.

(5) Pacific Northwest River Basins Commission, Power Planning Committee, "Pumped-Storage Potential of the Pacific Northwest," January 1972, North Pacific Division Corps of Engineers, Portland, Oregon.

(6) Federal Power Commission, Bureau of Power, "Potential Pumped Storage Projects in the Pacific Southwest," 1975.

(7) Ellis T. Cox, "Pumped Storage Generation Factors to be Considered," ASCE Engineering Foundation Conference Publication, "Pumped Storage," August 18-23, 1974, pp. 75-84.

(8) Electrical World "1975 Annual Statistical Report," March 15, 1975.

Appendix C

PUMPED STORAGE - TECHNICAL CHARACTERISTICS

Table A-2 of Appendix A lists 11 selected plants for which certain technical characteristics have been analyzed. These characteristics, which are to be considered in this Appendix C, are size, head, over-all conversion efficiency, charge/discharge ratio, and energy storage. The basic data for the 11 plants are shown in Table C-1; for data on unit sizes, reference should be made to Table A-1.

Size and Head

A trend toward use of larger pump/turbine units is evident in Figure C-1, which shows existing and proposed unit sizes versus year of installation. Small units are omitted from this diagram, and unit sizes are those listed in Table A-1. Planned projects show a distinct preference for units with nominal capacities of about 250 MW.

There is also a trend toward larger plant size, but this is more a matter of site and system limitations than of individual unit size. In the absence of special purposes of the project, it appears likely that most pumped storages, developed for future utility use, will have capacities larger than 500 MW.

Plant heads are determined by the topography of the available sites. Because costs generally decrease with an increase in head, there is incentive to use as high heads as can be made available with adequate energy storage capacity. Absent special purposes, pumped storages for utility application are likely to have heads in excess of 300 feet.

Conversion Efficiencies

Conversion efficiency can be determined for existing plants, on the basis of actual experience, by dividing annual net generation by pumping energy input. The reported energy amounts may be metered as of either the high or low voltage side of the station transformers, but the location of the metering is not usually stated. Inclusion of the transformer losses in the conversion efficiency calculation may lower this efficiency by about 1%. The indicated range of actual efficiencies, however, is a somewhat greater amount, so that the uncertainty as to metering is of little consequence.

A trend toward higher conversion efficiencies is evident in Figure C-2. This trend is in part related to the design and construction of bigger and better reversible units; but it is also related to more liberal design (i.e., lower water velocities)

Table C-1 PUMPED STORAGE CHARACTERISTICS

	FPC Form No.(a)	Taum Sauk	Yards Creek	Muddy Run	Cabin Creek	Seneca	Northfield	Blenheim Gilboa	Ludington	Jocassee	Bear Swamp	Raccoon Mountain
1. Initial Unit Operation	1	1963	1965	1967	1967	1969	1972	1973	1973	1973	1974	1978
2. Last Unit Operation	1	63	65	68	67	69	73	73	73	75	74	
3. Gross Head - Max. ft.	12	863	760	411	1226	813	825	1143	362	325	770	1039
4. Min.	12	755	687	361	1092	669	720	1055	295	295	680	897
5. Avg.		809	723	386	1159	741	772	1099	328	310	725	968
6. Net Plant Cap. - Max. MW	12	350	330	920	324	462(b)	1000	1150	1950	702	624	1540
7. Min.	12	350	330	840	268	380(b)	1000	1000	1608	610	520	1330
8. Avg.(20%max.,80%min.)		350	330	855	280	380(b)	1000	1030	1675	628	540	1370
9. Pumping Load - Max. MW	12	344	426	880	246	436	1000	1128	2091	680	520	1280
10. Min.	12	408	432	925	274	464	-	1200	-	(est.)690	600	1505
11. Avg.		376	429	902	260	450	1000	1164	2091	695	560	1392
12. Charge/Discharge Ratio(11/8)		1.07	1.30	1.05	0.93	1.29	1.00	1.13	1.25	1.11	1.04	1.02
Efficiency -												
13. Reported Forecast %	12	55.0	-	72.1	50.4	66.7	75.0	70.5	70.9	79.0	77.0	75 - 78
14. Actual 1972	1	45.0	67.3	70.9	47.8	70.5(c)	-	-	-		-	
15. " 1973	1	44.5	65.9	70.2	55.8	69.5(c)	75.4	67.5	70.2		-	
16. " 1974	1	42.0	64.8	71.0	54.1	69.5(c)	74.3	69.7	71.5	(f)	74.0	
17. Use as Estimated Avg.		45.0(d)	66.0	71.0	55.0(d)	69.0	74.5	70.0(e)	71.0		72.0(e)	
18. Energy Storage MWH	12	2700	2894	12200	1635	3920	8500	12000	15000	58757	3019	33000
19. Equiv.Time at Rated Cap. - Hrs.(18/8)		7.7	8.75	14.25	5.85	11.2	8.5	11.6	9.0	93.5	5.6	24.0
Conduit Losses -												
20. Max. Head %	12	3.9	3.3	2.4	-	2.7	1.2	4.8	-	1.2	2.6	-
21. Min. Head %	12	5.4	5.3	4.1	-	4.0	2.8	5.2	-	1.4	2.9	-
Approx.Avg.Loss -												
22. Generating %		4.6	4.3	3.3	-	3.3	2.0	5.0	-	1.3	2.7	2.6
Estimated Loss -												
23. Pumping %		2.7	3.7	1.9	-	2.8	1.0	3.2	-	0.8	1.5	1.6
24. Approx.Avg. - Combined %		7.3	8.0	5.2	-	6.1	3.0	8.2	-	2.1	4.2	4.2

NOTES:

(a) Data are obtained from indicated FPC Form 1 and 12 Reports, except for those related to Raccoon Mountain and forecast efficiency for Jocassee, which were obtained from correspondence with owners. Actual efficiencies and conduit losses are not directly reported in the FPC Reports, but are derived from reported MWH output and input and from gross and net heads.

(b) Includes 30 MW of capacity in a nonreversible unit, which is excluded in computation of various ratios.

(c) Additional output that results from downstream discharge and consequent use of gross head in excess of that applicable to pump input has been excluded in computation.

(d) Plant used for load regulation at some sacrifice in efficiency.

(e) Estimated average influenced by 1975 experience (for other plants, this experience was not materially different from earlier years).

(f) Not available because of substantial inflow to upper reservoir.

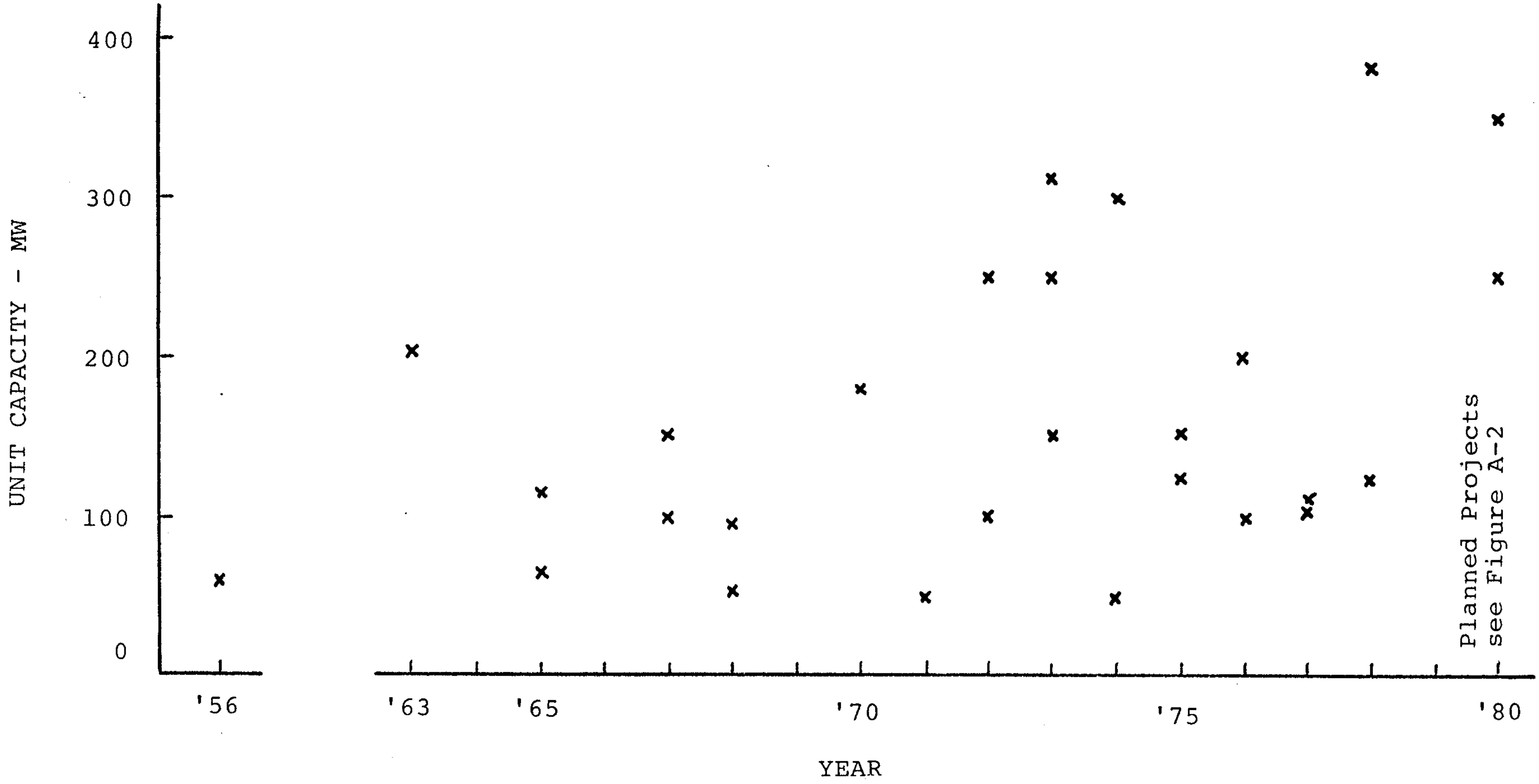


Figure C-1 REVERSIBLE UNIT SIZE VERSUS YEAR OF INSTALLATION for the penstocks, tunnels, etc. The head losses in the water conduits can be estimated from the reported differences between gross and net heads. Although these differences are reported only for turbine operation, reasonable estimates can be made for pump operation. The combined losses are also shown in percent of gross head in Figure C-2 for comparison with the over-all efficiencies. The trend is downward, reflecting the probability that later designs have minimized losses in recognition of their relatively higher costs in recent years.

Also shown in Figure C-2 are representative component efficiencies of the generating-pumping cycle. The continuing products of all the component efficiencies produce the over-all conversion efficiencies equal to the extremes shown in the upper diagram.

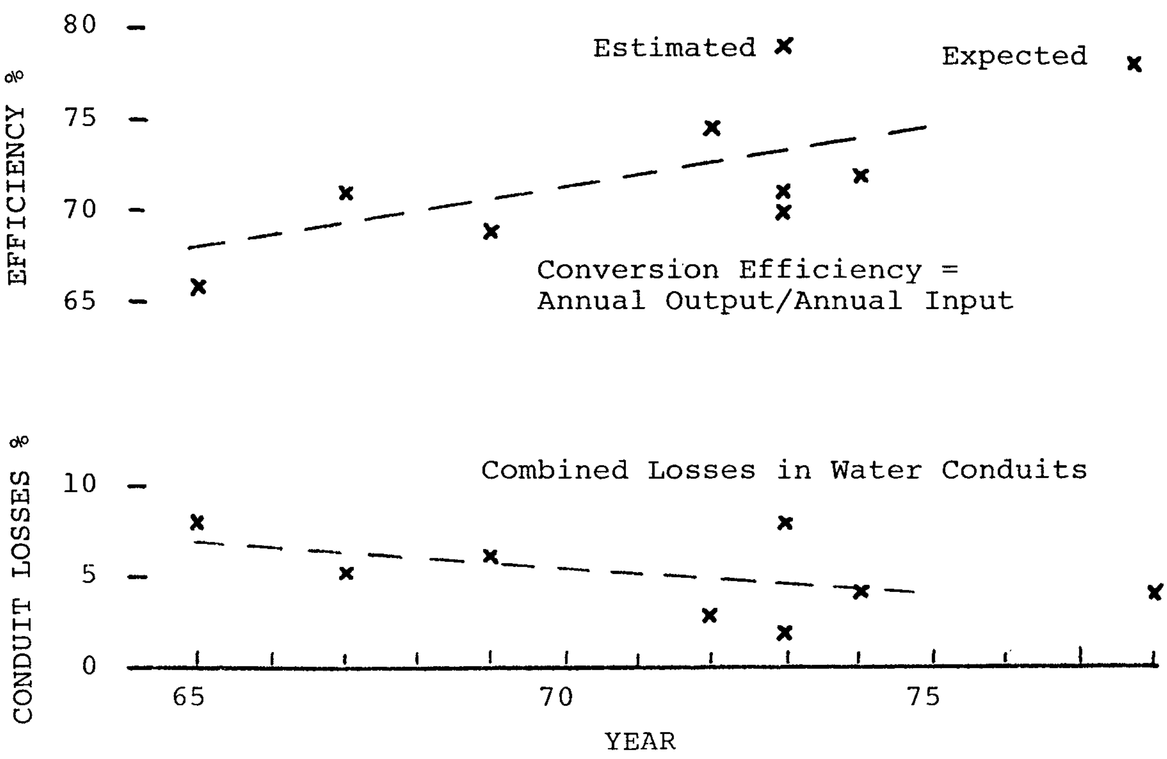
Attention is directed to the final component, "Allowance for operation under other than optimum conditions." This allowance, which is here an estimated rate, covers both the condition of the unit and also the duty assigned to the unit. Because of assigned duty this final component might be as low as 70%. For example, two of the selected 11 plants have demonstrated over-all efficiencies in the order of 50%, because these plants have sacrificed efficiency for load regulating ability. Because the unit cannot continuously operate at or near its best efficiency when regulating load, the over-all efficiency deteriorates. The experience of these two plants has been omitted from the diagram, because it is believed to be not typical of future pumped storage operation.

Based on the indicated trend of Figure C-2, it is expected that future plants can be built and operated with over-all efficiencies in the range of 70 to 75%.

Charge/Discharge Ratio

The charge/discharge ratio of a pumped storage unit or plant can be measured as the ratio of power input (average pumping load in MW) to power output (rated capacity in MW). Note that, whereas the input is the actual average pumping load, which varies with head, the output is stated in terms of rated capacity. This is because it is preferable that the output, which can also vary with head, be measured by some constant amount that is representative of the value of the plant capacity in system operation. For consistency in comparisons among the plants a capacity rating has here been adopted which gives 80% weight to capacity at minimum head and only 20% weight to capacity at maximum head, except in those cases where the owner is believed to have rated its plant capacity at minimum head.

The charge/discharge ratios, along with other data, are tabulated in Table C-2. The selected plants, with one exception, show a range in this ratio from 1.0 to 1.3. In another section of this Appendix, it is suggested that a reasonable range to consider for future units is 1.0 to 1.4. At a ratio of unity, the average



COMPONENTS OF CYCLE EFFICIENCY

	Representative Ranges, %	
	LOW	HIGH*
Pumping - Motor & Transformer	97.5	98.5
Pump	91.5	92.5
Water Passages	96.5	98.5
Generating - Water Passages	95.5	97.5
Turbine	89	92.5
Generator & Transformer	97.5	98.5
Allowance for operation under other than optimum conditions	92	98
Over-all cycle efficiency	66%	78%*

*Not yet confirmed by experience.

Figure C-2 CONVERSION EFFICIENCY AND CONDUIT LOSSES VERSUS YEAR OF INSTALLATION

Table C-2 CHARGE/DISCHARGE RATIO AND ENERGY STORAGE

Plant	Charge/Discharge Ratio Pump Load/Plant Cap.	Energy Storage kWh/kW of Plant Capacity = Hours
Taum Sauk	1.07	7.7
Yarks Creek	1.30	8.8
Muddy Run	1.05	14.2
Cabin Creek	0.93	5.8
Seneca (Kinzua)	1.29	11.2
Northfield	1.00	8.5
Blenheim-Gilboa	1.13	11.6
Ludington	1.25	9.0
Jocassee	1.11	94.0
Bear Swamp	1.04	5.6
Raccoon Mountain	1.01	24.0
Suggested Range	1.0 to 1.4 (b)	(a)

(a) A variable to be determined by system conditions.

(b) Ratio controlled by selection of pump/turbine; higher ratio requires larger hydraulic and electrical equipment, hence higher costs.

electrical input is in balance with the rated output; while at a ratio of 1.4, the balance is between the rate of water delivery in pumping and the rate of water use in generation.

The charge/discharge ratio is within the control of the plant designer and the higher values are obtainable at some cost. The higher values of this ratio permit a longer duration of generation based on a limited pumping time. In fact, the duration of generation available from one hour of pumping is equal to this ratio times the conversion efficiency.

Energy Storage

The energy storages at the existing selected plants are also shown in Table C-2 in terms of hours of operation at rated capacity available from use of the reported energy storage. The maximum value in this list is the 94 hours shown for Jocassee; but this is not typical of a "pure" pumped storage and is related to the fact that there is a substantial natural inflow into the upper Jocassee reservoir, and the reservoir serves additional purposes.

For storages from about 6 to 9 hours, the predominant operation could be on a daily cycle, although for very short durations of daily generation, there will also be some drawdown and refill on a weekly basis. For larger storages, operation on a weekly as well as a daily cycle is inevitable. The 24-hour storage shown for Raccoon Mountain is close to the practical limit of storage for use on a weekly cycle.

The storages provided at existing plants are not necessarily indicative of those to be provided in future plants. These are variables to be determined by expected future system load conditions and by economic studies. There is no need to recommend a range of storage, based on the presently available experience.

Investigation of the Characteristics of a Specific Pump/Turbine Installation

One of the characteristics that was investigated for the existing pumped storage plants was the charge/discharge ratio. It was found to vary from 1.0 to 1.3. It is here determined that, when and if economic conditions warrant, this ratio could be made even larger. A high charge/discharge ratio and a consequently high ratio of generating time to pumping time is desirable when the daily generating duty approaches or exceeds the number of hours of operation that can be provided for by the daily off-peak period of pumping.

An examination has been made of the characteristics of a specific pump/turbine unit, proposed by a United States manufacturer for installation at one of the selected plants. This unit is believed to be fairly typical in its discharge, power and efficiency characteristics of other units proposed and actually installed in other pumped storage plants. These characteristics are summarized in the curves shown on Figure C-3.

These curves are developed from the information supplied by the pump/turbine manufacturer, all of which is on a net head basis for the turbine and on a total dynamic head basis for the pump. Also, the manufacturer's data are in terms of shaft horsepower. For this presentation, the head has been converted to gross plant head by adjusting for the penstock and discharge conduit losses; and by the amount of these losses, gross head is greater than turbine net head and is less than pump dynamic head. The losses for both conditions are functions of the plant discharge. Also, power has here been converted to electrical output or input, in MW, assuming an electrical efficiency of 98% for a generating and for pumping operations.

Note that the curves cover a range of head from 650 to 870 feet, which represents a far greater relative variation in head (about 30%) than would be found in the usual pumped storage plant. Nevertheless, the proposed unit is capable of operation over this range, with wide variations in discharge and in power, but relatively less variation in efficiency. More usual variations in head, similar to the one for which the unit was considered, are in the range of 10 to 15%.

In the initial consideration of the curves, the dotted lines should be ignored and attention should be directed only to the solid lines, which define certain characteristics over the full head range.

At the top of the diagram, discharge is shown as a function of gross head for generation at maximum output, for generation at most efficient loads and for pumping. Although output at a given head can be varied by gate opening when the unit is generating, input is ordinarily not similarly varied when the unit is pumping. As a pump, the unit operates at a fixed gate opening that provides for most efficient operation and optimum power and discharge for a given head. At low heads, the pump discharge can equal or exceed the turbine discharge. As heads increase, the pump discharge falls, while the maximum turbine discharge rises. Near the upper limit of the heads shown, the turbine discharge is more than twice the pump discharge.

Since the ratio of available generating time to available pumping time is the reciprocal of the ratio of generating discharge to pump discharge, it is evident that the time ratio can be varied, within the range of heads shown, from more than 1.0 to less than 0.5. For various other reasons, however, it may not be desirable to operate at or near either end of this range.

Below the discharge curves are those for power, either generation or pumping load. Pumping load is highest at the lowest heads,

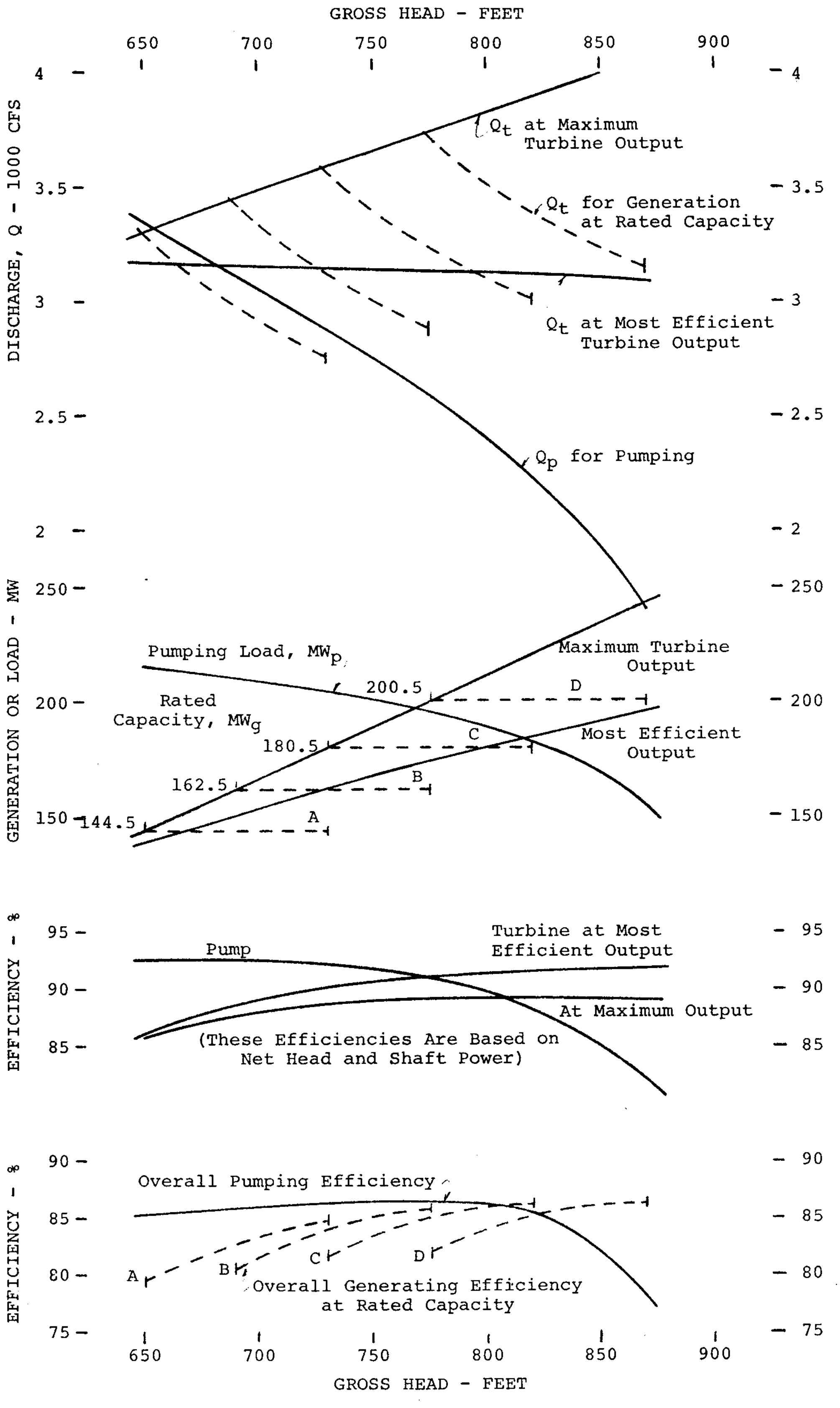


Figure C-3 DISCHARGE, POWER AND EFFICIENCY VERSUS HEAD OF A REVERSIBLE PUMP/TURBINE UNIT because of the larger volumes delivered as discharge under these conditions. Generation is highest at the highest heads. The pumping load and generation are balanced, at about 200 MW at 770 feet gross head. If the ratio of generating time to pumping time is not of great importance, it might be desirable to have this particular unit operate in the range of heads where the power output and input are nearly in balance.

Below the discharge curves are efficiency curves for the turbine and pump. Although these are plotted against gross head, the efficiencies are the same as those determined by the manufacturer, i.e., without adjustment for water conduit and electrical losses. Note that pump efficiencies are highest at low heads, and that turbine efficiencies are highest at high heads.

At the bottom of the sheet are additional efficiency curves, only the one of which for pump operation is shown in a solid line. This pump efficiency curve is derived from the one above, but is lower because of recognition given to water conduit losses and to electrical losses. This is the over-all pumping efficiency that is expected to be experienced in actual operation. Corresponding over-all generating efficiency curves have been omitted, except as shown by the dotted lines, which are still to be discussed.

Here we have a pump/turbine unit capable of operation in some fashion over a wide range of heads, wider than would be expected in a usual pumped storage plant. Suppose (contrary to actual possibilities) that we could select the range of heads for a pumped storage plant in which this unit is to operate; these selected ranges are as follows:

A - 650 - 730 ft.
B - 690 - 775 ft.
C - 730 - 820 ft.
D - 775 - 870 ft.

By design, the range of heads in each case is about the same percentage (12.5) of the lower limit of the range. Certain characteristics of the unit, operating in each range, are now to be examined.

As a first step, it is necessary to define how the generating capacity of the unit is to be rated for each head range. A convenient and conservative definition is a rating based on the unit capability at minimum head. Such ratings for the several ranges of head are shown by the horizontal dotted lines in the power portion of the diagram. For each head range, as above defined, the rated capacity of the unit will be:

A - 144.5 MW
B - 162.5
C - 180.5
D - 200.5

Note that the pumping load is substantially greater than the rated capacity as a generator for A, B and C ranges and only in D does the generating capacity rating slightly exceed the pumping load. Considering the flatness of this pumping load versus head, up to the point where it becomes less than the rated generating capacity, it seems likely that a single size of electrical unit would be required, regardless of the range of head in which the unit is to operate. This obviously means that the costs per KW will be higher for the small capacity ratings necessary in the lower head ranges.

If it is assumed that the unit operates as a generator at its rated capacity in each of the several indicated ranges of head, then the discharges will be as shown by the dotted lines in the upper part of the diagram. For the A range of heads, the turbine discharge is less than the pump discharge, but for the other ranges, it becomes progressively greater. This means that for a given reservoir size and given off-peak pumping time, the unit can generate for more hours in the A range than in the D range. Perhaps this may be an offset to the above noted higher per kW cost in the A range.

Finally, at the bottom of the diagram, there are shown the over-all generating efficiencies for the several head ranges, assuming again that the unit operates at the rated capacities.

There are now available in the diagram the data needed for determining various characteristic ratios for this unit when used in several different ranges of head. However, in ordinary circumstances the head is not selected to fit the unit characteristics that are desired. Rather the head is fixed by physical conditions, the capacity of the unit (or plant) is fixed by load requirements and available reservoir size, and the unit is selected to give the desired relative characteristics that result in an optimized design for the particular site and system conditions.

In other words, if the head available at a particular site were that defined by the D range, it would be entirely possible to have the relative characteristics exhibited in the A range. This would require a pump/turbine designed for a higher head range than is here shown, so that the D range is a lower rather than a higher range of heads for that particular design of unit. Therefore, if unit size and costs are for the present ignored, the relative characteristics determined for a specific unit and the several ranges of head can be considered as relative characteristics for several different units, all operating in a single range of heads.

These several relative characteristics can be summarized as follows:

unit design	Ratios (averaged over head range)		
	Q_p/Q_T	avg. MW_p/rated MW_g	conversion efficiency
A	1.04	1.46	71.0%
B	0.91	1.26	72.5
C	0.78	1.07	72.8
D	0.64	0.90	72.0

As noted earlier, the ratio of available generating time to available pumping time is the same as the ratio, Q_p/Q_T. It is also equal to the product of the conversion efficiency and the charge/discharge ratio, average MW_p/rated MW_g.

An alternative approach to the provision for a desired ratio of generating time to pumping time for a given range of head must be considered. To a large extent, the same variations in this ratio (i.e., in the Q_p/Q_T ratio) that can be obtained by change in design can be obtained also by a change in the capacity rating assigned to the unit. For example, if the actual range of head available at the site were that corresponding to the C range (730-820 ft.) in the original discussion, and the generating time to pumping time ratio of the B range were desired, it would not be necessary to change the design from that shown in the original diagram. Alternatively, the capacity rating of the unit could be reduced. Instead of the 180.5 MW rating earlier indicated for the C range, the unit could be rated at something less than the 162.5 MW found for the B range. (This rating doesn't mean that the unit could not generate at a higher rate whenever necessary, and be credited in some fashion with this additional capability.) The reduced rating in the C range has to be less than that available in the B range, because the pumping discharge is less in the C range, and it is the ratio, Q_p/Q_T, that is to be preserved in this alternative approach. This lower rating in the C range is found to be about 147 MW, assuming there is no material change in efficiencies as the result of the change in rating. Although the desired result, in terms of generating time, is thus obtained, it probably is obtained only at a higher cost per kW than would be possible with the change in design.

Unit design A involves a higher cost per kW than unit design D. The increase in generator size is obvious, because of the relatively higher pumping load. The pump/turbine would also be larger and operate at a higher speed. These differences in turn affect various components of the structures and electrical equipment; some parts and components would be larger and would cost more. The cost consequence of the different designs of unit, primarily to obtain different charge/discharge ratios, are further considered in Appendix D.

The intent of this investigation is satisfied by the above summary tabulation. This shows that the charge/discharge ratio (avg. MW_p/rated MW_g) can be varied from less than unity to more than

1.4, which is a somewhat wider range than is exhibited in the design of existing plants. The 1 to 1.4 range is suggested as typical of future installations.

The summary also shows that some small sacrifice in efficiency (as well as increased cost of equipment) must be incurred in order to have the higher ratios. These differences in efficiency, however, are only indicative and not absolute. The several efficiencies were determined on the assumption that the unit always operated at the rated generating capacity assigned for each head range. This, of course, is not necessarily the best operation or the likely operation. The unit could be operated, if desired, at or near the most efficient output for each head range. This would tend to raise all the efficiencies somewhat, but would probably be more beneficial in the D range than in the A range. Deviations from the desired loading would, on the other hand, tend to lower the average efficiencies. Because of the flatter efficiency curves (for variable loads) at higher heads and more peaked curves at the lower heads, deviations from desired loads would depress the efficiency in the A range more than in the D range. It is likely, therefore, that the differences in efficiency will be greater than are indicated in the summary table. Although such differences may be important in the optimized design of a specific plant, they need not be considered, and in fact are necessarily unknown, in a generalized comparison of pumped storage with other energy storage systems.

Appendix D

PUMPED STORAGE - CONSTRUCTION COSTS

The investigation of pumped storage construction costs has been based primarily on the actual costs for selected pumped storage plants, after certain necessary adjustments. Construction cost data for these existing plants are recorded in Table D-1; these costs have been obtained from reports filed with the Federal Power Commission or by correspondence with the plant owner. The estimated costs for future plants that are based on this experience have been confirmed by published estimates of future plant costs.

The available data indicate wide variations in the unit costs ($/kW) of the existing plants. The major cause of these variations is the time of construction; but resulting differences in cost can be minimized by correction of the costs to a common date (here January 1, 1974) and cost level. This adjustment has been made, using the Handy-Whitman indices of cost for utility plant construction(1). A January 1, 1974 index of cost is intended to represent wage and material costs for a particular type of construction as of that date. It is therefore necessary to select a time, as well as an index, that reasonably represents the average cost conditions during construction of each plant. In the absence of any information concerning the actual construction schedules, use was made of the July 1 index for the year preceding the year of initial operation for each plant.

There are also variations in cost due to plant and unit sizes and to differences in head, as well as those differences inherent in other site conditions. Finally, there are large differences due to the relative amounts of energy storage provided by the plant reservoirs.

In the analysis of construction costs, the costs of dams and reservoirs have been separated from the balance of plant costs. This separation serves two purposes: (1) it partly eliminates the major element of cost peculiar to the site and permits the development of a more consistent relationship between the balance of plant cost and size and head and (2) it provides a basis for separate consideration of the capacity related costs and energy related costs in economic comparisons.

It appears that the costs, as of January 1, 1974, for plants with capacities above 300 MW and heads above 300 feet might be represented by the following ranges:

Energy related costs (storage)	$2 to $10/kWh
Capacity related costs (balance of plant)	$100 to $150/kW

Table D-1 PUMPED STORAGE CONSTRUCTION COSTS

	Taum Sauk	Yards Creek	Muddy Run	Cabin Creek	Seneca	Northfield	Blenheim Gilboa	Ludington	Jocassee	Bear Swamp	Raccoon Mountain	Avg.
Initial Unit Operation	1963	1965	1967	1967	1969	1972	1973	1973	1973	1974	1975(c)	
Last Unit Operation	63	65	68	67	69	73	73	73	75	74	76	
Net Plant Cap.Rating - MW	350	330	855	280	380	1000	1030	1675	628	540	1370	
Energy Storage - MWH	2700	2894	12200	1635	3920	8500	12000	15000	58757	3019	33000	
Construction Costs(a) - $\$10^6$												
Land & Land Rights	0.2	0.9	1.4	.0	.0	1.1	2.3	4.8	4.1	5.7	1.8	
Structures & Improvements	4.7	4.0	14.5	6.9	9.4	19.4	28.1	33.7	13.7	15.9	27.2	
Reservoirs,Dams & Waterways	23.7	13.5	33.2	18.2	36.5	49.7	58.0	197.9	48.7	49.9	70.7	
Turbines & Generators	14.6	10.0	19.9	6.3	12.6	36.2	22.7	48.1	28.4	22.2	42.7	
Accessory Electrical Equip.	2.1	1.3	7.0	1.7	3.6	5.6	8.0	11.6	5.3	10.1	14.2	
Misc.Power Plant Equip.	0.5	0.8	2.2	0.3	1.9	3.4	3.3	5.3	0.9	1.8	2.2	
Roads,Railroads & Bridges	0.0	0.4	1.0	0.4	-	4.8	4.0	3.4	0.4	4.3	1.5	
Total Production Plant(a)	45.8	30.9	79.2	33.8	64.0	120.2	126.4	304.8	101.5	109.8	160.3	
Total Direct Costs	30.3	23.7	51.0	30.0	41.0	85.2		236.9				
Indirect Construc.Costs	9.9	1.1	13.6	2.8	8.7	8.4		35.2				
Engineering & Supervision	3.5	2.4	6.9	3.4	5.9	10.6		11.5				
Interest During Construc.	4.9	2.5	4.5	3.1	8.3	18.7		32.8				
Other Overhead Costs	0.8	0.6	1.1	0.2	1.2	3.8		10.6				
Total Project (Incl.Transmission)(b)	49.4	30.3	77.1	39.5	65.1	126.7		326.9				
Costs as Related to Totals - %												
Land & Land Rights	0.3	2.9	1.7	-	-	0.9	1.8	1.6	4.0	5.2	1.1	1.8
Structures & Improvements	10.3	13.0	18.3	20.5	14.7	16.1	22.2	11.0	13.5	14.5	17.0	15.6
Reservoirs,Dams & Waterways	51.8	43.7	41.9	53.6	57.1	41.4	45.9	64.9	48.0	45.4	44.1	48.8
Turbines & Generators	31.7	32.2	25.1	18.5	19.7	30.1	18.0	15.8	28.0	20.2	26.6	24.2
Accessory Electrical Equip.	4.6	4.3	8.9	5.2	5.6	4.7	6.3	3.8	5.2	9.2	8.9	6.1
Misc.Power Plant Equip.	1.2	2.5	2.8	1.0	2.9	2.8	2.6	1.8	0.9	1.6	1.4	1.9
Roads,Railroads & Bridges	0.1	1.4	1.3	1.2	-	4.0	3.2	1.1	0.4	3.9	0.9	1.6
Total Production Plant	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total Direct Costs	61.3	78.4	66.2	76.0	63.0	67.2(d)		72.5				69.5
Indirect Construc.Costs	20.0	3.7	17.7	7.1	13.3	6.6		10.7				12.1
Engineering & Supervision	7.2	8.0	8.9	8.6	9.1	8.4		3.5				7.6
Interest During Construc.	9.9	8.1	5.8	7.8	12.7	14.8		10.0				9.0
Other Overhead Costs	1.6	1.8	1.4	0.5	1.9	3.0		3.3				1.8
Total Project (Incl.Transmission)	100.0	100.0	100.0	100.0	100.0	100.0		100.0				100.0

NOTES:

(a) Data are obtained from FPC Form 1 and 6 Reports and by correspondence with plant owners, when such reports were not available.

(b) These total project costs are from Form 6 Reports, filed shortly after project completion. Project costs differ from production plant costs because of the inclusion of substations and possibly other transmission. Nevertheless, project costs may be less than production plant costs, because of plant additions covered in current Form 1 Reports.

(c) The costs reported here are those estimated in anticipation of a 1975 in-service date. Initial operation has now been delayed to 1978 by construction difficulties. A revised estimate of cost would be of no use for purposes of this report.

(d) These data were not available at the time of preparation of the draft report and are excluded from the averages shown in the right-hand column.

Table D-1 PUMPED STORAGE CONSTRUCTION COSTS (Continued)

	Taum Sauk	Yards Creek	Muddy Run	Cabin Creek	Seneca	Northfield	Blenheim Gilboa	Ludington	Jocassee	Bear Swamp	Raccoon Mountain
Details of Reservoirs, Dams & Waterways(e)											
Direct Costs - $\$10^6$											
Upper Reservoir		3.3	7.6	4.6	11.4	8.5		83.0			
Lower Reservoir		1.1	-	3.1	-	-		-			
Waterways		6.2	11.4	4.1	11.7	26.7		59.2			
Total Direct Costs		10.6	19.0	11.8	23.1	35.2		142.2			
Estimated Total Costs											
Upper Reservoir	12.3	4.2	13.3	7.1	18.0	12.0	20.3	115.4	35.9	19.9	41.0
Lower Reservoir	2.4	1.4	-	4.7	-	-	17.3	-	-	17.4	-
Waterways	9.0	7.9	19.9	6.3	18.5	37.7	20.4	82.5	12.8	13.8	29.6
Total Project Costs	23.7	13.5	33.2	18.1	36.5	49.7	58.0	197.9	48.7	51.1	70.6
Plant Less Reservoir Cost = Balance of Plant Costs	31.1	25.3	65.9	22.0	46.0	108.2	88.8	189.4	65.6	72.5	119.3
Unit Costs(f)											
Upper Reservoir $/KWH	4.6	1.45	1.1	4.3	4.6	1.4	1.7	7.7	0.6	6.6	1.2
Lower Reservoir	0.9	0.5	-	2.9	-	-	1.4	-	-	5.8	-
Subtotal - Storage	5.5	1.95	1.1	7.2	4.6	1.4	3.1	7.7	0.6	12.4	1.2
Storage $/KW	42.0	17.0	15.6	42.2	47.4	12.0	36.5	69.0	57.3	69.0	30.0
Balance of Plant	88.8	76.6	77.0	78.6	121.0	108.2	86.2	113.2	104.7	134.2	87.2
Total	130.8	93.6	92.6	120.8	168.4	120.2	122.7	182.2	162.0	203.2	117.2
Adjustments to 1-1-74 Costs											
Assumed Mid-Construction Date(g)	1962	1964	1966	1966	1968	1971	1972	1972	1972	1973	1974
Factor for Storage(h)	1.81	1.82	1.70	1.58	1.54	1.21	1.11	1.11	1.13	1.04	1.0
Factor for Balance of Plant(h)	1.78	1.78	1.67	1.53	1.54	1.22	1.16	1.11	1.12	1.05	1.0
Adjusted Unit Costs(i)											
Upper Reservoir $/KWH	8.3	2.6	1.9	6.8	7.1	1.7	1.9	8.5	0.7	6.9	1.2
Lower Reservoir	1.6	0.9	-	4.6	-	-	1.6	-	-	6.0	-
Subtotal - Storage	9.9	3.5	1.9	11.4	7.1	1.7	3.5	8.5	0.7	12.9	1.2
Storage $/KW	76.0	31.0	27.0	67.0	73.0	15.0	40.0	76.0	65.0	72.0	30.0
Balance of Plant	158.0	136.0	129.0	124.0	186.0(j)	132.0	100.0	126.0	117.0	141.0	87.0
Total	234.0	167.0	156.0	191.0	259.0	147.0	140.0	202.0	182.0	213.0	117.0

NOTES:

(e) Direct costs have been obtained from FPC Form 6 Reports, where available; and these costs have been proportionately increased so that their total equals the reported cost of Reservoirs, Dams and Waterways in Form 1. Where Form 6 was not available, costs have been estimated from other data or were obtained from the plant owners.

(f) Unit costs relate the storage and balance of plant costs to the energy storages and net plant capacity ratings shown on page 1 of this tabulation.

(g) In the absence of better information, it is assumed that actual costs of construction can be reasonably related to a construction cost index at July 1 of the year immediately prior to the year of initial plant operation.

(h) These factors are determined from the Handy-Whitman cost indices of "Public Utility Construction Costs" by dividing the January 1, 1974 index by the July 1 index for the indicated year of construction. The H-W indices are separately reported for various major components and total plants and for various areas of the country. The indices for reservoirs, dams and waterways and for total hydraulic production plant were used respectively for storage and balance of plant.

(i) The adjusted unit costs are no more than approximate representations of costs at January 1, 1974 cost levels; but errors in these adjusted costs are not likely to influence materially the conclusions drawn from this investigation. Known sources of error include the assumption of a mid-point of construction, with consequent approximation of the adjustment factors, and the limitation of the H-W indices to direct costs, i.e., they reflect none of the increase in overheads due to higher interest rates or longer construction periods.

(j) The cost of this balance of plant can be reduced to about $175/KW to eliminate costs associated with downstream discharge, which permits the plant to utilize during generation the additional head created by the lower reservoir dam.

Components of Plant Cost

The distribution of pumped storage plant costs among the various components, as these are defined by the Federal Power Commission for accounting purposes, has been determined for the typical (average) plant in Table D-1 to be approximately as follows:

Land and land rights	2%
Structures and improvements	15
Reservoirs and dams (storage costs)	28
Waterways	21
Turbines and generators	24
Accessory electrical equipment	6
Miscellaneous power plant equipment	2
Roads, railroads and bridges	2
Total production plant	100%

Not only do reservoirs and dams represent the largest of the above listed components, but their costs are also subject to the widest variations. This range has been from about 17 to 38%. Consequently, as noted earlier, the separate treatment of the storage costs leads to more consistency in the balance of the plant costs.

Note that, by the Federal Power Commission definition, the pumped storage production plant does not include the plant step-up substation. The substation is not included in the plant costs discussed in this appendix, although it is usually included in total project costs and in estimates for new projects. Substation costs are generally in the range of $5 to $10/kW.

Project costs can also be broken down in another manner to reveal the extent of certain classifications of cost that are spread over the above listed components. These have also been determined for the typical (average) plant in Table D-1 to be approximately as follows:

Direct costs	69%
Indirect construction costs	12
Engineering and supervision	8
Allowance for funds used during construction	9
Other overhead costs	2
Total	100%

Storage Costs

It is assumed that the energy related storage costs are represented only by the costs of dams and reservoirs, although it is possible that some part of the land costs and other minor costs might be properly assigned to storage. On the other hand, some of the reservoir and dam costs are probably fixed and are not functions of the amount of energy storage (e.g., cost of a spillway, which depends on drainage area). Nevertheless, on the basis of

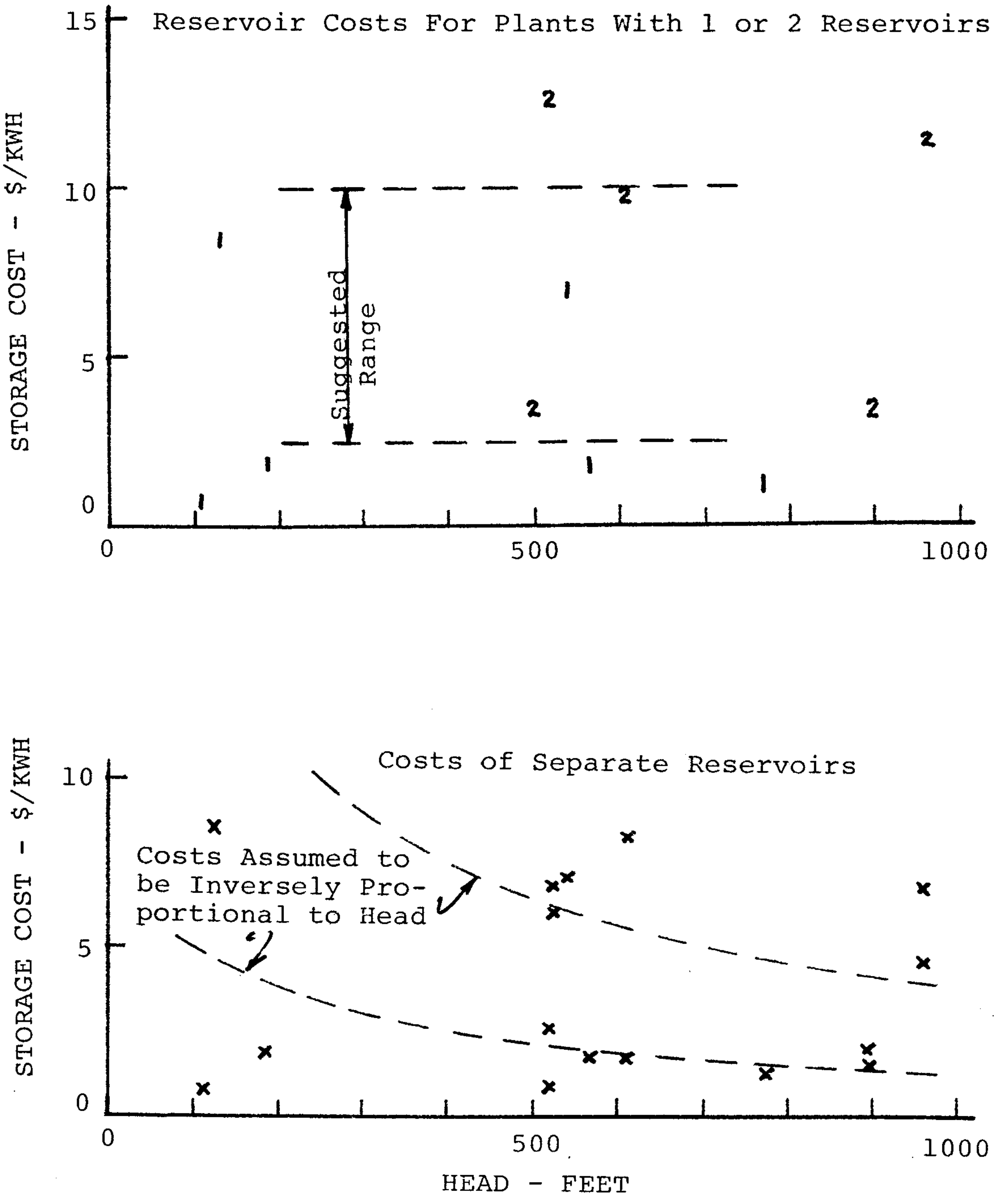


Figure D-1 ENERGY STORAGE COSTS VERSUS HEAD
(Costs for dams and reservoirs, adjusted to 1-1-74 level.)

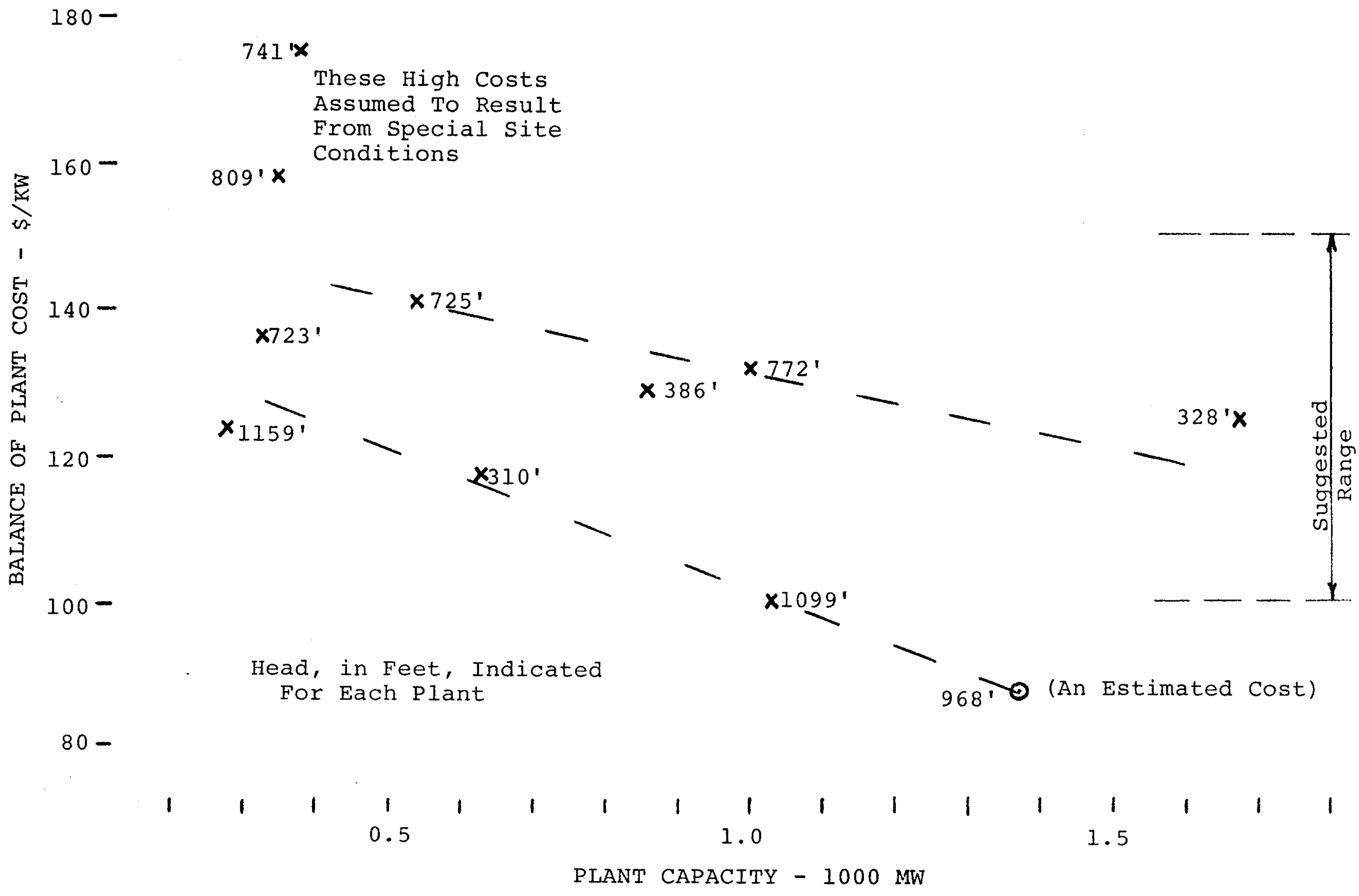


Figure D-2 BALANCE OF PLANT COSTS VERSUS PLANT CAPACITY
(Costs exclude dams and reservoirs and are adjusted to 1-1-74 level.)

the available information it seems likely that the best estimates of energy storage costs can be obtained from the reported costs of reservoirs and dams.

The storage costs in $/kWh, adjusted to January 1, 1974, are plotted in Figure D-1. There are relatively wide variations in storage costs, some of which can perhaps be explained by differences in head; but an even larger part of the variation must be related to site differences. Several of the selected plants required construction of only a single reservoir; but to compensate for this condition, storage costs have been plotted for each separate reservoir as well as for each project.

It might be expected that the separate reservoir storage costs would decrease with an increase in head, for a smaller quantity of water must be stored to produce a given amount of energy. There is some tendency in this direction, particularly if the two storage costs for the highest head plant (1159 feet) are ignored. The dotted lines show a reciprocal relationship between head and energy storage costs.

It is evident that storage costs must be largely determined by site conditions. Also, it is likely that less favorable sites for reservoirs may be accepted in order to make use of higher heads. In the study of pumped storage in the Susquehanna River Basin, referred to in Appendix B, the costs of storage at 25 sites were analyzed. These costs, which were generally in the $3 to $7/kWh range after adjustment to January 1, 1974 conditions, actually showed a slight tendency toward higher costs at higher heads. This rising storage cost was more than offset, however, by the decreasing cost of the balance of plant as the heads increased. Consequently, it is not safe to assume that the storage costs for surface reservoirs, in $/kWh, will always decrease with an increase in head as shown by the dotted lines in Figure D-1.

Considering the effect of site differences, it is perhaps reasonable to neglect some of the extremely high storage costs for existing plants. Those that might be neglected are the two plants with the smallest storage capacities (less than 6 hours), these small storages being some indication of less favorable sites. There is also no need to project costs as low as have been estimated for the most favorable sites, particularly where these have been developed with a single new reservoir.

In consideration of the above discussion, it is suggested that estimated energy storage costs for future surface reservoirs be considered to be not materially affected by plant size and head and to lie generally in the range of $2 to $10/kWh.

Balance of Plant Costs

Balance of plant costs are plotted in Figure D-2. They vary less widely than do storage costs, the range being more nearly 2 to 1 than 5 or more to 1. Also, there are evident relationships between unit cost and plant size and plant head; costs decrease with increases in both size and head. The relationship that depends on size is probably more influenced by unit size than by the number of units in a plant. However, for the small available sample, where the site differences are large, the plot against plant size exhibits more consistency than a plot against unit size.

Differences in balance of plant costs also do depend on site differences, other than head, particularly the length and nature of the water passages and whether the plant is underground or on the surface. Differences also result from the designer's choice of the charge/discharge ratio, water velocities in the conduits, and other options as to equipment and structures.

Before using the costs plotted in Figure D-2 as the basis of estimates for future pumped storage costs, it is desirable to eliminate from consideration several extreme values. It is believed that the costs for Taum Sauk and Seneca cannot be considered as typical of future costs. Taum Sauk was the first of the large "pure" pumped storages, and Seneca involves several unusual features that added to its cost. Also, they are both smaller in size than the plants that are planned for future construction (see Table A-1, Part C).

Seneca is located just downstream of a Federal multipurpose dam, and its construction took place under cramped conditions. It contains one 30-MW nonreversible unit in addition to the two large reversible units, and the small unit discharges downstream rather than into the lower reservoir. Also, one large unit is equipped with special discharge conduits and valves so it too can discharge downstream, as well as to the lower reservoir, thus at times utilizing a substantially higher head for generation than is required for pumping. It was possible to make reasonable adjustments for these conditions in determining the reported characteristics of the plant, but similar adjustments of cost are more difficult and are unlikely to bring the costs in line with other plants of like size and head.

It also appears reasonable to ignore the lowest costs estimated for Raccoon Mountain, which is still under construction. (This estimate was based on expected completion in 1975; now that construction has been delayed, the cost will be increased as compared to the original estimate.) Although plants may be built at such costs under favorable conditions, it is not necessary to assume the general availability of such conditions to justify a further economic interest in pumped storage.

With the balance of plant costs for eight of the 11 selected plants falling within the approximate range of $100 to $140/kW, it appears reasonable to propose $100 to $150/kW as a range of future costs (excluding storage and adjusted to January 1, 1974 cost levels).

The upper extension of this range to $150/kW is sufficient to cover any additional adjustments of older plant costs that are not provided for in the Handy-Whitman indices, which relate only to labor and materials. A separate adjustment would be required for the older plants because of increased interest rates and the effect of this on the allowance for funds used during construction. It is estimated this may be in the order of 3 to 5%. Also, it is likely that new plants may have somewhat greater costs than older plants to meet environmental and recreational needs. No estimate has been made of such costs, but they are believed to be relatively small.

Effect of Charge/Discharge Ratio

As noted earlier, balance of plant costs can be affected by the choice of the charge/discharge ratios and by the water velocity in the several required conduits.

No attempt has been made to estimate the effect of water velocity on either cost or conversion efficiency, for these effects are functions of head, length and character of waterways (tunnel and type of rock, exposed penstock or penstocks, etc.) and perhaps other site conditions. In any case, the effect on cost is not likely to be large, for it results only from an incremental change in less than 20% of the plant costs. Note that the trend toward lower conduit losses, shown in Figure C-2, results not only from change in velocity, but may also result simply from larger conduits in larger plants or relatively shorter conduits (e.g., the lowest losses are reported for a low head plant).

The charge/discharge ratio may have a greater effect on costs, and is expected to be the more important option in design, if additional hours of daily operation are required of future plants. Reference should be made to the discussion of the charge/discharge ratio in Appendix C, where it is shown that this ratio may be varied over a range from about 1.0 to 1.4. The higher ratio permits more hours of daily generation based on a limited pumping time, but leads to slightly lower efficiencies and to higher plant costs.

To increase this ratio from 1.0 to 1.4 it is necessary to increase the rating of the generator/motor, which will be determined by the higher pumping load, and to increase the physical size of the pump/turbine to deliver the larger quantity of water. The costs of structures and of some equipment (e.g., cranes) will also increase. At the outside, the increase in cost will be something less than 40% applied to about 40% (structures, some equipment, turbines and generators) of the total plant costs; but because these are incremental increases in cost, the more likely increment is perhaps 20% of 40%. If the total plant cost is $150/kW, the estimated cost of a change in ratio from 1.0 to 1.4 is more nearly $12/kW, rather than $24/kW.

On this basis the adjustment of the cost of the selected plants to an average charge/discharge ratio would involve individual plant cost adjustments of less than about $5/kW. The suggested range of plant cost is sufficiently large to cover such adjustments.

The choice of a charge/discharge ratio is primarily an economic decision related to site and system conditions. Where system conditions require longer hours of generation and storage costs are high, the selection of a higher ratio may have advantage over a larger energy storage, particularly if the storage must operate on a weekly cycle.

Published Estimates of Costs

If the above suggested ranges of cost are represented by their midpoints, $6/kWh for storage and $125/kW for balance of plant, then the total cost (excluding substation) of a plant with 10 hours of storage would be $185/kW as of January 1, 1974. This is a useful (possibly too high) number to compare with published estimates of cost.

In a paper on pumped storage in the Pacific Northwest(2), the following statements are pertinent to the discussion in this appendix:

> "The North Pacific Division office of the Corps of Engineers began developing procedures for inventorying and evaluating sites in 1967. In 1971 a report was prepared and subsequently published by the Pacific Northwest River Basins Commission. . . .
>
> "General Plant Description. The inventory concentrated on pumped-storage sites capable of operating on a weekly cycle basis. It was assumed that the power plants would be build(t) underground and would in most cases employ reversible pump-generating units (separate pumps and turbines would be used for sites developing in excess of 2,000 feet). It was also assumed that earthfill dams or dikes would be used for forming the reservoirs and that concrete-lined penstocks would be used. . . .
>
> "Head. Generating and pumping heads ranged from about 700 feet to over 3,000 feet with averages about 1,500 feet. Sites with heads less than 700 feet were found to be quite costly and were usually rejected. . . .
>
> "Generating Capacity. Because of the large number of sites available in the region, it was decided to limit the inventory to sites capable of developing at least 1,000 megawatts. The maximum capability is determined by the amount of reservoir storage available. Some sites were capable of developing as much as 10,000 megawatts, but the average was about 3,000 megawatts.

> "Operating Pattern. It was assumed that pumped-storage would operate on a weekly cycle, . . . it is necessary to provide reservoir storage for about 14 hours of equivalent full load generation. . . .
>
> "Results of the Inventory. Although our inventory is not complete at this time, some areas within our region are complete. . . .
>
> "A total of 242 pumped-storage sites were located in the western sector, all having costs less then(than) $185 per kilowatt (indexed to January 1974 cost levels). . . . Out of 242 total sites, 160 sites appear to have no conflict with special land use areas. . . ."

Reference was made to this same site survey in Appendix B, where a statement is quoted to the effect "The region is blessed with an abundance of sites with investment costs . . . in the range of $100 to $130 per kilowatt." These costs were on a 1971 basis, and when adjusted to 1974 they become about $130 to $170, which is not inconsistent with the $185 upper limit on all sites.

An August 1973 estimate made for one of the "planned" plants listed in Table A-1, and of which one of the General Public Utilities companies is to be part owner, placed the cost of this project at $161/kW. This included $30/kW for a 10-hour storage and $131/kW for the balance of plant. Adjusted to January 1, 1974 levels, the total project cost would be about $170/kW.

Similar estimates could be reported for other plants, either under construction or planned. Such estimates, however, would add little of value, because they are not completely independent and are therefore likely to be cumulative evidence of the same costs that have been experienced at existing plants. In addition, adjustment of estimates to a uniform cost level is difficult, because of uncertainties as to how the estimated costs are related to time, particularly in this present period of rapid cost escalation.

It is useful, however, to consider several published estimates that relate costs to unit size and head. Several papers presented at the August 1974 conference on Converting Existing Hydro-Electric Dams & Reservoirs into Pump Storage Facilities provided such generalized estimates of costs. Two diagrams, Figures 3 and 7, from a paper(3) presented by representatives of Ebasco Services and two, Figures 14 and 16, from a paper(4) from International Engineering have here been identified as Figures D-3 to D-6.

Figure D-3 shows powerhouse structures and pump/turbine and generator/motor costs as a function of head at 1974 cost levels for projected plant sites. It is not stated whether these are the total related costs or only the direct costs; more than likely they are the latter. In any case, they represent only about 50%

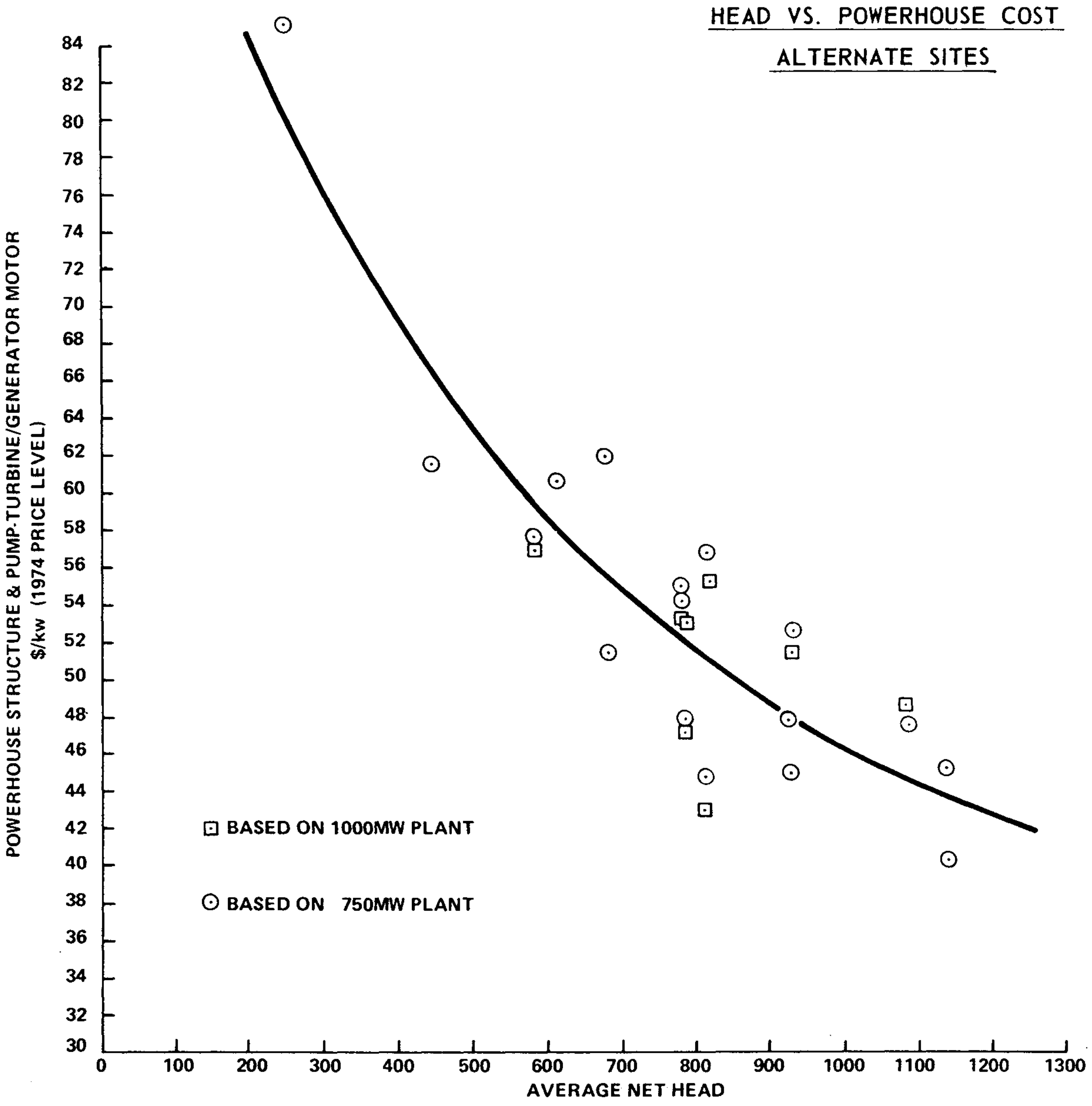


Figure D-3 POWERHOUSE COSTS VERSUS HEAD

Source: "Pumped Storage Site Selection: Engineering and Environmental Considerations," by R.H. Resch and D. Predpell, in ASCE Engineering Foundation Conference Publication, <u>Pumped Storage</u>, Aug. 1974, page 44.

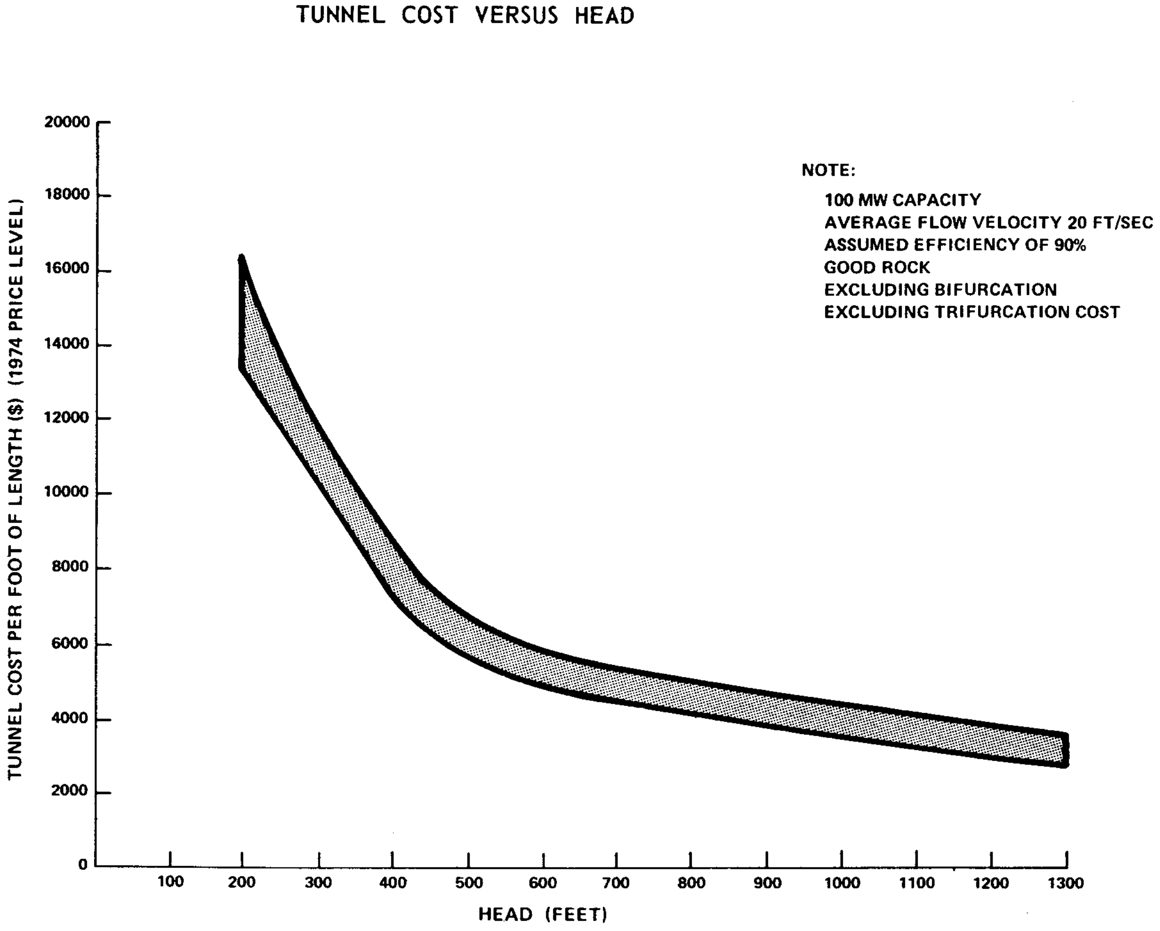


Figure D-4 TUNNEL COSTS VERSUS HEAD

Source: "Pumped Storage Site Selection: Engineering and Environmental Considerations," by R.H. Resch and D. Predpell, in ASCE Engineering Foundation Conference Publication, Pumped Storage, Aug. 1974, page 48.

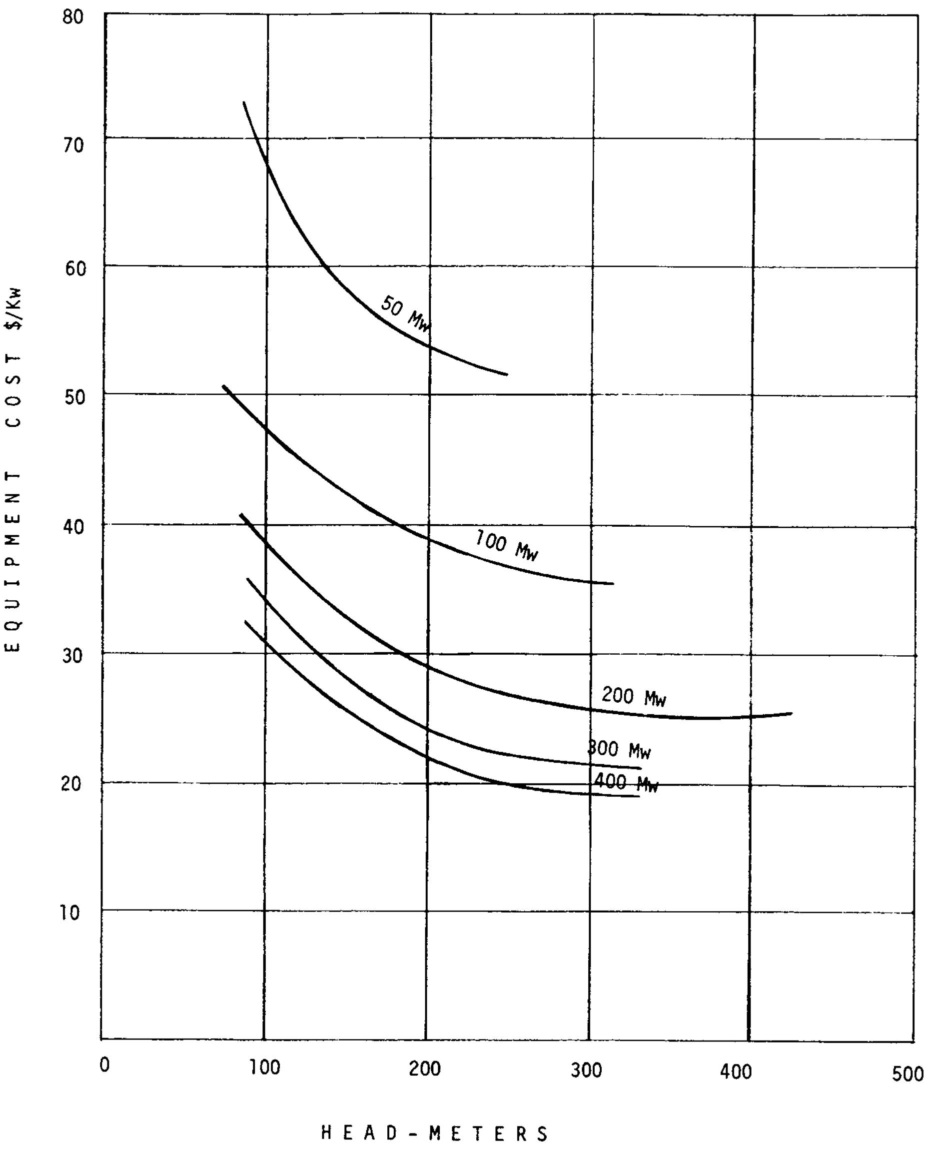


Figure D-5 MAJOR EQUIPMENT COSTS VERSUS HEAD

(Equipment includes single stage pump/turbine, valve and generator/motor.)

Source: "Considerations in Converting Conventional Power Plants to Pumped Storage Facilities," by James Carson and Sam Fogleman, in ASCE Engineering Foundation Conference Publication, Pumped Storage, Aug. 1974, page 558.

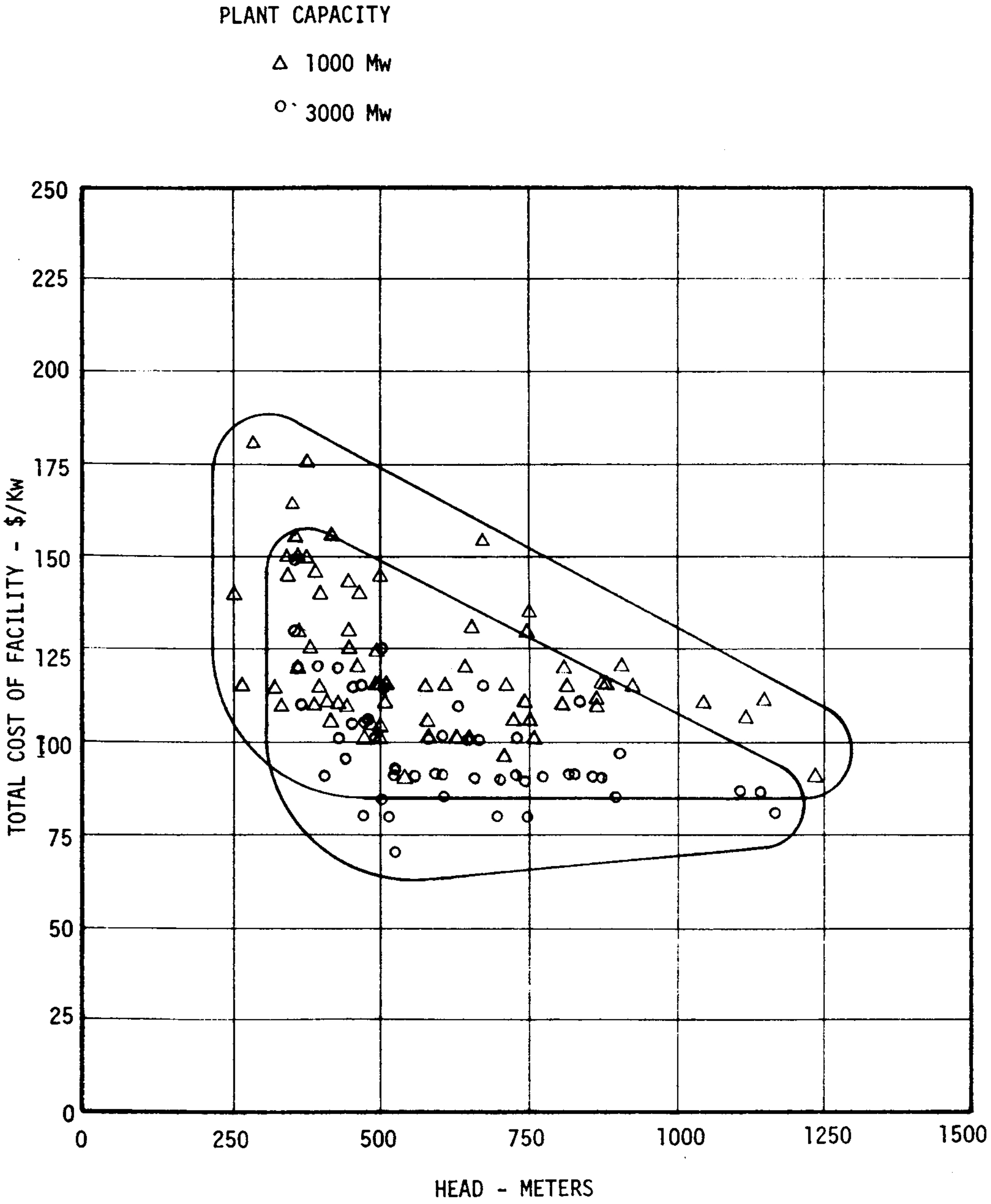


Figure D-6 TOTAL COSTS OF PROPOSED INSTALLATIONS VERSUS HEAD

(Date of cost estimates is not stated.)

Source: "Considerations in Converting Conventional Power Plants to Pumped Storage Facilities," by James Carson and Sam Fogleman, in ASCE Engineering Foundation Conference Publication, Pumped Storage, Aug. 1974, page 560.

of the plant cost, exclusive of storage. They do, however, show those costs that are most affected by head, decreasing from about $69/kW at 400 feet to $43/kW at 1200 feet.

Figure D-4 shows tunnel costs per foot as a function of head. Again it is not clear whether these are direct or total costs, but in any case the costs are low relative to actual costs of waterways, since components such as intake structures and draft tubes are not included. If the tunnel length is assumed to be, for example, five times the head, the cost increases from about $16/kW at 400 feet to $21/kW at 1200 feet.

Although Figures D-3 and D-4 relate to segments of plant that account for about 80% of the total, exclusive of storage, there are too many uncertainties involved to permit an independent estimate of total plant cost. Nevertheless, it is evident that plant costs should decline by $20/kW, more or less, with an increase in head from 400 to 1200 feet.

Figure D-5 shows only equipment costs, but relates these to both unit size and head. The tendency for plant costs to decrease with increase in size and head, as indicated in Figure D-2, is again confirmed. More important, this diagram indicates equipment costs are levelizing for heads above 1000 feet (300 m.) and that they may be approaching the limit of reduction for increases in unit size.

Figure D-6 shows estimated total plant costs for very large (1000 and 3000 MW) proposed installations and for very high heads, extending from about 800 to 4000 feet. As might be expected, and without regard to the date of the estimate, the range of costs found in Figure D-6, about $80 to $160/kW, is below the mid-range cost estimated in this appendix.

An additional diagram, Figure G-4, which is referred to in connection with later discussion of underground pumped storage, also shows the cost of plants with surface reservoirs decreasing from about $200/kW at about 800 feet head (250 m.) to $150/kW at 1600 feet (500 m.). This diagram is more useful in the comparison of costs for conventional and underground pumped storage than in the indication of the absolute values of such costs.

Although the available estimates of costs for future plants indicate that the previously suggested ranges as of January 1, 1974 are not unreasonable, consideration of these estimates indicates that there can be wide variations in future costs, depending on the optimism of the estimator and the assumptions as to cost escalation.

REFERENCES

(1) Handy-Whitman Index, Bulletin No. 99, to January 1, 1974, Whitman, Requardt and Associates, Baltimore, Md.

(2) Orval W. Bruton and Richard L. Mittelstadt, "Planning for Pumped-Storage in a Hydro-Thermal System," Paper Presented Before the ASCE, 22nd Annual Hydraulics Division Specialty Conference, Knoxville, Tenn., July 31, 1974.

(3) Robert H. Resch and Dan Predpall, "Pumped Storage Site Selection: Engineering and Environmental Considerations," ASCE Engineering Foundation Conference Publication, "Pumped Storage," August 18-23, 1974, pp. 39-70.

(4) James Carson and Sam Fogleman, "Considerations in Converting Conventional Power Plants to Pumped Storage Facilities," ASCE Engineering Foundation Conference Publication, "Pumped Storage," August 18-23, 1974, pp. 539-562.

Appendix E

PUMPED STORAGE - OPERATION AND MAINTENANCE EXPENSES

Based on the operating experience of existing pumped storage plants, O&M expenses have been found to average about $1.60/kW/year, after adjustment to January 1, 1974 wage levels. Adjusted averages for six large plants with more than three years of operating experience have ranged from $1.14 to $2.52/kW/year. If the extreme values are ignored, the range for four plants is $1.38 to $1.81. Because these ranges are small in comparison to the typical total annual costs per kW ($50-60) for a pumped storage plant, no significant accuracy is sacrificed if the O&M expenses are represented by a single annual rate.

The data supporting this rate are summarized in the following table. These expense data are obtained from Federal Power Commission publications(1) and from company Form 1 reports filed with the Federal Power Commission. All reported expenses have been adjusted to January 1, 1974 wage levels by using a Bureau of Labor Statistics record of hourly earnings for transportation and public utility workers.(2) Expenses per kW are also influenced by the capacity used in their derivation. To make this as consistent as possible, the capacity has been based 80% on capability at minimum head and 20% on capability at maximum head, except where the owner rates the plant at minimum head capability.

The average expenses for each of the six plants with more than three years of operation are arranged here in order of increasing total expense. These are followed by the records of four plants with less than three years of operation.

			adjusted annual expenses $/KW/Year		
plant	full years of operation	capacity MW	operation	maintenance	total
Yards Creek	9	330	0.36	0.78	1.14
Cabin Creek	7	280	0.97	0.41	1.38
Taum Sauk	11	350	0.38	1.25	1.63
Smith Mountain	9	440	0.56	1.00	1.56
Muddy Run	7	856	0.66	1.15	1.81
Kinzua (Seneca)	4	380	1.09	1.43	2.52
Average (6 plants, unweighted)			0.67	1.00	1.67
Average (without Kinzua)			0.59	0.92	1.51

plant	full years of operation	capacity MW	adjusted annual expenses $/KW/Year operation	maintenance	total
Blenheim-Gilboa	1	1030	0.19	0.12	0.31
Jocassee	1	312	0.52	0.07	0.59
Ludington	1	1675	0.35	0.46	0.81
Northfield	2	1000	0.86	0.32	1.18

The four records have been given no weight in determination of the recommended average O&M expenses. The longer records show that Operation Expenses, after adjustment to January 1, 1974 wage levels, are fairly constant over time. Consequently, the Operation Expenses for the four recently completed plants may be representative of future experience; and if so, they tend to confirm the experience of the older plants. But the longer records also indicate that Maintenance Expenses vary widely from year to year and are likely to be subsequently higher than those experienced in the first year or two of operation.

The record for Kinzua has also been given less than full weight in the determination of the recommended average. This discounting of Kinzua's high cost is based on the short record and on its known but unusual maintenance requirements. (The first and last plants in the above list of six are both operated in the General Public Utilities System. It is believed that the Yards Creek experience is more likely to typical of future pumped storage plant operations than is the Kinzua experience.)

Included in the above list of six plants is Smith Mountain, which is not a pure pumped storage, because it combines reversible units with a conventional hydro installation. Nevertheless, it was considered to be a useful supplement to the relatively few data otherwise available. Because the Smith Mountain experience is so near the recommended average, no different average could be proposed, even if the Smith Mountain experience were excluded.

Because the amounts involved are small, there is no need to consider separately the average expenses for operation and for maintenance; but several comments on these expenses are in order:

1. Adjusted operation expenses for each plant have been found to be fairly constant over time.

2. Operation expense can be considered to be a fixed expense, i.e., independent of the amount or duration of annual generation.

3. Operation expenses, per unit of capacity, might be expected to decrease with an increase in plant size; but such relation to size is not yet evident in the above data. Other differences among plants

and company practices overshadow such a size relationship, if any exists.

4. Adjusted maintenance expenses vary widely from year to year (from about $0.10 to almost $4.00/kW).

5. Maintenance expenses are in part related to the amount of annual generation, and to this extent might be treated as a variable expense. The probable division between the fixed and variable portions has not been determined; and because of the relatively small amount of this expense, such a determination is not essential to the comparisons with other systems.

6. Maintenance expenses can be expected to decrease after correction of design and construction deficiencies during the early years of operation; but this trend presently shows in the record of only one plant.

In the determination of the reported Operation Expenses, there have been excluded for several plants the expenses reported as "Water for Power" and "Rents," Accounts 536 and 540. However, the amounts involved, on a per-kW, per-year basis, appear to be large only for the Northfield plant. The excluded amounts are believed to represent primarily the payments for use of an existing lower reservoir. Such payments are properly included in the economic evaluation of any specific installation, but they are not indicative of probable O&M Expenses at other sites.

The data supporting the above results and discussion are shown on Table E-1.

REFERENCES

(1) Federal Power Commission Annual Supplements, "Hydroelectric Plant Construction Cost and Annual Production Expenses," Fifteenth Annual Supplement, 1971.

(2) Monthly Labor Review, U.S. Dept. of Labor, Bureau of Labor Statistics, Vol. 98, No. 3, March 1975, p. 100.

Table E-1 PUMPED STORAGE, O&M EXPENSES

Plant		Taum Sauk						Smith Mt.						Yards Creek					
Year of Initial Operation		1963						1965						1965					
Capability	MW		Max. 350		Min. 350	Use(a) 350			Max. 460		Min. -	Use(a) 440			Max. 330		Min. 330	Use(a) 330	
		Operation(c)			Maintenance(c)			Operation(c)			Maintenance(c)			Operation(c)			Maintenance(c)		
Wage Index (b)	Year	$1000	Adj.	$/KW	$1000	Adj.	$/KW	$1000	Adj.	$/KW	$1000	Adj.	$/KW	$1000	Adj.	$/KW	$1000	Adj.	$/KW
55.5	1964	86	155	0.44	78	141	0.40	-	-	-	-	-	-	-	-	-	-	-	-
58.3	65	84	144	.41	113	194	.55	-	-	-	-	-	-	-	-	-	-	-	-
59.9	66	99	165	.47	187	312	.89	143	239	0.54	81	135	0.31	200	334	1.01	151	252	0.76
62.4	67	93	149	.43	440	705	2.01	167	268	.61	120	193	.44	75	120	.36	159	255	.77
65.8	68	93	141	.40	181	275	.79	183	278	.63	231	351	.80	50	76	.23	178	271	.82
70.0	69	87	124	.35	303	433	1.24	208	297	.68	406	580	1.32	67	96	.29	149	213	.64
74.2	70	77	104	.30	188	254	.73	182	245	.56	444	598	1.36	52	70	.21	170	229	.69
80.8	71	87	108	.31	114	141	.40	193	239	.54	654	809	1.84	64	79	.24	460	569	1.72
89.2	72	103	126	.36	264	296	.85	184	206	.47	408	458	1.04	91	102	.31	170	191	.58
97.0	73	112	116	.33	741	765	2.18	188	194	.44	381	393	.89	92	95	.29	160	165	.50
103.5	74	137	132	.38	1333	1290	3.68	-	-	-	-	-	-	93	90	.27	195	189	.57
	Averages		133	0.38		437	1.25		246	0.56		440	1.00		118	0.36		259	0.78

Plant		Muddy Run						Cabin Creek						Kinzua(Seneca)					
Year of Initial Operation		1967						1967						1970					
Capability	MW		Max. 920		Min. 840	Use(a) 856			Max. 324		Min. 268	Use(a) 280			Max. 462		Min. 380	Use(a) 380	
65.8	1968	(d)227	355	0.41	193	294	0.34	(d)205	312	1.11	43	65	0.23	-	-	-	-	-	-
70.0	69	(d)328	469	.55	581	830	.97	209	298	1.07	62	89	.32	-	-	-	-	-	-
74.2	70	(d)437	589	.69	482	650	.76	209	282	1.01	95	128	.46	-	-	-	-	-	-
80.8	71	(d)543	672	.79	641	794	.93	218	270	.97	82	101	.36	(d)342	423	1.11	255	316	0.83
89.2	72	(d)549	616	.72	900	1008	1.18	242	272	.97	99	111	.40	(d)398	446	1.18	670	752	1.98
97.0	73	(d)605	624	.73	1690	1740	2.04	232	240	.86	126	130	.46	(d)380	392	1.03	585	603	1.59
103.5	74	(d)651	630	.74	1658	1602	1.87	227	220	.79	176	170	.61	(d)411	397	1.04	522	505	1.33
	Averages		565	0.66		988	1.15		270	0.97		113	0.41		414	1.09		544	1.43

Additional Short Records - (same columnar headings as above)

Northfield	1000 MW	1973	(d) 640	660	0.66	170	175	0.18
		74	(d)1100	1060	1.06	480	465	.46
Jocassee	312 MW	74	167	161	.52	22	21	.07
Ludington	1675 MW	74	598	578	.35	775	749	.46
Blenheim-Gilboa	1030 MW	74	198	191	.19	124	120	.12
Salina	(e)130 MW	1970	23	31	0.24	38	51	0.39
		71	41	51	.40	48	59	.46
San Luis	(e)424 MW	70	197	266	.63	173	233	.55
		71	301	373	.86	203	251	.59

NOTES:

(a) The capacity used here is based on 80% of the capability reported at minimum head and 20% of that reported at maximum head.

(b) The wage index is obtained from the hourly earnings of transportation and public utility employees as reported in the "Monthly Labor Review." The index equals the reported wage rate for the year divided by the rate at January 1, 1974, which is assumed to be the average of the rates reported for December 1973 and January 1974.

(c) Expense data are obtained from FPC "Hydroelectric Plant Construction Cost and Annual Production Expenses," Annual Supplements, 1964 to 1971 and from plant owners' FPC Form 1 Reports for 1972 to 1974.

(d) Operation expenses used here exclude "Water for Power," Acct. 536, and "Rents," Acct. 540.

(e) These reported capacities are not consistent with the determination for other plants, where both maximum and minimum capacities were available.

Appendix F

SITES FOR UNDERGROUND PUMPED STORAGE

The availability of sites for underground pumped storage depends on the identification of suitable underground conditions, coupled of course with a surface topography or land use conditions which permit construction of a surface reservoir. Some sites may be readily identified in connection with existing mine operations, but otherwise the location of good sites is likely to involve a very extensive geological investigation. Several such investigations have been made over limited areas.

Sites in New England

One such investigation that has reached the stage of publication is a 1974 report to Northeast Utilities Service Company on "Geological Survey of Potential Cavern Areas in New England."(1) The "Abstract" of this report is as follows:

> "The storage of compressed air and/or water in underground caverns is being investigated in several countries among alternatives for meeting peak power demands. Cavern depth would be as much as 800 meters.
>
> "Geological feasibility depends upon suitable bedrock. Data for this New England study are derived from various maps and reports of previous geological surveys and from additional field reconnaissance. Over 1180 rock formations have been identified and studied in the six-state region. More attention has been paid to certain parts of Connecticut and western Massachusetts, and less attention to eastern Massachusetts, Maine, New Hampshire, Rhode Island, and Vermont.
>
> "Three levels of evaluation are used. Each formation is examined according to a set of ten criteria at a first stage, and 190 are ranked high enough to be discussed at a second stage. Some of those regarded as most suitable are reconsidered in detail at a third stage.
>
> "About 90 formations are listed as equally favorable pending further tests, and their positions are shown on index maps. Most of them are uniform masses of relatively undeformed granite. Although this type of rock is considered most suitable, tunneling technology developed in recent years would permit excavation of caverns in some other materials, generally at greater cost and risk.

> "Preceding the identification and ranking of the bedrock units in this presentation is a review of existing underground works and plans in New England and of rock properties that affect them. The report ends with a bibliography on the two interwoven subjects of crustal geology in New England and geological aspects of removing rock from subterranean depths.
>
> "The objective of the survey is to assess only the suitability of geological conditions for retaining compressed air and/or water below ground. The conclusion reached is as follows. The evidence is sufficient to indicate that a number of rock formations in New England can be considered to have characteristics favorable for possible excavation of large underground caverns to be used for storage purposes."

A map showing the location of suitable rock formations in New England is identified as Figure F-1.

Suitable Areas for Underground Pumped Storage

Figure F-2, prepared by Dr. Bennett L. Smith, Consulting Geologist, identifies potentially suitable areas for underground pumped storage. Since the map covers the 48 states, these areas have been identified and rated in relation to the major geological subdivisions of the country, which are fairly well defined geographically. Offsetting the advantage of such presentation is the fact that, in certain provinces, there are areas which are highly favorable as well as those which are unfavorable to the development of underground storage. A map that differentiates between such areas requires a detailed examination of local conditions, such as has been made in New England, and quite likely in other localities. Table F-1 provided additional explanation of the general geology of each area and of the potential for underground storage.

Site Requirements

Harza Engineering Company has supplied the following comments in response to an inquiry regarding site availability. These comments include excerpts from a proposal made to the Research Committee of the ASCE Power Division relative to the inventorying of sites for underground pumped storage.

> "In general, underground reservoirs must be in good rock which is relatively free from residual tectonic stresses. Many parts of the Rocky Mountains, for example, have lots of rock that appears good, but the rock is under heavy residual stress and contains unpredictable water-bearing crushed zones. A lower reservoir in such rock would be prohibitively expensive because of support requirements.
>
>> ' . . . In an underground pumped-storage plant the major structures -- powerstations, lower

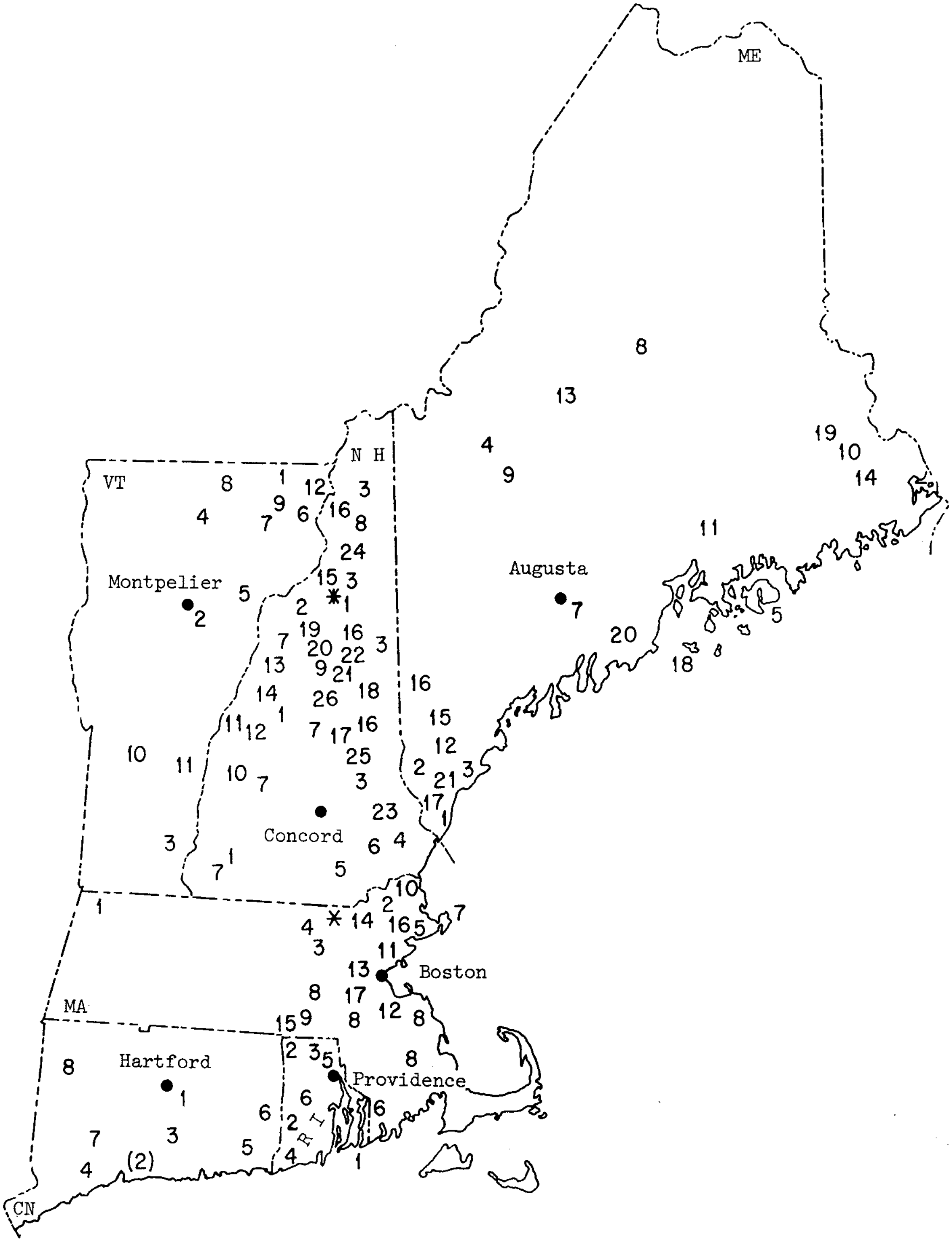


Figure F-1 SUITABLE ROCK FORMATIONS FOR UNDERGROUND PUMPED STORAGE

Source: "Geological Survey of Potential Cavern Areas in New England," by O.C. Farquhar, a Report to Northeast Utilities Service Company, 1974, NTIS PB 250 107, page 320.

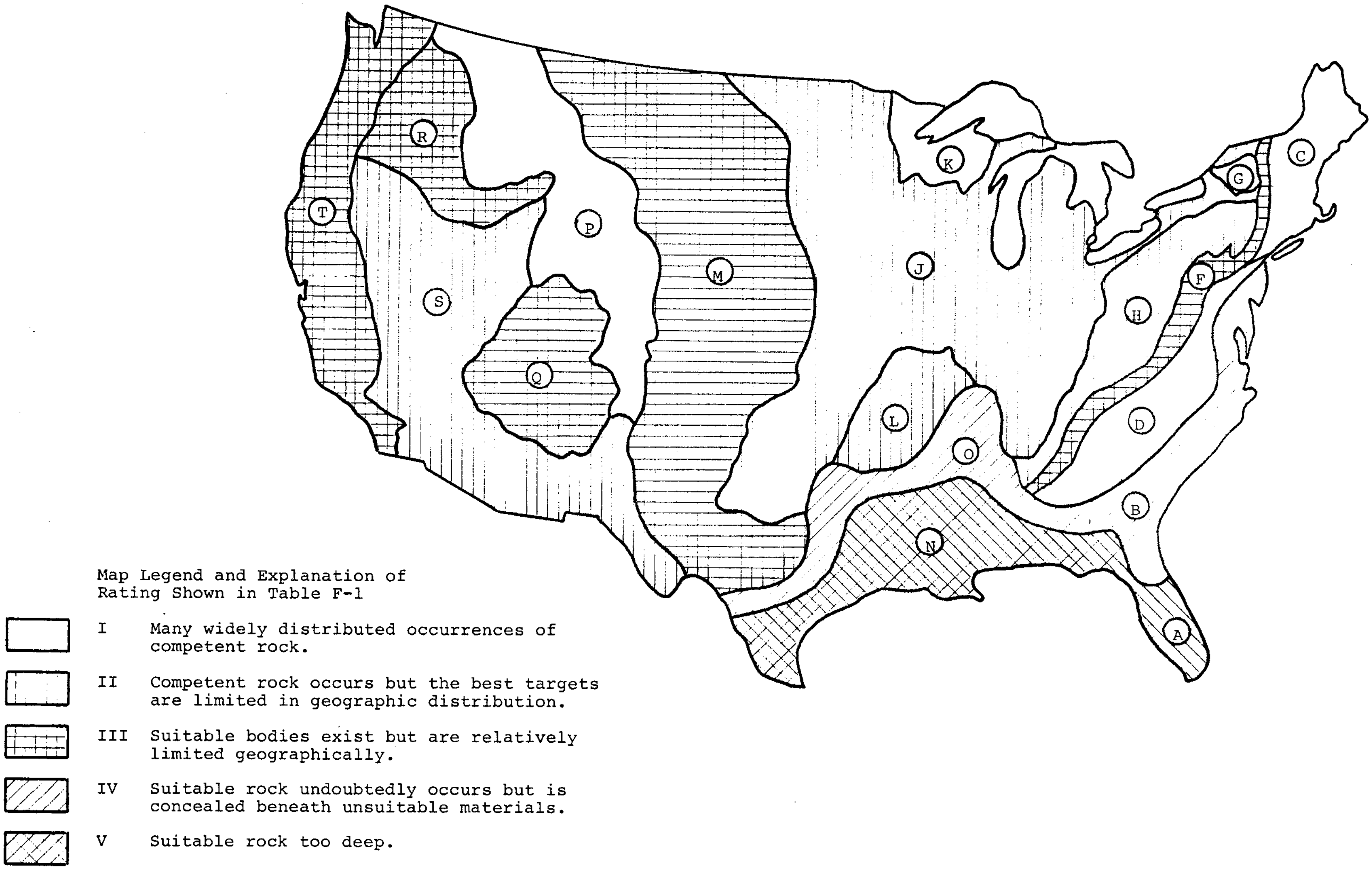


Figure F-2 RATING OF MAJOR GEOLOGICAL PROVINCES ON BASIS OF SUITABILITY FOR UNDERGROUND PUMPED STORAGE

Table F-1 EXPLANATION AND COMMENTS ON RATING OF MAJOR GEOLOGICAL PROVINCES

Area	Rating	General Nature of Geology	Potential Targets
A. ATLANTIC COASTAL PLAIN - Outer Part	V	Unconsolidated sediments, underlain by basement rock at depths of more than 5,000 ft.	Suitable rock is too deep to be of interest.
B. ATLANTIC COASTAL PLAIN - Inner Part	IV	Sands, clays and other sediments underlain by consolidated rock at depths ranging from 5,000 ft. at the outer margin of the indicated area to zero depth at the inner margin.	Basement rocks believed to be mostly crystallines except for northern Florida where there are unmetamorphosed and little-disturbed Paleozoic rocks. Because the suitable rocks are concealed, the best targets might be difficult to find, but it is of some interest that aggregates could be produced where none are available on the surface.
C. NEW ENGLAND	I	Complex assemblage of igneous, sedimentary and metamorphic rocks within a great variety of rock types and of structural conditions. Precambrian to Triassic in age. For present purposes the New Jersey Highlands is included here.	Many bodies of granite and other plutonic rocks. (Plutonic is used in the sense of a rock of deep-seated origin; includes syenites, granodiorites and the like as well as gneisses.)
D. PIEDMONT AND BLUE RIDGE	I	Geology relatively complex; considerable variety of igneous and metamorphic rocks.	Throughout large parts of the Piedmont there are potential targets in granite and other plutonic rocks.
E. TRIASSIC LOWLANDS	III	These are areas in the Connecticut Valley, in New Jersey and Pennsylvania and in the southern Piedmont, too small to be shown separately on the map. There are sedimentary rocks of Triassic age as well as sills and flows of basalt and diabase. Structure relatively simple.	The thicker basalt and diabase bodies present attractive targets.
F. RIDGE AND VALLEY PROVINCE	III	Folded and faulted sedimentary rocks of Paleozoic age.	Potential targets, particularly in carbonate rocks in the crests and troughs of some of the broader, more open folds.
G. ADIRONDACKS	I	Precambrian igneous and metamorphic rocks.	Widespread potential targets in igneous and other plutonic rocks.
H. APPLACHIAN PLATEU	II	Sandstones, shales and limestones of Paleozoic age, flat-lying to very gently dipping. Coal deposits.	In general, the sandstones and limestones should be competent enough at depth to permit a wide variety of targets.
J. INTERIOR PLAINS	II	Paleozoic sedimentary rocks, very gently deformed into broad basins, troughs, domes and arches.	Carbonate rocks and sandstones provide possible targets. Basement Precambrian is close enough to the surface in some parts to be of interest.

Table F-1 EXPLANATION AND COMMENTS ON RATING OF MAJOR GEOLOGICAL PROVINCES (cont.)

Area	Rating	General Nature of Geology	Potential Targets
K. CANADIAN SHIELD	I	Precambrian igneous and metamorphic rocks in northern Michigan, Wisconsin and Minnesota.	Widespread targets in plutonic rocks.
L. OZARK HIGHLANDS	I	Highlands of Precambrian igneous and metamorphic rocks, overlain by Paleozoic carbonates and other sedimentary rocks.	Widespread targets in plutonic rocks. The southern part of the area shown is similar geologically to the Ridge and Valley Province.
M. THE GREAT PLAINS	III	Mostly Cretaceous and younger sediments and sedimentary rocks underlain by older sedimentary rocks and by basement igneous and metamorphic rocks.	Precambrian basement appears at the surface in the Black Hills and is close enough to the surface to be of interest in an area east and southeast of the Black Hills. There are small intrusive bodies in the vicinity of the Black Hills and in Montana.
N. GULF COASTAL PLAIN - Outer Part	V	Unconsolidated sediments; salt domes.	Suitable rock too deep.
O. GULF COASTAL PLAIN - Inner Part	IV	Unconsolidated sediments underlain at depths of 5,000 ft. or less by basement rock consisting mostly of Paleozoic sedimentary rocks which range in structure from flat-lying to intensely folded and metamorphosed.	Potential targets in the basement but because the suitable rocks are concealed, the targets might be difficult to define.
P. ROCKY MOUNTAINS	I	Mostly igneous and metamorphic rocks in the ranges, over which are draped sedimentary rocks. Alluvium fills the valleys.	Widespread bodies of igneous and other rock types offer possible targets.
Q. COLORADO PLATEAU	III	At the surface, mostly gently deformed sedimentary rocks.	Some igneous bodies. Basement too deep except around part of the margin. Some sedimentary formations might be used.
R. COLUMBIA PLATEAU	III	Volcanic rocks form a thick cover over older rocks of complex geology.	May be technically feasible to establish storage in some of the volcanic rock. Basement may be shallow enough in places but targets would be concealed.
S. BASIN AND RANGE PROVINCE	II	Ranges of igneous, sedimentary and metamorphic rock with basin containing younger alluvial material.	Local targets in the ranges.
T. PACIFIC COAST REGION	III or II	Geology complex. A number of igneous intrusions in addition to the huge Sierra Nevada batholith.	Local targets in igneous intrusions and in some of the more competent sedimentary and metamorphic rocks.

reservoir, water conduits, transformers -- are underground. The larger is the head, the smaller are the structures and the volume of water required. Thus, in general and within reasonable limits, the deeper the lower reservoir can be beneath the ground surface the greater are the plant's economy and benefit and the less is its environmental impact.

'There are limits to the location of such projects. The lower reservoir is a large excavation and must be in rock that is resistant to chemical and physical erosion and structurally is sound so that it requires minimum support or lining. The most favorable areas are those where the Precambrian basement rocks are within depths of 2,000 feet or less, where geologic processes which shatter rock, such as faulting, have not occurred or have been of minimal intensity, and where aquifers lying above the basement are not sufficiently significant to preclude reasonable construction water-control techniques.

'Inventorying the sites requires several steps. The first is the development of reasonably reliable contours for the top of Precambrian rock. At the present time some State and Federal geological agencies publish maps of inferred elevations, but they are based on fragmentary information and where maps meet at state lines they sometimes disagree.

'There currently is underway a co-operative program of gravimetric surveys between the U.S. Geological Survey and some State geologic agencies. Evidently the program has moved slowly and spottily, so that large areas remain to be covered and results have been forthcoming very slowly. I do not know the extent to which Federal research funds are supporting the program. It appears, however, that the specific objective of mapping the top of Precambrian rock should be added to the program and the program should be accelerated.

'The gravimetric survey requires confirmation and calibration from boring data, which are available in limited amounts. Deep borings and seismic surveys are being made in various locations in search for oil, geothermal energy, etc., and arrangements should be made so that as much as possible, data from these activities will be available for the program.

> 'An important factor in economic feasibility of underground pumped-storage, even if suitable rock is present, is the absence or presence of high stresses locked into the rock by natural causes before excavation. Such stresses, if beyond such reasonable limit, would make the lower reservoir prohibitive in cost. Thus, after Precambrian contours are defined, the next step would be identification of areas of favorable rock stress.
>
> 'At present there is no way to predict stresses other than by penetrating the rock and measuring by various geophysical and physical means. The measurements involve elasticity and deformation, which are approximated or measured in various ways. At depths suitable for underground pumped-storage, such investigation is very expensive because of the deep boring.'"

There is evident need for further work in this area.

REFERENCES

(1) O. C. Farquhar, "Geological Survey of Potential Cavern Areas in New England," a Report to Northeast Utilities Service Company, 1974.

Appendix G

UNDERGROUND CONSTRUCTION COSTS

As for the conventional pumped storage, it is necessary to consider separately the cost of storage and the balance of plant costs. In fact, an additional reason applies to the costs for underground plants, for here the separate estimates derive from quite different basic sources. There are as yet no excavated underground hydro reservoirs, so the estimated costs for these are derived in part from experience in other industries. The balance of plant, however, is not much different from that which has already been built underground for use with surface reservoirs.

Differences in Balance of Plant Components

The general similarities in underground construction are evident from a comparison of sections through an underground plant with surface reservoirs and an underground plant with one underground reservoir. Figure G-1 is a simplified cross section through the Raccoon Mountain plant(1) and Figure G-2 is a cross section through a proposed underground plant.

An obvious difference between the two underground plants is the relatively shorter water conduits required for the one with an underground reservoir, because the long and nearly horizontal pressure and tailrace tunnels are there unnecessary. Also unnecessary with the underground reservoir is the usual surge chamber on the tailrace tunnel. These differences are very favorable to the underground reservoir. Partially offsetting this savings in tunnel and surge chamber costs is the fact that access to the underground plant is more costly, when provided by shafts rather than by tunnels.

Less obvious cost differences may result from measures taken to protect the underground plant from flooding, because the consequences of flooding are possibly more severe and of much longer duration where the whole lower reservoir may have to be emptied by temporary or emergency pumps before restoration of operation can be accomplished. Also it is necessary to protect against full head of the project being imposed on the downstream side of the plant, or to make such an event impossible of occurrence. These measures add to the underground costs.

Another difference, not illustrated by the comparison of Figures G-1 and G-2, is the difference in the powerhouse and equipment layout when heads exceed those that can be served by a single-stage reversible unit. For such heads, a decision may be made to utilize separate turbines and pumps, as has been typical of European practice for high head plants. In this case there is a step increase in cost of equipment to serve the higher heads, as shown by the upper portion of Figure G-3.(2). A somewhat smaller

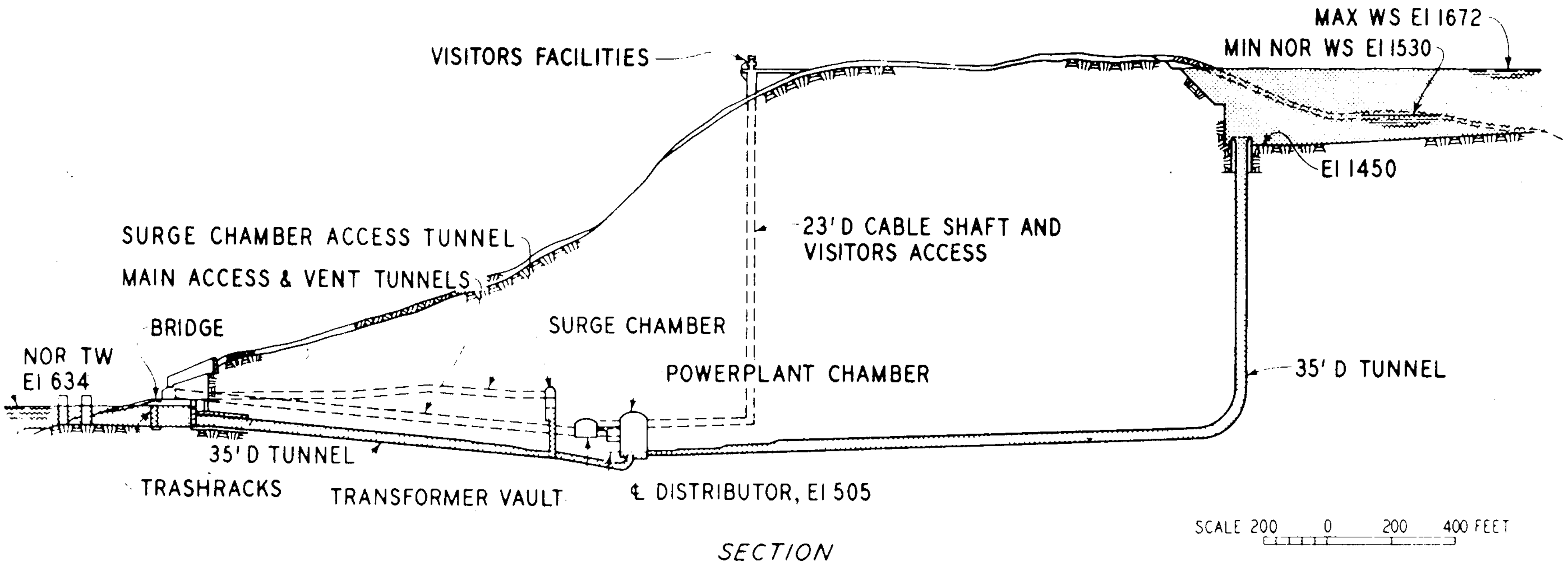
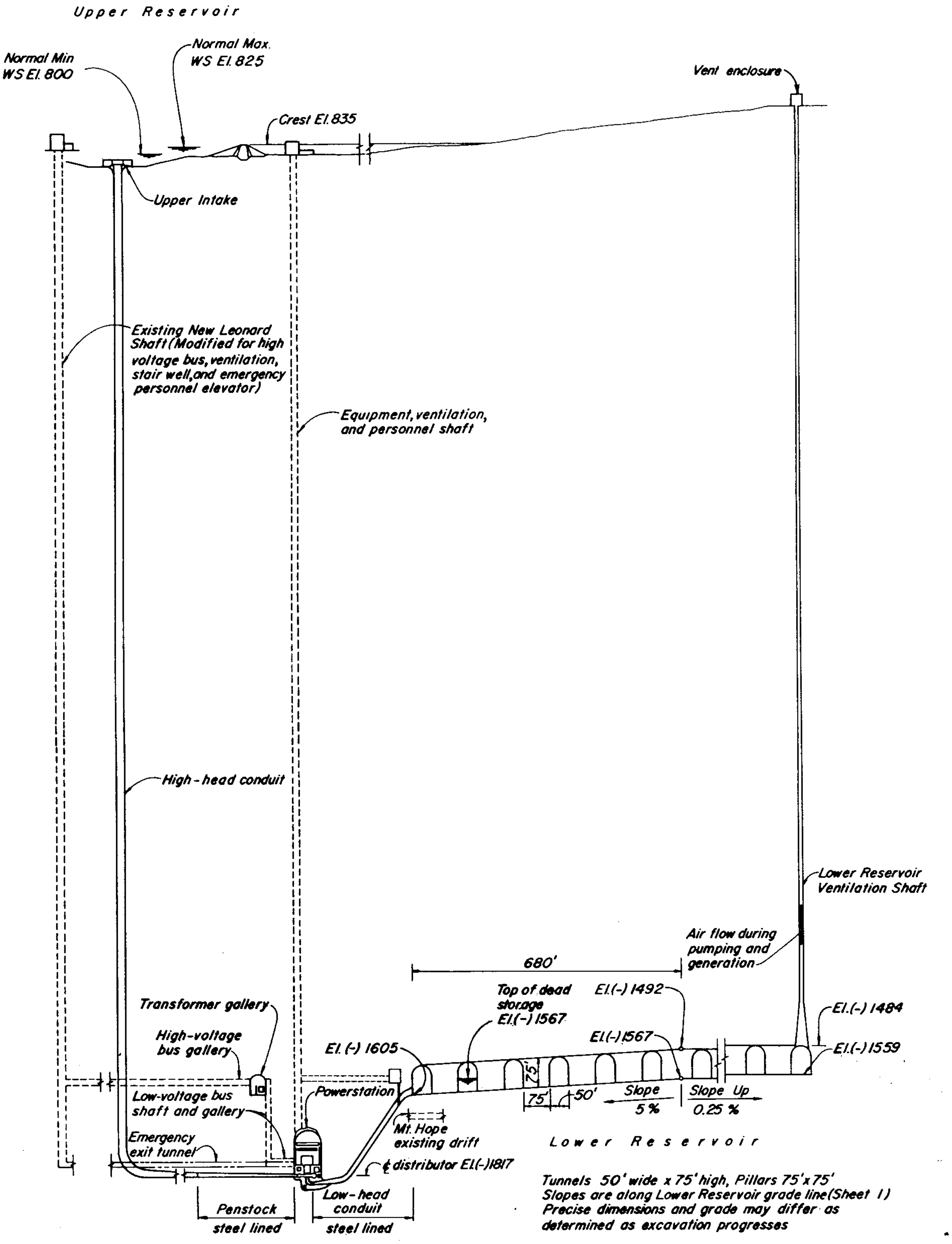


Figure G-1 SECTION, RACCOON MOUNTAIN PLANT

Source: "Reversible Pump/Turbines for Raccoon Mountain," by H.H. Wirschal, in Pumped Storage Development and Its Environmental Effects, University of Wisconsin, page 324.



Tunnels 50' wide x 75' high, Pillars 75' x 75'
Slopes are along Lower Reservoir grade line (Sheet 1)
Precise dimensions and grade may differ as determined as excavation progresses

SECTION THROUGH POWER PLANT

Not to Scale

Figure G-2 SECTION - PROPOSED MT. HOPE PLANT

Source: GPU Service Corporation
FPC License Application

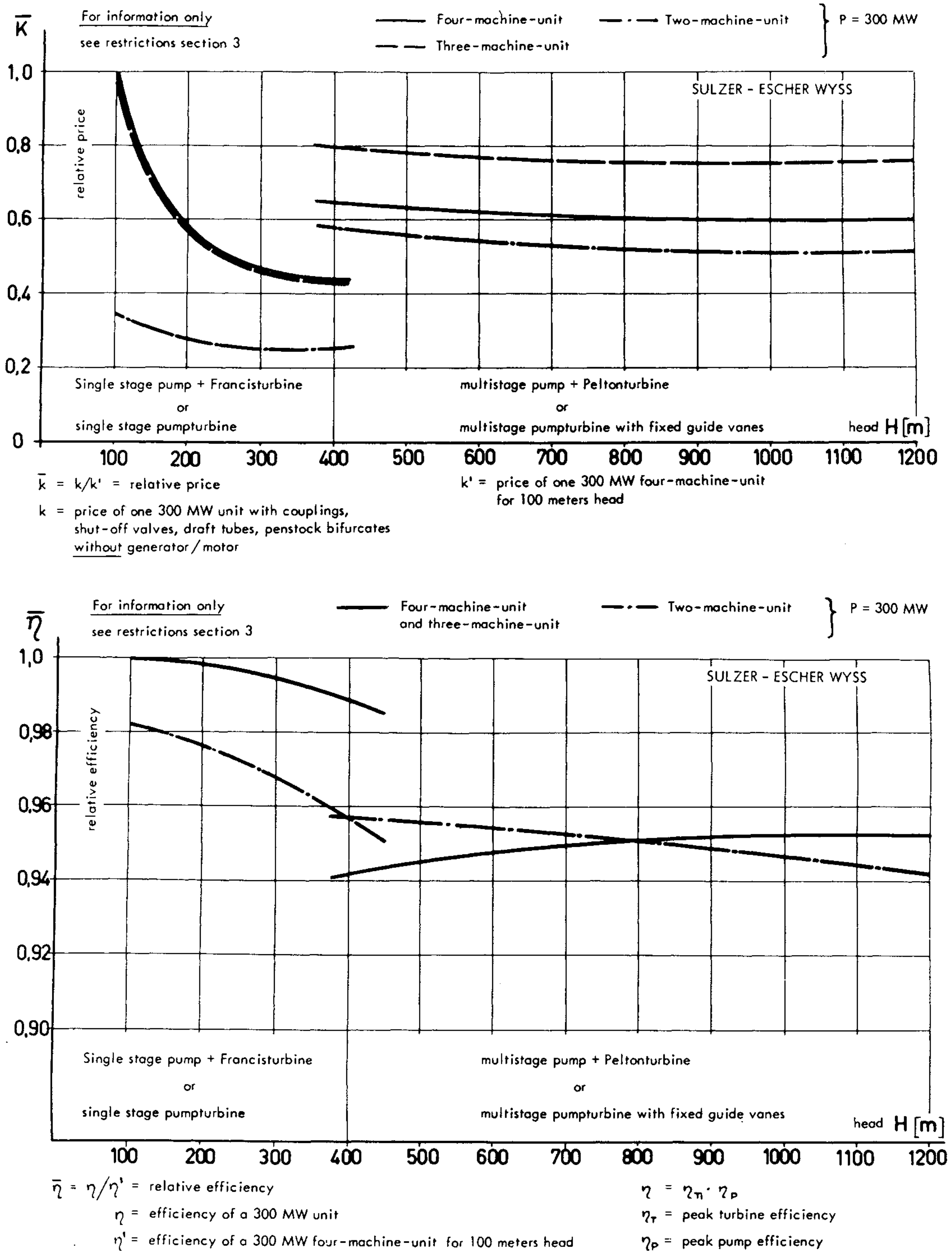


Figure G-3 COSTS AND EFFICIENCIES VERSUS HEAD FOR VARIOUS TYPES OF UNIT

Source: "Arrangements of Hydraulic Machines for Pumped Storage and Comparison of Cost, Efficiency and Starting Time," by E.H. Muhlemann, in Pumped Storage Development and Its Environmental Effects, University of Wisconsin, page 289.

step increase is also shown for multistage reversible units that might be substituted for separate turbines and pumps. The head at which these increases occur is now greater than the 400 meters shown in this 1971 diagram. In any case, however, there is not much variation in equipment costs in the high-head range, beyond the point where this increase occurs.

Alternatively, the higher heads may be accommodated by use of single-stage units in series. With this arrangement, equipment costs, for example for 4000 feet of head, would be essentially the same as for 2000 feet, but there would be added cost for the required intermediate reservoir.

These differences (except for the possibility of plants in series) are recognized in the "order-of-magnitude cost comparison" shown in Figure G-4.(3) Attention is directed to the costs other than those for the two reservoirs, the total of these other costs being lower for the underground pumped storage plant. The major differences shown in Figure G-4, as suggested by the above discussion, are higher equipment costs for the higher heads of the underground plant, but lower power station costs because of decreased volume, also lower costs for the relatively shorter penstocks, and elimination of the tailrace tunnel costs.

Other Elements of Estimated Costs

Before proceeding to further discussion of estimated costs for a specific project, attention is directed to the importance of allowances made for overheads, contingencies, and interest in these estimates. Allowances are also made for price escalation, but we need not consider these here, for all costs are to be adjusted to a common basis, the cost levels of January 1, 1974.

In Appendix D it was found that the costs of a conventional pumped storage might be classified as follows:

Direct costs	69%
Indirect construction costs	12
Engineering and supervision	8
Allowance for funds used during construction	9
Other overhead costs	2
Total	100%

For present purposes, we might equate 100% of cost to $100/kW, which is the lower limit of the suggested range of cost for balance of plant, which in turn is related to experience for larger plants and higher heads. The above breakdown can then be rearranged in the following fashion for comparison with certain estimated costs:

Construction costs	$ 81/kW	
Engineering, supervision and other overheads	10	(= 12.4% of 81)
Allowance for funds	9	(= 9.9% of 91)
	$100/kW	

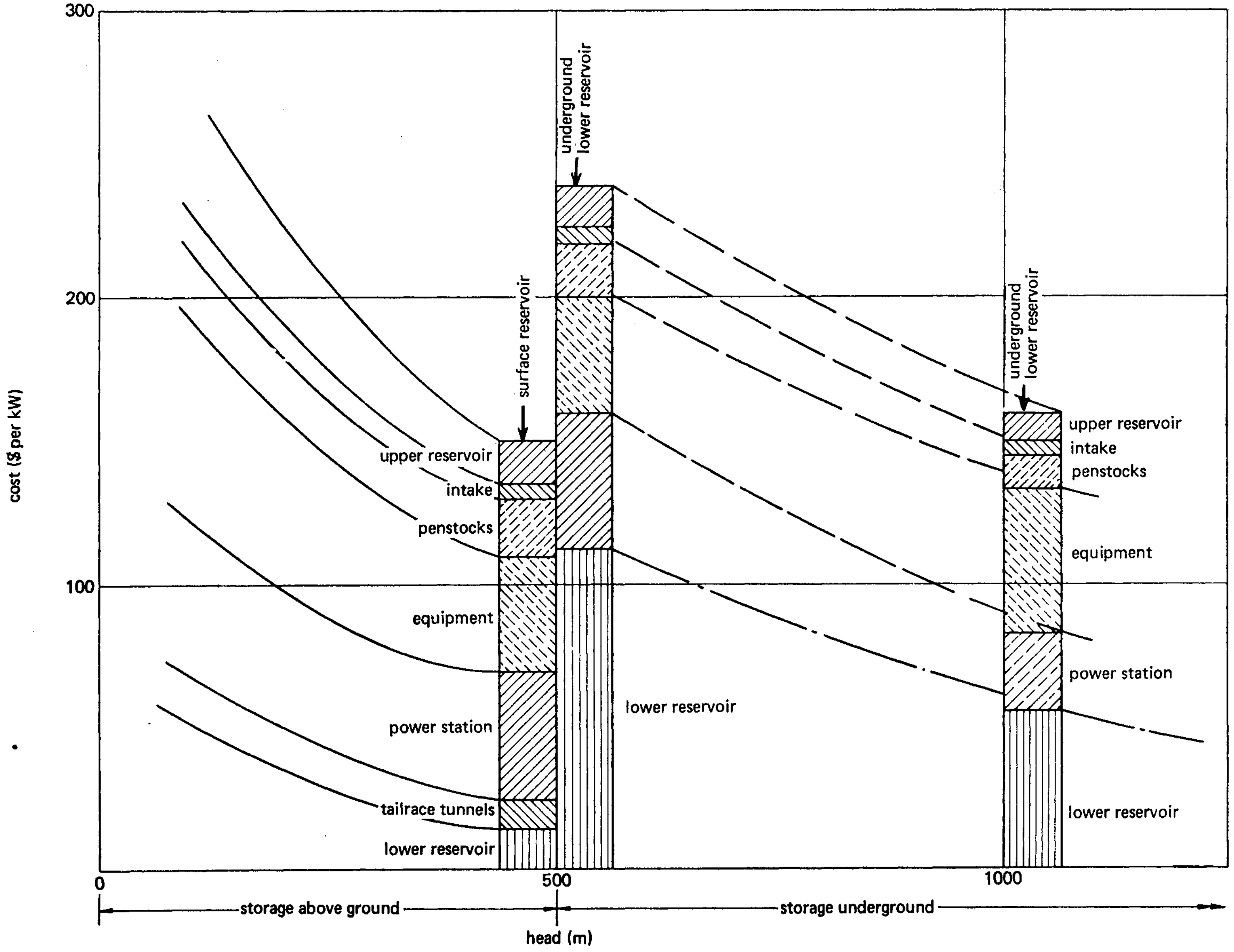


Figure G-4 AN ORDER-OF-MAGNITUDE COST COMPARISON BETWEEN SURFACE AND UNDERGROUND PUMPED STORAGE

Source: "Pumped Storage Underground," by J.G. Warnock and D.C. Willet, presented in the Symposium on Hydro Electric Pumped Storage Systems conducted by United Nations Commission for Eur[illegible]thens, Nov. 1972.

Current estimates for an underground plant might show quite different allowances for the amounts to be added to construction costs. The allowance for overheads and contingencies might be as much as 25%; and the allowance for interest on funds used during construction might be as much as 40%. If the construction cost remains at $81/kW, the use of these higher allowances results in a total estimate of $142/kW for the balance of an underground plant, as compared to the $100/kW for a conventional plant.

The added provision for contingencies, here about 12.5%, is a conservative practice, particularly where some new problems may be encountered in construction. Expert opinions will vary as to what is a reasonable allowance. Note particularly that this is not an allowance for changes in costs due to changes in labor rates or price of materials; it is entirely an allowance for unknown, but adverse factors. In subsequent discussion of estimates, the allowance for overheads and contingencies will be assumed to be in the range of 20 to 25% of the estimated construction costs.

The allowance of 40% for interest is the result of the current high interest rates and an extremely long construction time (the Mt. Hope estimate used 38%). Neither of these factors is reflected in the indicated interest allowance (about 10%) for conventional plants. Those for which the required cost data were on file with the Federal Power Commission were, with one exception, completed before the period of high interest cost. Also, they do not include the recent underground plants (with surface reservoirs), for which the construction time is also long. A recent estimate for such a plant, reflecting both the higher rates and longer time, showed an allowance for interest of 24%. In subsequent discussion of plants with underground storage, the allowance for interest will be assumed to be in the range of 25 to 40% of the construction costs plus overheads.

These assumptions mean that the combined added costs for overheads, contingencies and interest applicable to underground construction lie in the range of about 50 to 75% (1.20 x 1.25 = 1.5 and 1.25 x 1.40 = 1.75), these rates being much larger than the approximate 25% in the actual costs of constructed projects (100/81 = 1.24).

Estimates for Mt. Hope Project

Application has been made by Jersey Central Power & Light Company (a GPU subsidiary) for a Federal Power Commission license for the Mt. Hope Project. The application is based on a 1000-MW plant capacity, in four reversible units operating at about 2500 feet of head, with storage adequate for 10 hours of operation. The plant is to be located in northern New Jersey at the site of an existing shaft, previously used in iron ore mining. The preliminary design and cost estimates for this project have been prepared by Harza Engineering Company.

A series of preliminary cost estimates for Mt. Hope were made in 1973, based on July 1972 costs. These show estimated costs for construction of the balance of plant in the range of about $75 to $85/kW; these include $6/kW for land, it being considered reasonable to include this relatively high land cost as compensation for the existing mine shaft. The highest cost is for construction of an eight-unit plant (125 MW each) in four stages, this higher cost being compensated by the shorter construction time for each stage and a resulting lower interest cost (estimated for this case at only 16%). Other variations in plant description and in assumed costs of excavation of the powerhouse cavern were considered; but major uncertainties would be involved in any comparison among them, particularly with respect to equipment costs for very high heads.

Estimates were revised in 1975, based on March 1975 costs for the purposes of the license application, but were again made on a July 1972 basis for direct comparison with the 1973 work. The cost estimated in 1975 on the basis of July 1972 costs and considered to be directly comparable with the 1973 estimates for balance of plant is $78/kW. The cost estimated in 1975 is the result of a different plant layout and the better understanding of various problems that result from continued study of them. It is very probable that the balance of plant cost would be lower for a larger plant.

If the 1975 estimates, based on 1972 costs is stepped up to January 1, 1974, the $78/kW becomes $90/kW. The comparable estimate in the license application, based on March 1975 costs, is $113/kW, but Harza notes that costs of major equipment were very uncertain as of that date.

It is believed that the above estimate of balance of plant cost, adjusted to January 1, 1974 levels, of $90/kW is conservatively high. One entirely independent estimate for an underground plant with larger capacity and higher head is substantially lower. Also, another recent estimate by Harza for an underground plant with surface reservoirs, is lower by about $5/kW, and this is not out of line with the $80/kW, more or less, indicated by the experience of the larger, higher head existing plants.

Recommended Range of Costs

Considering (1) the evidence of estimated costs, (2) the expert opinion of Harza and Acres as to the comparability of the balance of plant costs for underground construction, whether both reservoirs are on the surface or one is underground, and (3) the fact that the range of high heads and large capacities underground is likely to have much less effect on costs than that encountered in the selected list of existing plants, it is suggested that the construction cost for the balance of plant might lie in the range of $80 to $90/kW as of January 1, 1974. These costs must be increased by about 50 to 75% to cover the overheads, contingencies and interest.

The recommended range of estimated costs should therefore be about $120 to $160/kW.

Underground Storage Costs

The Mt. Hope estimates for construction costs of the storage reservoirs, before the additions for overheads, contingencies and interest, are approximately as follows:

	July 1972 costs	March 1975 costs
Upper reservoir	$0.60/kWh	$0.85/kWh
Lower reservoir	2.30	3.30

These costs adjusted to January 1, 1974 would be roughly halfway between the estimates. For comparability with existing reservoir costs, they must be increased by some factor in the 50 to 70% range. After such increase, the upper surface reservoir cost, about $1.20/kW, is in line with the lower costs shown in Figure D-1 for separate surface reservoirs, but without consideration of the effect of the higher head available at Mt. Hope. The adjusted cost for the lower Mt. Hope reservoir, between $4 and $5/kWh, is in line with the higher cost in Figure D-1, but again without consideration of head. It is only the cost of the lower, or underground reservoir that needs to be further examined.

The costs estimated for the Mt. Hope underground reservoir are determined under generally favorable conditions. The rock is good, there is expected to be a credit for the sale of excavated material, and labor rates and productivity are based on the expectation of a mining rather than a construction type operation. These are the major factors governing an estimate of cost for excavation of a large underground cavern, with labor rates and productivity being most important.

Costs are also greatly affected by the duration of the excavation period, as evidenced by possible wide swings in the added interest cost. As noted above, these varied from 16% for staged construction to 38% in the final estimate. It is evident that all means of reducing the construction period need to be investigated.

The GPU Service Corporation and its consultants made an extensive investigation of underground excavation and mining costs. Actual costs were determined and analyzed for several large mining operations and for major cavern excavations associated with underground power plants. Estimates and advice were obtained from several recognized experts.

For mining operations, the costs adjusted to January 1, 1974 are generally in the range of $4 to $6 per cubic yard. For construction projects, with higher labor rates and lower productivity, the range is $8 to $10 per cubic yard. For Mt. Hope, the rate used, adjusted to January 1, 1974, is about $2.70 per cubic yard, this being a net cost after credit for sale of the excavated material to the operator of the existing quarry at the site.

Considering the wide range of these estimates and of the corresponding conditions applicable to as yet unknown sites, it is not unreasonable to consider a range of net costs from $3 to $10 per cubic yard. These costs must be increased by 50 to 75% for overheads, contingencies and interest. The resulting possible range of the underground reservoir costs is shown in the upper half of Figure G-5. The conversion from cost per cubic yard to cost per kWh is based on a factor of 0.77 cy/kWh at 2500 feet of head, including therein an allowance for 5% excess volume in the lower reservoir. There are, of course, some elements of cost for the lower reservoir which are not proportional to size, but these are small and are neglected in this estimate.

Costs for the surface reservoir are also shown in the upper part of Figure G-5. These are based on the assumption that they may range from the costs indicated by the lower curve of Figure D-1, extended to cover a higher range of heads, to an amount three times as much, as shown by the upper curve.

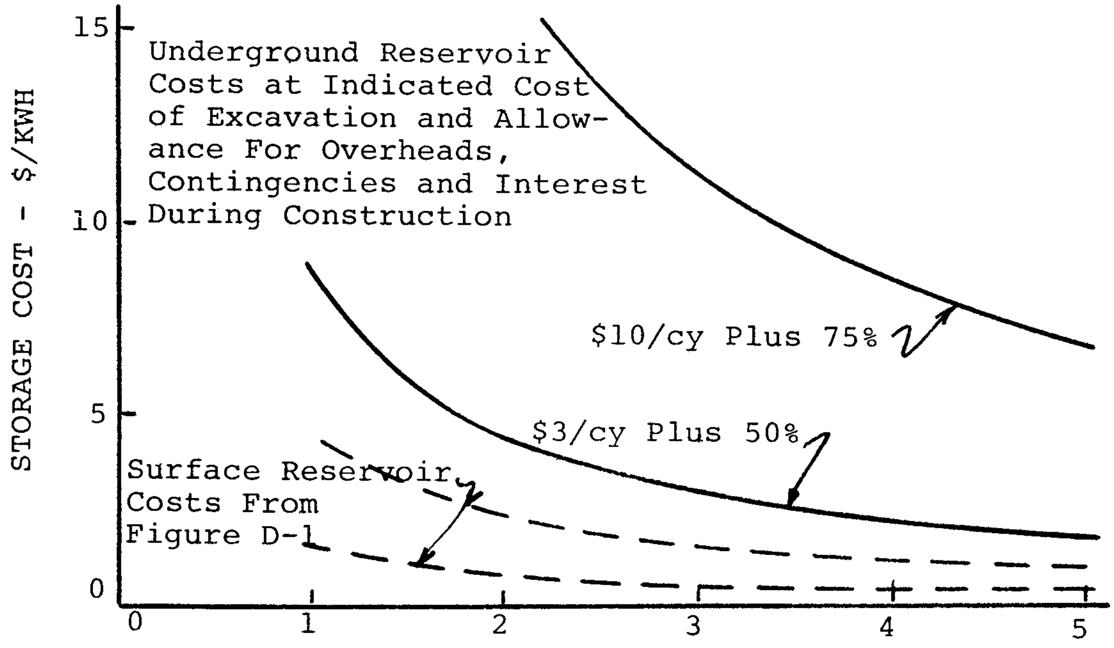
The total costs for storage are shown in the lower half of Figure G-5. All the favorable elements are combined to produce the lower curve and all the unfavorable elements, to produce the upper curve. If we consider that the likely head range is about 2500 to 4000 feet, and that, where excavation costs are high, plants are not likely to be built for heads in the lower portion of this range, it appears that storage costs can be reasonably represented by a range of $3 to $12/kWh.

REFERENCES

(1) Helmut H. Wirschal, "Reversible Pump/Turbines for Raccoon Mountain," Pumped Storage Development and Its Environmental Effects, edited by Gabor M. Karadi, Raymond J. Krizek and Sandor C. Csallany, American Water Resources Association, p. 323.

(2) E. H. Muhlemann, "Arrangements of Hydraulic Machines for Pumped Storage and Comparison of Cost, Efficiency and Starting Time," op.cit., p. 280.

(3) J. G. Warnock and D. C. Willett, "Underground Reservoirs for High Head Pumped Storage Stations," Water Power, March 1973, pp. 81-87.



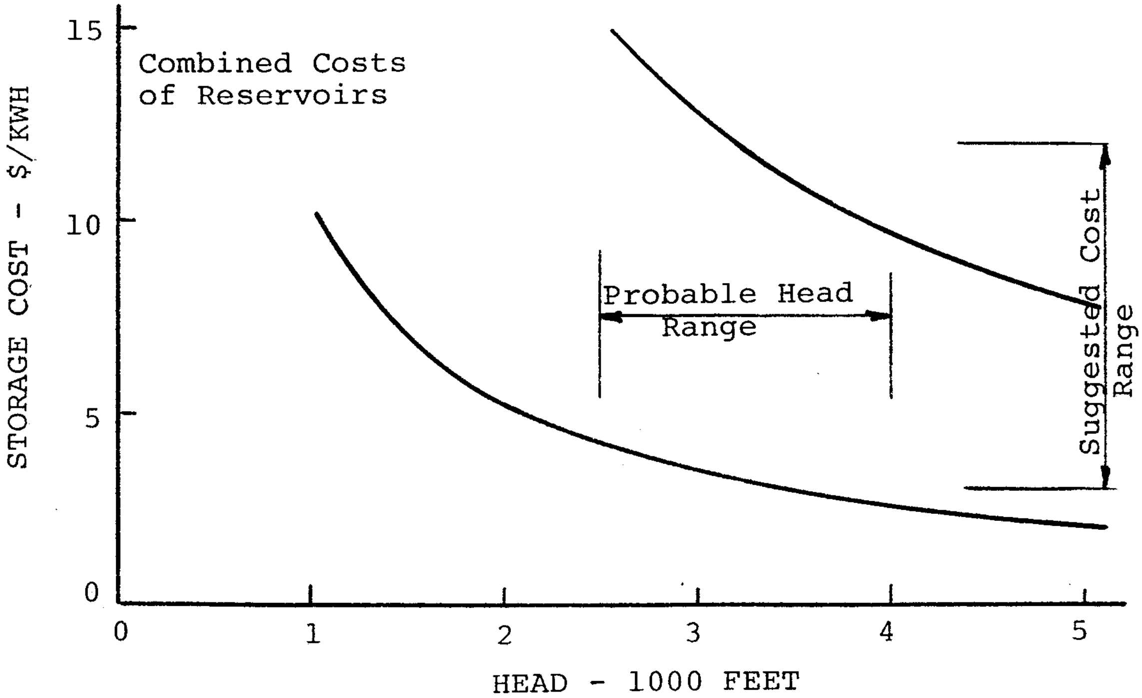


Figure G-5 ENERGY STORAGE COSTS VERSUS HEAD FOR UNDERGROUND PUMPED STORAGE

Appendix H

COMBINED HYDRO AND AIR STORAGE

Because of the high cost of excavated underground storage space, it is desirable that any excavated storage cavern be used as intensively as possible for the storage of energy. For underground hydro pumped storage, this means that the lower reservoir cavern should generally be at the maximum practicable depth. For air storage, it generally means a pressure greater than that used in conventional combustion turbines. More intensive use of the storage cavern can also be obtained by combining the underground storage of water and compressed air in a single storage space. Several combined hydro and air storage schemes have been proposed(1)(2) in recent years, but one of these contemplates combined use of only the surface reservoir.

In connection with the planning for an underground pumped storage at Mt. Hope, New Jersey, in 1972-73, an idea was developed for combined storage of water and compressed air in its excavated lower reservoir. This combination could approximately double the energy density of the cavern storage space, the increment related to compressed air being dependent on the selected storage pressure. It appears that the likely air storage pressure will be in the range of that employed in conventional combustion turbines, and hence less than the optimum for a single-purpose air storage system. Consequently, any use of the proposed combined storage would probably develop from initial planning for an underground hydro pumped storage, rather than from an interest in a compressed air storage project.

The combined hydro and air storage that is described in this appendix is covered by a patent (#3,939,356) that has been assigned to General Public Utilities Corporation. To explain the advantages of the combined project, as related to both economy and safety, it is desirable that the separate projects be first described in a suitable parallel form.

Underground Hydro Pumped Storage

An underground hydro pumped storage consists of the following principal elements, as shown in the attached Figure H-1:

1. A surface reservoir with suitable outlet and control structures.
2. A vertical conduit or penstock, branching at its lower end, with valves on the branches at their connections to the hydraulic units.
3. An excavated underground powerhouse with one or more generating units. Each of these may be connected to

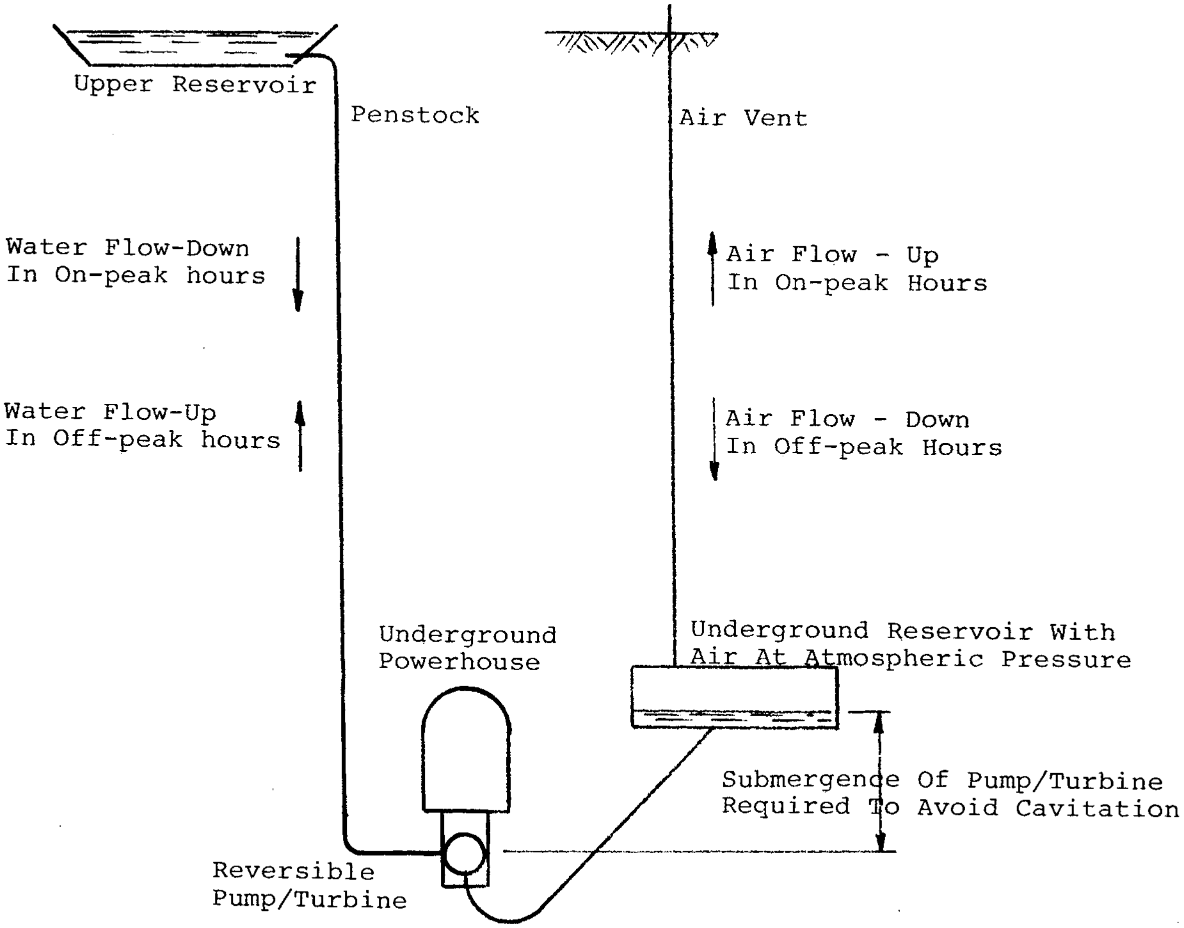


Figure H-1 HYDRO PUMPED STORAGE

either a reversible pump/turbine or to a separate pump and turbine on a single shaft. The powerhouse will have all the necessary auxiliaries and will be connected to the surface by one or more additional air shafts (not shown) for access and electric transmission.

4. An excavated lower reservoir, connected to the hydraulic units by suitable draft tubes. In order to provide the required positive head on the turbines and pumps, or pump/turbine combination, the lower reservoir would normally be located above the level of the underground powerhouse. For a high-head installation, such as would usually be contemplated, the required submergence on the pumps may be in the order of 200 feet.

5. A vent shaft to the surface, to permit movement of air from and to the lower reservoir.

Such a facility would normally operate as generating plant during the heavy load hours of the day. Water from the surface reservoir would pass through the penstock and turbines to the excavated lower reservoir, and its energy would drive the electric generators. Air would be forced out of the lower reservoir and exhaust to the atmosphere.

During the off-peak or light load nighttime hours, the flow is reversed. The electrical units are operated as motors to drive the pumps, and water is taken from the lower excavated reservoir and delivered to the surface reservoir. Air would be drawn down the vent shaft and would replace the water in the lower reservoir.

Air Storage

A constant pressure air storage scheme consists of the following principal elements, as shown in the attached Figure H-2:

1. A surface reservoir for water with suitable outlet and control structures.

2. A vertical conduit connecting to the underside of the excavated reservoir.

3. An excavated lower reservoir for air and water (note that this would not have to be at the same low elevation as the hydro pumped storage reservoir).

4. An air shaft to the surface.

5. A surface installation of the following parts of a combustion turbine generating plant: compressor and clutch, generator/motor, combustion-turbine and clutch, fuel storage, and suitable valves, heat exchangers and auxiliaries.

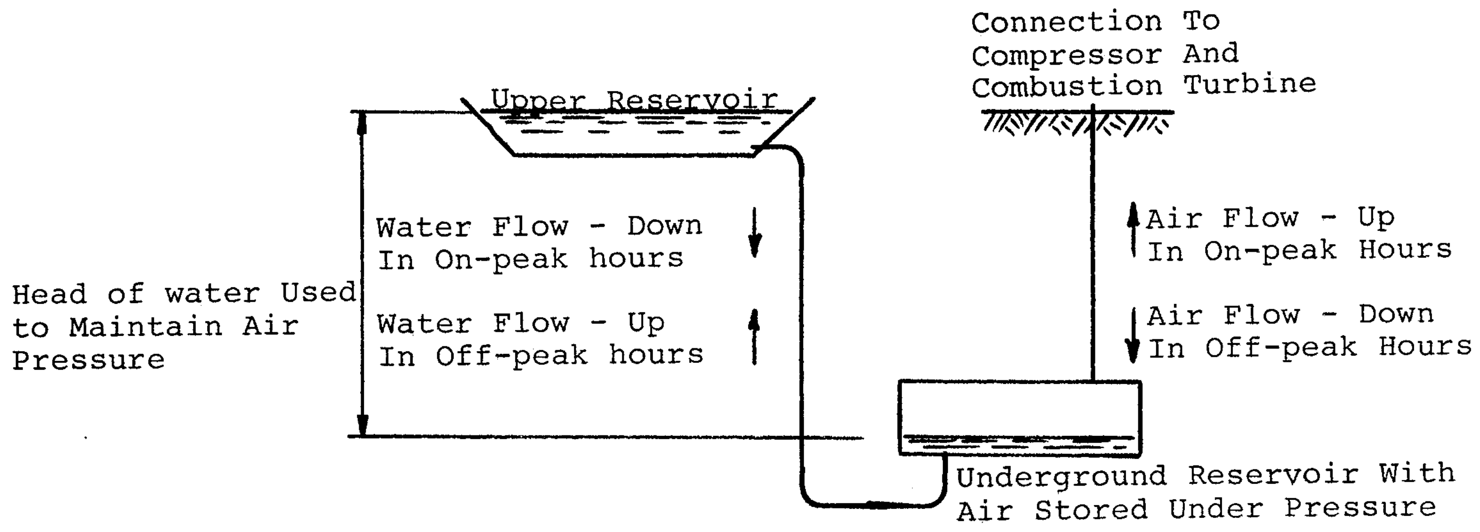


Figure H-2 COMPRESSED AIR STORAGE

Such a facility would normally operate as a generating plant during the heavy load hours of the day. Compressed air would be drawn from storage, pass through a heat exchanger, and be mixed with fuel in combustion chambers. The hot pressurized gas then drives one or more combustion-turbines and exhausts through heat recovery equipment (which heats the air from storage) to the atmosphere. The combustion-turbine drives an electric generator, which is at that time uncoupled from the compressor. As the air is withdrawn from storage, an essentially constant pressure is maintained by the hydraulic system, which delivers water to the lower reservoir.

During the off-peak or light load nighttime hours, the air and water flows are reversed. The electric units are operated as motors to drive the compressors, and air is delivered (with inter-cooling and after-cooling) to the underground storage. The compressed air displaces the water, which is returned to the surface reservoir.

Combined Plants

From the above descriptions of the two plants, it is evident that the water and air flows in both are in the same directions during both on-peak and off-peak hours. This suggests the combination of plants, with no change in facilities other than that the air in the underground reservoir of the hydro plant will now have to be under pressure. This can be arranged without serious detriment to either plant.

Parts A and B, Figure H-3, show the relative elevations of the underground reservoir for the separate hydro pumped storage and for the combined plants.

For the separate plant, as noted earlier, the underground reservoir must be above the underground powerhouse in order to provide a large positive tailwater pressure on the turbine and a high positive suction head on the pump. This is necessary to avoid cavitation and to assure satisfactory operation of the high head hydraulic units.

For the combined plant, the reservoir can be lowered and still provide the positive head on the hydraulic units, if the surface of the water is pressurized. Consequently, there is here the opportunity for storing the compressed air needed for the air storage generation. It may be that the desired air pressure is higher than is needed to provide the desired hydraulic condition; but this is of little consequence, since compensation can be provided by lowering the entire underground excavation (both powerhouse and reservoir), in order to maintain the intended net head on the pump-turbines.

The operation of the plants is not changed by the combination, except that both parts must operate at essentially the same time.

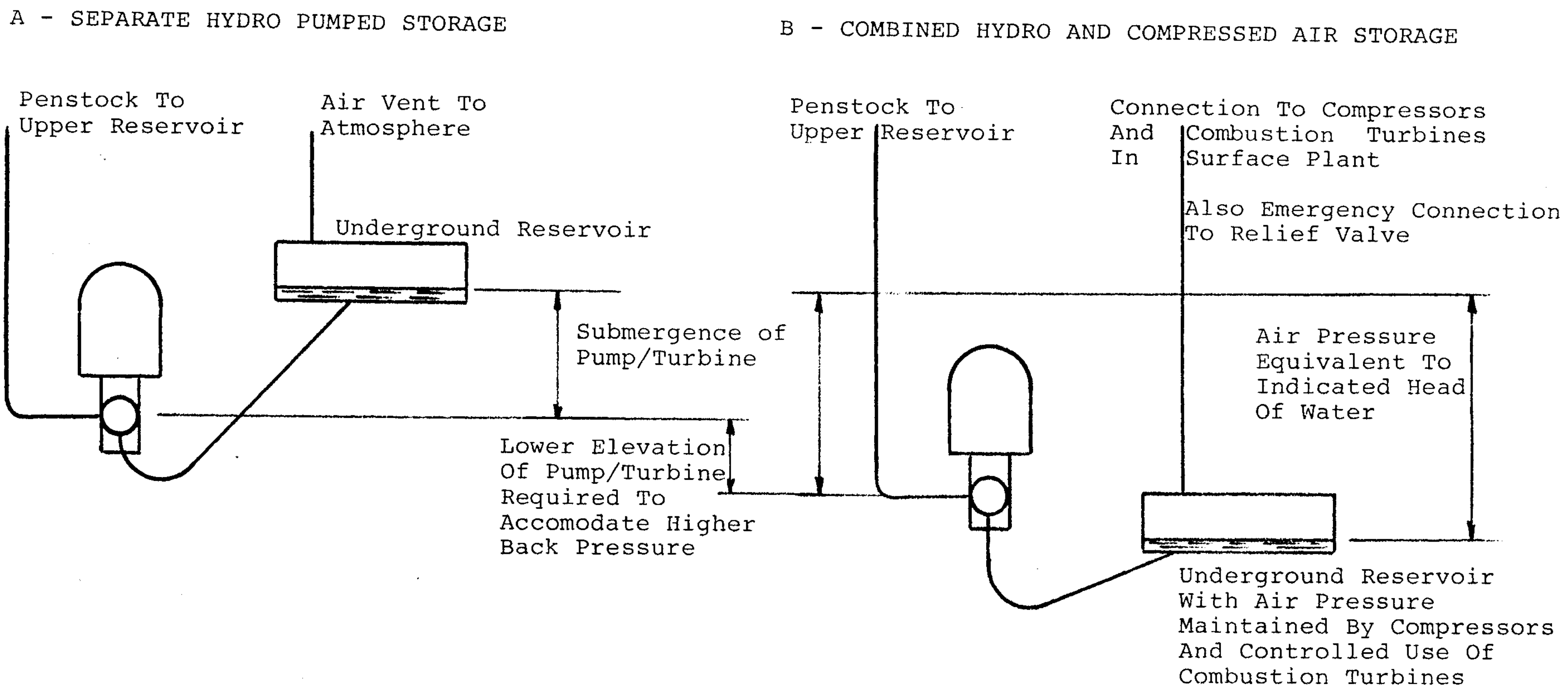


Figure H-3 RELATIVE ELEVATIONS OF UNDERGROUND RESERVOIRS FOR SEPARATE AND COMBINED PLANTS

Cost Savings

The principal cost savings result from the fact that the two plants can use the same excavated lower reservoir, the two shafts that are required by each one, and the surface reservoir. Because the combination of plants, based on a given storage volume, may have a capacity from 50% to 100% greater than for the hydro plant alone, a given generating capacity can be based on a smaller lower reservoir. This means less excavation and a shorter construction schedule, which in turn means less interest during construction and less exposure to price escalation.

Safety Feature

It is noted in Figure H-1 and Figure H-3, Part A, that the lower reservoir for the separate pumped storage would be at a higher elevation than the generator room floor of the underground powerhouse. Any water leakage from the lower reservoir that results from equipment malfunction, improper operations, or other cause, will be into the powerhouse and will be drained to a sump. Sump pumps of large capacity would be provided to return this leakage to the lower reservoir, so that a reasonably safe operation is expected.

If the sump pumps, however, are unable to handle an excessive leakage, flooding will result. This has happened to an underground plant, even though it had above-ground reservoirs. To a plant with an underground reservoir, the problem may be even more serious, for the flooded volume to be subsequently unwatered by pumping is not only the powerhouse, but also the far larger volume of the lower reservoir. The required high-head pumping with relatively small emergency pumps would take a long time.

The combined scheme cannot eliminate all possibility of flooding, for even though the reservoir is below the generator room floor, it is under air pressure, so that leakage from the lower reservoir will be into the powerhouse area. Under normal conditions, this leakage will be handled by the sump pumps.

However, if the sump pumps are unable to handle the leakage, there is now a second line of defense. This is the rapid reduction of air pressure by opening of appropriate relief valves and direct discharge of air to the atmosphere. With reduction in pressure, leakage from the lower reservoir would be reduced.

If flooding nevertheless results, in spite of sump pump operation and reduced air pressure, it would be only a temporary flooding and possibly far less severe. This is because all the water that enters the powerhouse can now drain into the lower reservoir by gravity, as soon as the air pressure drops to atmospheric. Work on clean-up, drying out and repair can start immediately.

REFERENCES

(1) Eberhard Hartmann and Jean-Paul Hoffmann, 1974, "Luftspeicher-Gasturbinen-Kraftwerke vor der Realisierung" (Air Storage Gas Turbines on Threshold of Realization): Symp., AIM, Liege, paper 69, 10 p. Oct. 14-18.

(2) Justin Vivod, Ljubljana, "Kombinacija crpalne elektrarne z akumulacijsko plinsko elektrarno" (Combination of a Pump Water Power Plant with a Storage Gas Electric Power Plant), Elektrotehniski Vestnik, 1974, No. 11-12, pp. 285-287.

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