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Underground Pumped Hydroelectric Storage

**R. D. Allen
T. J. Doherty
L. D. Kannberg**

July 1984

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
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UNDERGROUND PUMPED HYDROELECTRIC
STORAGE

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Pacific Northwest Laboratory
Richland, Washington 99352

FOREWORD

Underground pumped hydroelectric storage (UPHS) is a technique for storing baseload electrical energy and releasing it to satisfy peak load requirements. The concept incorporates reversible pump-turbines or single function pumps and turbines and an underground reservoir mined from hard rock. Pump-turbines are coupled to motor-generators within a subterranean powerhouse that converts the energy of a water column flowing from a surface reservoir to the subterranean reservoir and then pumps the same water mass back to the surface. The powerhouse is located below the lower reservoir to maintain pump submergence. The UPHS concept is like that of conventional surface pumped storage except that the subterranean reservoir eliminates dependence upon natural topography and enables design for higher head operation. A typical plant would have a capacity of 1000 to 3000 MW, an operating head of 1000 to 2000 m, and reservoir storage capacities equivalent to 8 to 10 hr of generation at full load.

To date, no UPHS plants exist, either operating or under construction. However, studies indicate that the UPHS concept is technically feasible and economically viable. Most elements of UPHS technology are sufficiently developed to enable plant construction. Advances in high head turbomachinery design and geotechnical excavation techniques are expected to enhance the economic attractiveness of UPHS.

This report presents a summary of research and development in UPHS technology. It encompasses efforts sponsored by the U.S. Department of Energy, as well as other organizations. It discusses turbomachinery options, plant layout, design parameters, site-selection considerations, geologic requirements, environmental concerns, and economics. It also reports on a number of specific UPHS research projects. The report was originally prepared as a chapter in a book on energy storage being prepared under the auspices of Oak Ridge National Laboratory.

R. D. Allen
Underground Pumped Hydroelectric Program

SUMMARY AND CONCLUSIONS

Underground pumped hydroelectric energy storage was conceived as a modification of surface pumped storage to eliminate dependence upon fortuitous topography, provide higher hydraulic heads, and reduce environmental concerns. A UPHS plant offers substantial savings in investment cost over coal-fired cycling plants and savings in system production costs over gas turbines. Potential location near load centers lowers transmission costs and line losses. Environmental impact is less than that for a coal-fired cycling plant. The inherent benefits include those of all pumped storage (i.e., rapid load response, emergency capacity, improvement in efficiency as pumps improve, and capacity for voltage regulation). A UPHS plant would be powered by either a coal-fired or nuclear baseload plant.

The economic capacity of a UPHS plant would be in the range of 1000 to 3000 MW. This storage level is compatible with the load-leveling requirements of a greater metropolitan area with population of 1 million or more.

The technical feasibility of UPHS depends upon excavation of a subterranean powerhouse cavern and reservoir caverns within a competent, impervious rock formation, and upon selection of reliable and efficient turbomachinery--pump-turbines and motor-generators--all remotely operable.

Domestic cities that are relatively near known favorable bedrock formations include Atlanta, Baltimore, Boston, Buffalo, Chicago, Cleveland, Denver, Los Angeles, Louisville, Milwaukee, Minneapolis-St. Paul, Omaha, Phoenix, Portland (Oregon), Sacramento, St. Louis, San Diego, San Francisco, Seattle, Tucson, and Washington (D.C.).

Single-stage, reversible, Francis-type pump-turbines with adjustable wicket gates are the most economical option for heads between 500 and 1000 m and unit capacities to 500 MW. Two-stage, reversible, regulated pump-turbines are the most promising conceptually for heads of 1000 to

1500 m and unit capacities to 500 MW. Multistage unregulated pump-turbines operate at heads of 1000 to 1500 m and unit capacities to 500 MW, but significant shortcomings include relatively high equipment cost, lack of regulating capability, and lack of synchronous condensing capability.

Increasing the operating head reduces the excavation cost of an UPHS plant by decreasing the required volume of the lower reservoir. The optimal head is near 1500 m. To achieve this, single-stage pump-turbines can be used in a double-drop, dual lower-reservoir scheme; development now underway would permit use of the two-stage pump-turbine design with a single lower reservoir. For heads above 1000 m the two-stage reversible pump-turbine is economically more attractive than either the two-drop single-stage reversible pump-turbine configuration or the single-drop tandem pump and turbine configuration. Plant costs per unit of power are relatively constant from 1300 to 2700 MW.

The total direct cost of a UPHS plant is estimated at $\$500 \times 10^6$ for a 1000-MW plant in 1983 dollars. Underground pumped hydroelectric storage has a relatively long construction schedule, so financing costs and escalation can significantly increase cost. This is a substantial commitment for even a large utility. The justification for such a plant requires high confidence in utility load predictions, accurate cost estimating, and excellent predictability of plant performance. Beyond the technical considerations, however, the quality of the bond market and availability of support through a utility consortium may ultimately determine economic practicability.

In conclusion enhancement of UPHS prospects will require certain technical, economic, and institutional developments (e.g., successful demonstration of high-head reversible two-stage pump-turbines; increasing load growth within metropolitan areas; and implementation of regulatory reforms) to favor capital investment in generating facilities.

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UNDERGROUND PUMPED HYDROELECTRIC STORAGE

1.0 INTRODUCTION

Underground pumped hydroelectric storage (UPHS) is a technique for supplying electric power to meet peak load requirements of electric utility systems. It incorporates reversible pump-turbines or single-function pumps and turbines in tandem and an underground reservoir mined from hard rock. The essential features are shown in Figures 1 and 2. During night and weekend off-peak periods, low-cost power would be used to pump water from the underground reservoir to a surface reservoir located 1000 to 2000 m higher. During the subsequent daytime peak-load periods, the surface water would supply hydroelectric power over 8 to 10 hr, by refilling the lower reservoir through the turbines. This would reduce or eliminate the consumption of petroleum fuels by conventional peaking gas turbines.

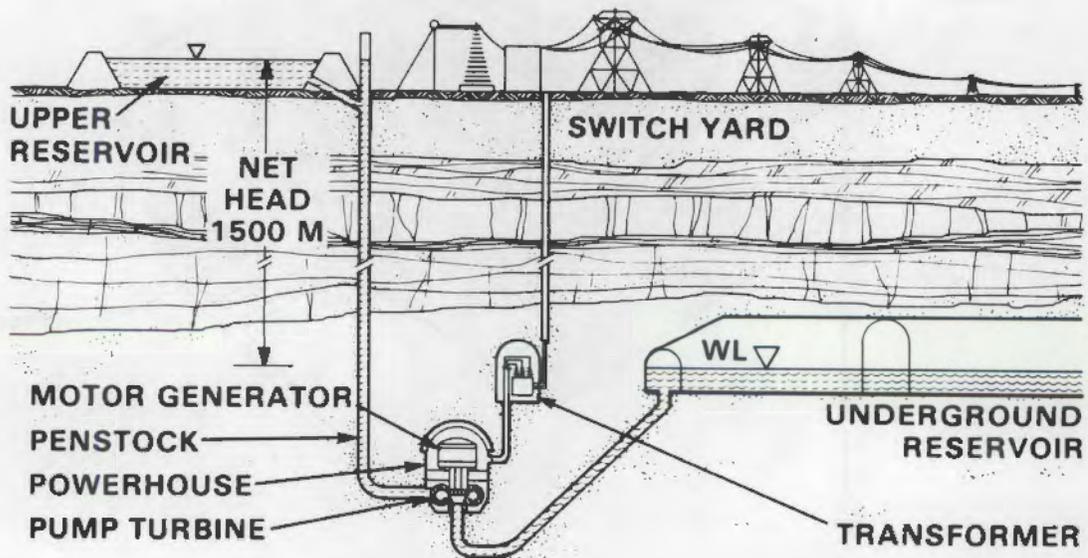


FIGURE 1. Cross Section of UPHS Plant

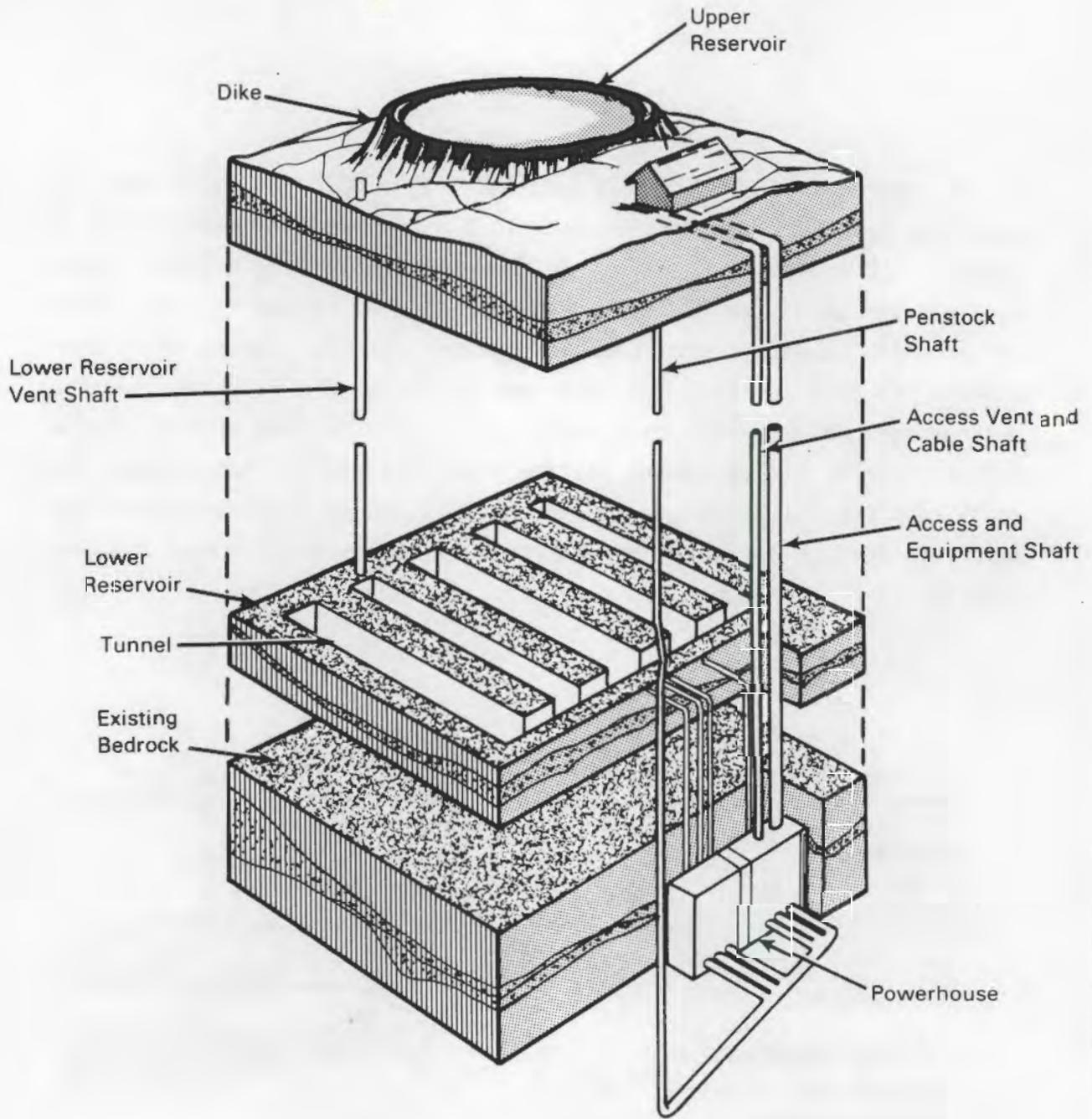


FIGURE 2. Three-Dimensional Conception of UPHS Plant (adapted from Allen et al. 1980)

Underground pumped hydroelectric storage plants are not limited by the topographic siting difficulties of conventional pumped-hydro plants. A well designed UPHS plant could have a smaller adverse impact on the environment than a conventional peaking plant.

Underground pumped hydroelectric storage plants follow the conventional pumped storage principle of accumulating potential energy in the form of water in an upper reservoir. However, in the case of UPHS, the lower reservoir consists of excavated caverns deep below the surface. Further, unlike a conventional aboveground pumped hydroelectric plant where topographic considerations generally restrict the choice of operating head (i.e., the difference in levels between the water in the upper and lower reservoirs), the nominal operating head for UPHS can be chosen from a wide range. The UPHS concept offers a design approach for pumped storage facilities that can optimize the nominal operating head in relation to the pumping/generating equipment and to the size of the underground caverns (Willett 1981).

The economics of pumped storage plants in general, and of UPHS facilities in particular, are influenced favorably by increasing the operating head. The lower reservoir of the UPHS plant represents a relatively significant proportion (about 30%) of the overall cost; reduction in its volume, arising from higher nominal operating head, allows energy storage economy (Doherty and Loscutoff 1981). The nominal operating head can be developed in one or more "steps", each applied to an individual pumping/generating plant; this can increase overall nominal operating head and consequently reduce lower reservoir size.

The UPHS concept evolved because of the dwindling number of conventional pumped storage sites, decreasing public acceptance of large reservoirs, the need for increased capacities of turbomachinery at higher operating heads, and the desirability of locating UPHS plants nearer load centers to reduce transmission capital and operating costs. The USSR has completed a feasibility study for a plant near Minsk and preliminary

designs have also been developed for plants in the eastern and midwestern USA. A typical conceptual UPHS plant would have a capacity of 1000 to 3000 MW, an operating head of 1000 to 2000 m, and a reservoir storage capability of 8 to 10 hr generation at full load. An upper reservoir capacity of about 8 million m³ is contemplated.

2.0 UNDERGROUND PUMPED HYDROELECTRIC STORAGE RESEARCH PROJECTS

This section is a chronology of the most important research conducted in development of the UPHS technology. It is not inclusive and considers primarily the larger studies conducted in the last 5 years that made notable contributions to the technological readiness of UPHS in this country. Underground pumped hydroelectric storage is not now an active area of research within the Department of Energy and is primarily being pursued by the utility industry. Indeed, over half of the work described in the following subsections was funded by the utility industry and is available here as a result of that industry's desire to disseminate information on this promising near-term technology.

2.1 CHARLES T. MAIN STUDY (1978)

Charles T. Main, Inc. (1978) conducted a study for the Bureau of Reclamation's UPHS Program. Its objective was to enhance the state of the art through research and development. The study reviewed current technology, evaluated technical feasibility and economic viability, identified further research needs, and recommended a continuing program of development.

2.1.1 Overview

Criteria of 2000-MW capacity, 1200-m (400-ft) head, and 10-hr storage were used in the C.T. Main study. The application of these criteria resulted in three potential schemes: two single-drop schemes and one double-drop type. One of the single-drop schemes is based on multistage reversible units, and the other on tandem units with separate multistage pump and Pelton impulse turbine. The double-drop type is predicated on the use of an intermediate powerhouse and small intermediate reservoir at approximately half depth. This scheme utilized single-stage, reversible pump-turbines.

The costs for the three schemes ranged from \$318/kW to \$346/kW [1977 dollars, excluding allowance for funds during construction (AFDC) and

escalation]. Total estimated cost of the multistage reversible unit scheme, the most advantageous, was \$636,500,000 (at the 1977 price level) including contingencies, engineering, supervision, and overhead but excluding AFDC and escalation.

The underground construction involved does not introduce new technology, because experience in this type of work is well defined. The large volume of rock to be removed--7,400,000 m³ (9,700,000 yd³)--lengthens the construction period over that of conventional pumped storage by 3 to 3-1/2 yr, which also increases AFDC.

Precedent in equipment development exists for all schemes except the design with deep multistage reversible units. Although the head introduces no significant problem, these units are currently limited to 140 MW compared with recommended units of 333 MW. European manufacturers, however, gave assurance that these units could be developed if demand were demonstrated.

Results of the system studies and economic analysis show that UPHS offers substantial savings in capital cost over coal-fired cycling plants. Capital costs are about 60% of coal-fired plant costs. Substantial savings in system production costs over gas turbines also exist because of fuel savings. The total present worth of system operation cost, plus alternative unit investment cost, for the 50-yr life of the UPHS plant favors UPHS. Whereas UPHS is more economical than coal-fired cycling units in both scenario systems, the economy of UPHS over gas turbines is only marginal in systems with a small proportion of gas turbines but large in systems with a greater proportion of gas turbines.

Energy consumed during construction is estimated to be 2204 GWh for a 2000-MW UPHS plant versus 4202 GWh for four 500-MW coal-fired cycling plants.

Because they are installed below ground surface, most UPHS components have minor environmental influences. In contrast, a coal-fired cycling plant requires architecturally aesthetic features, site beautification measures, and emission controls.

Socioeconomic factors are those associated with any major project, predominantly shortages of housing and services caused by a temporary labor influx. Properly planned for in the design stage, these conditions are controllable. Natural environmental conditions at the upper reservoir will be impacted, but artificial effects are subject to mitigation. Major project impacts are disposal of large quantities of excavated rock, direct effects of terrestrial heat at the lower reservoir depth and transfer of thermal energy to the upper reservoir through the water column during cycling, water quality impact by partial solution of minerals, and potential increase of biological nutrient levels in the reservoirs. The construction of a man-made dedicated upper reservoir will significantly reduce the impact of these negative factors to acceptable levels.

Underground pumped hydroelectric storage compares favorably with conventional pumped storage. The construction costs were found to be essentially the same [i.e., in the range of \$300 to \$350/kW (1978 dollars)]. Operating and maintenance (O&M) costs are essentially the same, possibly favoring UPHS.

Underground pumped hydroelectric storage should appeal to a utility company in lieu of conventional pumped storage in that it minimizes site-selection and acceptance problems; develops greater head and capacity; is more applicable in water-scarce areas; and lowers transmission costs and line losses by being located near load centers.

Aside from normal evolutionary improvement, candidate areas for research and development are determination of in situ rock stress levels and behaviors at depths, air transfer into and out of the lower reservoir, geothermal and frictional heat dissipation and control, reservoir eutrophication control, and modeling to determine optimal head and various other parameters.

The C.T. Main study concluded that UPHS is technically feasible and economically viable with respect to expensive-to-run alternatives, such as combustion turbines. In addition, the inherent benefits include those of

all pumped storage (i.e., rapid load response, emergency relief capacity, improvement in efficiency as pumps improve, and capacity for voltage regulation).

2.1.2 Geologic Considerations

2.1.2.1 General

The geology of the United States and, in fact, of all of the heavily electrified parts of the world, is sufficiently well known that those areas whose geologic characteristics are generally favorable for the development of UPHS project locations can be delineated, as shown in Figure 3. Proven boring techniques are available with which to confirm geologic site suitability.

Numerous successfully constructed deep room and pillar mines in the United States exemplify the major techniques required to construct the shafts, adits, tunnels, and underground caverns associated with UPHS.

2.1.2.2 Upper Reservoirs

A reservoir with storage capacity to store a water supply for 20,000 MWH at 1200-m (4000-ft) head is typical of the UPHS projects judged most feasible. The volume of such a reservoir is 7.9 million m^3 (6400 acre-ft), so that if its average depth is 10 m (33 ft), its area will be 81 ha (200 acres or 0.31 sq mi).

Such a reservoir requires no unusual topography. The material required to be excavated from the mined lower reservoir should be more than sufficient to form the structural enclosure for the upper reservoir.

Assuming a 4-yr filling period (half the expected construction period), an average filling flow of 57 l/sec (2 cfs) is required. This is the normal average surface water runoff rate from a drainage area of 3.5 sq km (1.35 sq mi) in a typical temperate zone. The corresponding drainage area in a semi-arid zone would be several times greater. The capability of the region to provide storage capacity and makeup flow should be given early serious consideration.

Makeup flow necessary during project operation to replenish losses caused by evaporation and seepage would be about one quarter the filling rate indicated above. Where water is plentiful and makeup is no problem no incentive would exist to go to unusual extremes to minimize seepage losses. Where the opposite is true, costly seepage prevention measures might be economically justified. Seepage into the subsurface reservoir may be considered a mitigating influence but is operationally detrimental.

Given a zone of favorable geologic conditions for the shafts and deep underground caverns, it is unlikely that a satisfactory site for UPHS could not be found because of unsuitable upper reservoir geology. The technology is well established for designing and constructing dammed and diked water impounding surface reservoirs in a wide variety of natural and man-made situations.

2.1.2.3 Shafts

Four vertical shafts, averaging about 1200 m (4000 ft) in depth, are required for a typical UPHS plant:

- a penstock shaft connecting the upper reservoir to the pump-turbines
- a lower reservoir vent shaft
- a shaft for primary surface access, including equipment transport, to the underground powerhouse
- a shaft from the surface for power cables and other lines and secondary access to the underground powerhouse.

With sound rock from the ground surface down, temporary and permanent support and dewatering through overburden would not be required. Excessively thick overburden, over 45 m (150 ft), would not preclude the feasibility of an otherwise advantageous UPHS site. At greater depths of overburden, with the likelihood of significant ground water, the time and expense of sinking conventional shafts might outweigh the advantages of sound rock at greater depth.

Given geologic conditions suitable for the shaft below the top 45 m (150 ft) and at the 1200-m (4000-ft) depth of the lower reservoir, only the presence of a major aquifer might rule out a UPHS site. Even in this case it might be determined that the expense of necessary grouting before shaft sinking could be justified.

2.1.2.4 Underground Reservoir

Geologic conditions must be favorable for removing, by mining techniques, approximately 7.4 million m³ (9.7 million yd³) of rock at a depth of 1200 m (4000 ft) below the ground surface. With favorable conditions, rock removal for the powerhouse, associated caverns, and tailrace tunnels will not present any serious geologic problems. One of the UPHS designs considered promising has a two-stage in-series scheme involving a second powerhouse and small reservoir at intermediate depth. Because an intermediate reservoir requires much less excavation than the lower reservoir, the cost implications of less than optimal geologic conditions at the intermediate depth are not so critical.

The rock in, above, and below which the extensive excavations will be made should be essentially impervious. Pervious water-bearing sandstones, such as the artesian Dakota formation of the Great Plains, are not suitable for UPHS. Almost all other rocks are so dense as to be impervious for all practical purposes. The passage of water through such rock bodies as limestone, schist, and basalt is through joints and other fractures. At UPHS depths, rock joints are normally tight and require no grouting. Where minor grouting is required, chemical grouting should be used.

Sedimentary rocks that are flat bedded, well lithified, and structurally undeformed are most advantageous for UPHS. In this category is rock such as limestone, dolomite, impervious sandstone and pre-Cretaceous indurated shales. Almost without exception, however, post-Cretaceous rocks, whether shales, sandstones, or limestones, are poorly indurated. Shales such as the Pierre, which oxidize and expand when exposed to air, must be avoided, as should highly soluble evaporites like gypsum and rock salt and moderately soluble anhydrite and sulfates.

Igneous rocks, although satisfactory, may not be as advantageous as sedimentary rocks because igneous jointing is usually more intense and less regular in orientation. Also, igneous rocks are more likely to have weaknesses at depth because of hydrothermal alteration along faults. They are--where sound, unweathered and unfractured--usually stronger than sedimentary rocks. Igneous rocks retain higher than usual in situ stresses under similar tectonic conditions. Basalts are also usually so jointed that they are among the most pervious of any rock bodies, although this is not always the case. Although the Serra Geral basalts in the Brazilian shield are intensely and minutely fractured, joints and fractures are relatively tight, and little water passes through them. On the other hand, the Columbia River basalts in the Pacific Northwest are noted for their water-carrying capacity.

After excavation, the remaining rock should be able to stand alone or with only minimal support. Closely spaced joint sets should be avoided, as should rock badly fractured by tectonic activity. Rock that has been hydrothermally altered and/or significantly weathered is undesirable. Joints spaced closer than 300 mm (1 ft) should disqualify a site. Other joint characteristics, such as incipient joints, open joints, interrupted patterns, and continuous patterns, should be evaluated, as should the possibility of their being water-bearing.

Rock should be excavatable by proven techniques of mining and underground cavern construction, with the use of shotcrete, rock bolts, steel mesh and gunite, and structural steel supports where necessary.

Field investigations for underground features should consist of a core boring program with a minimum of three holes - one hole on the centerline of the shafts, one in the powerhouse area, and one in the lower reservoir area. These holes will extend the full depth of the proposed structures to accurately assess underground conditions and design parameters. Favorable and unfavorable geologic criteria for the upper reservoir, shafts and powerhouse cavern, and storage caverns are summarized in Table 1.

TABLE 1. Underground Pumped Hydroelectric Storage Geologic Considerations (Charles T. Main, Inc. 1978)

<u>Upper Reservoir</u>	<u>Shafts & Powerhouse Caverns</u>	<u>Lower Reservoir</u>
<u>Favorable</u>	<u>Favorable</u>	<u>Favorable</u>
(a) Available source of water: surface streams; large, shallow ground water aquifers	(a) Thin overburden at shaft head	(a) Thick bedded, massive, sedimentary rock
(b) Relatively impervious bottom conditions	(b) Minimum disintegration of rock near surface	(b) Impervious and insoluble rock
(c) Good foundations for dam or dike	(c) Rock capable of standing alone or with minimum support after excavation	(c) No significant aquifers
(d) Thin overburden (alluvium, colluvium, residuum, etc.)	(d) Rock layers with minimum structural deformation	(d) Shale or other aquicludes above and below
(e) Availability of construction materials	(e) Rock of low permeability	(e) One bed of sufficient size, to contain cavern excavation
(f) Low seismic risk zones	(f) Low seismic risk zones	(f) Roof rock of "good quality" shale has different support requirement than "good quality" sandstone to allow maximum spans
<u>Unfavorable</u>	<u>Unfavorable</u>	(g) Structurally undisturbed rock (not folded)
(a) Pervious and/or soluble bottom	(a) Thick overburden or unconsolidated materials at shaft head	(h) Low residual rock stresses, ratios (horizontal to vertical)
(b) Karst topography	(b) Aquifers intersecting shaft	(i) Low seismic risk zone
(c) Permeable and/or compressible thick overburden	(c) Fissile or soluble rock	(j) Without closely spaced or open joints
(d) High seismic risk zones	(d) Deformed, faulted, jointed rock (open discontinuities)	<u>Unfavorable</u>
	(e) Deep weathering in shaft rock	(a) Highly permeable rocks under artesian head
	(f) High residual stresses in rock	(b) Deformed rocks (folded)
	(g) Erodable rock	(c) Presence of faults, either active or dormant
	(h) "Squeezing" ground (overburden or shales)	(d) Fissile and/or soluble rock layers
	(i) Air slaking rocks	(e) Closely spaced or open joints
	(j) High seismic risk zones	(f) Rocks requiring costly support for moderate spans
		(g) Hydrothermal alteration zones
		(h) Excessive residual stresses
		(i) High stress ratios (horizontal to vertical)
		(j) Air slaking rocks
		(k) High seismic risk zones

2.1.2.5 Seismicity

The seismic character and earthquake possibilities of each proposed site must be evaluated individually. Underground openings such as tunnels, shafts, and large caverns are generally less susceptible to earthquake damage than surface structures. Despite this fact, underground features should not be located in or through active fault zones or in zones of potential seismic activity.

2.1.2.6 Rock Mechanics

The C.T. Main, Inc. study concludes that the geologic considerations controlling the UPHS site screening process should preclude any critical rock-support problems. Subsequent paragraphs outline the semi-empirical approach to the rock mechanics aspects of UPHS on which the conceptual designs of underground facilities used in feasibility studies were based.

A room and pillar configuration formed by a grid of tunnels intersecting at right angles was assumed for the lower reservoir. This shape is expected to be stable at selected sites and would minimize the excavation cost. A typical tunnel is 15 m wide by 25 m high (50 ft by 80 ft) with a crown of 7.5-m (25-ft) radius. The tunnels could be spaced on 60 m (200-ft) centers, leaving 45-m by 45-m (150-ft by 150-ft) pillars. The overall area covered by such a reservoir with equivalent capacity to store 20,000 MWh at a 1200-m (4000-ft) head would be about 800 m by 800 m (.5 mi by 0.5 mi).

The large area of the reservoir relative to its depth would substantially stress the 170 pillars, with the innermost pillars being stressed most highly. Preconstruction in situ vertical rock stresses at the lower reservoir level are assumed to be concentrated on the pillars after the reservoir is excavated. The concentration factor due to simple area reduction will be 1.8, so that a natural in situ vertical stress of 375 kg/cm^2 (5330 psi) will lead to a stress of 675 kg/cm^2 (9600 psi) on the pillars. Under this stress the pillars will undergo an elastic compression

of approximately 4 cm (1.6 in.), which may be reflected in ultimate settlement of the ground surface above the central portion of the mined reservoir.

Horizontal post-construction stresses are not as serious a problem as vertical stresses. Although horizontal in situ stresses exceed corresponding vertical stresses at some locations, the removal of rock adjacent to laterally stressed rock is of relatively lesser consequence, leading to only a minor elastic yielding toward the excavation and subsequent stability. This situation differs greatly from that represented by the vertical load of the rock overlying the large lower reservoir, which is substantial and requires the permanent support of the pillars. There is a possibility that at particular sites meeting the basic geologic criteria for UPHS, horizontal in situ stresses will result in popping rock (the sudden lateral ejection of rock fragments from the excavation walls) after excavation. Under such conditions, whose costs should be covered by a contingency item in construction estimates, danger to workers would be minimized by the quick installation of rock bolts and/or shotcrete and wire mesh. With tunnel excavation sequenced from the periphery inward, any popping is expected to progressively diminish and then cease, well before the reservoir excavation is completed. However, because the popping phenomenon is not easily predicted, confirmation for this expectation must await actual construction.

Where the intact unconfined compressive strength of the rock at a selected UPHS site is less than five times the in situ stress, it is prudent to assume that roof support in the form of rock bolts will be required. Geologic siting criteria would normally exclude rocks in strength ranges much below the five-times-stress level. Even minor rock falls that represent no threat to the structural integrity of the lower reservoir should be prevented in the interest of construction worker safety.

The assumed support system comprises 5-m (16-ft) grouted rock bolts at 1.8-m (6-ft) centers for the entire arch area, supplemented with wire mesh

and shotcrete for 30% of the arch area. A standard contingency allowance representing 25% of the estimated cost of all underground general construction is intended to cover any additional rock support dictated by specific occurrences of chemically or mechanically weakened rock.

2.1.2.7 Area Acceptability for UPHS

Areas of the United States where the geologic conditions are especially favorable for UPHS are shown in Figure 3. Although poor geology would preclude the development of UPHS in parts of virtually every state, only in Florida and Louisiana where overburden is excessively deep, does there appear to be a total absence of suitable sites.

2.2 ARGONNE NATIONAL LABORATORY/ALLIS CHALMERS STUDIES (1979 to 1980)

To utilize the full potential of UPHS, large-capacity turbomachinery for hydraulic heads of 1000 to 2000 m is required. Reversible pump-turbines appear to be the most cost-effective type of equipment. Argonne National Laboratory and Allis Chalmers have evaluated three types of equipment: single-stage regulated, two-stage regulated, and multistage unregulated pump-turbines (Blomquist, Frigo and Degnan 1979). Their findings are summarized in the following three subsections.

2.2.1 Single-Stage Regulated Pump-Turbines for Operating Heads of 500 to 1000 m

Single-stage, reversible, Francis-type pump-turbines with adjustable wicket gates appear to offer the most economically attractive option for heads between about 500 and 1000 m (Frigo et al. 1979). Single-stage units with capacities of about 500 MW are being built. The current maximum operating head is 625 m for these machines.

Preliminary designs for single-stage, reversible, Francis-type pump-turbines with adjustable wicket gates were produced for capacities of 350 and 500 MW and for operating heads of 500, 750, and 1000 m. Analyses indicate that these machines are feasible from mechanical, hydraulic, and

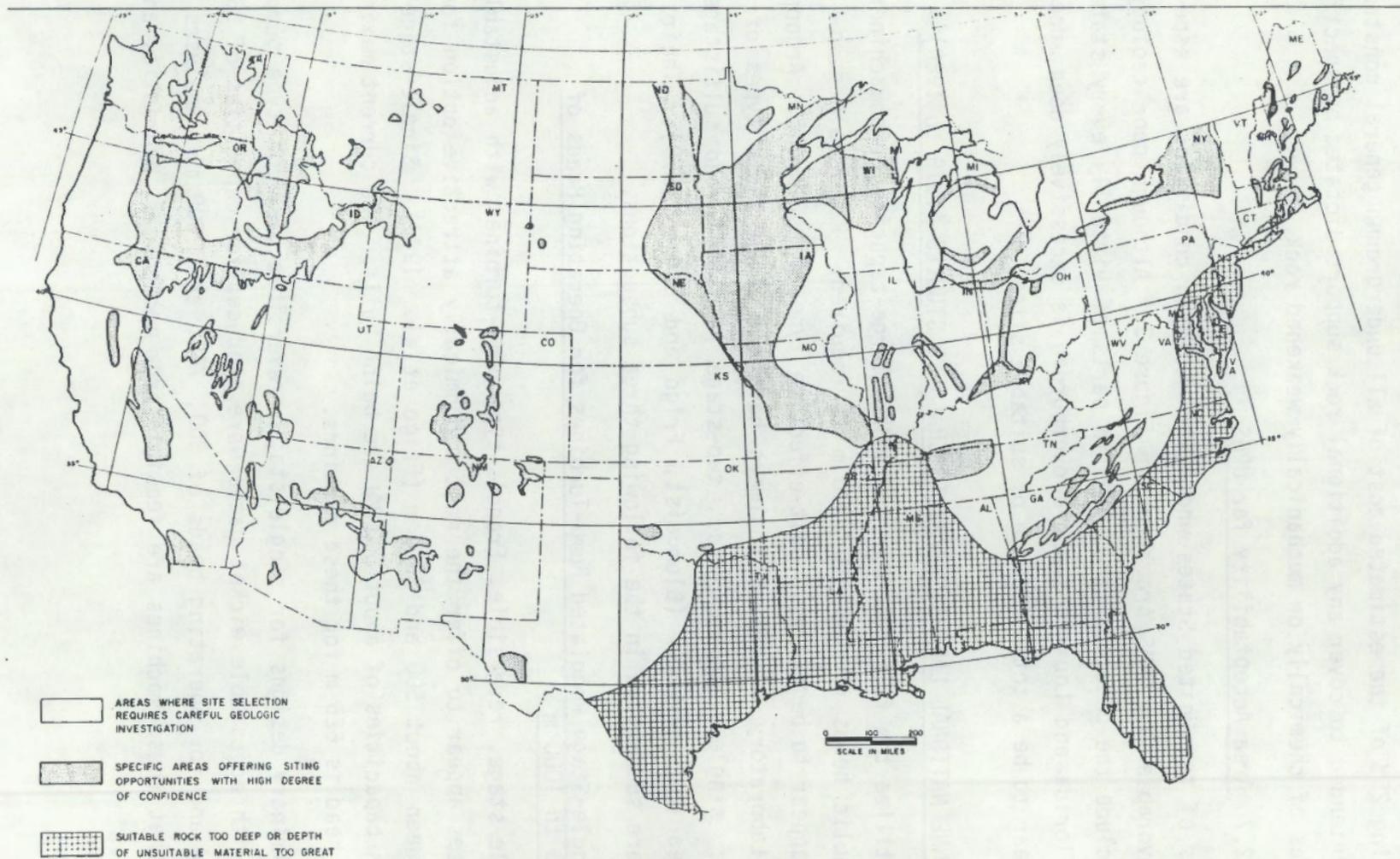


FIGURE 3. Geologic Siting Opportunities for UPHS (Charles T. Main, Inc. 1978)

economic viewpoints for the specified service conditions. The wicket gates can be expected to survive 10^7 cycles when subjected to normal design loads. For the 500-MW, 1000-m head pump-turbine, the stress and deflection responses to the various loading conditions and predicted hydraulic performance evidence the integrity of the conceptual design of this unit and the other five single-stage pump-turbines discussed in this report. The preliminary studies indicate no unresolvable problems. The next logical development step recommended is physical model studies to confirm the preliminary theoretical results.

Efficiencies of 90.7 and 91.4% in the generating and pumping modes, respectively, can be expected for a 500-MW, 1000-m head unit. Performances of the other five machines are comparable. The specific costs of the pump-turbines in mid-1978 \$/kW vary from 19.2 to 11.8 over a head range of from 500 to 1000 m for the 500-MW machines and from 20.0 to 12.3 for the 350-MW machines.

2.2.2 Two-Stage, Regulated Pump-Turbines for Operating Heads of 1000 to 1500 m

Development of a two-stage, regulated pump-turbine appears to be attractive because the proposed single-drop UPHS concept requires turbomachinery with a head range of 1000 to 2000 m. With turbomachinery of this range available, the single-drop scheme offers a simple and economic UPHS option (Blomquist et al. 1979).

A gated, two-stage pump-turbine has not yet been installed in service, but this machine has a number of advantages for high-head pumped-storage applications--especially for the proposed UPHS facilities. Three European manufacturers of pump-turbines (Escher Wyss, Neyrpic, and Voest Alpine) have conducted studies and some model testing on double-gated machines, and Electricite de France has placed an order with Neyrpic for a 35- to 40-MW capacity, 400-m head, double-gated, two-stage pump-turbine for the Le Truel plant.

Six different two-stage, top-gated pump-turbines have been analyzed: three that generate 500 MW and three that generate 350 MW. In each capacity, one machine has an operating head of 1000 m, another has a head of 1250 m, and the third has a head of 1500 m. The rated efficiencies of the machines vary from about 90% (1000-m head) to about 88% (1500-m head). Costs in 1978 \$/kW for the three 500-MW units are 20.5 (1000 m), 16.5 (1250 m), and 13.5 (1500 m). Corresponding costs for the three 350-MW units are 23, 18, and 14 \$/kW.

These studies have shown that the two-stage, regulated concept is feasible from the mechanical, hydraulic, and economic standpoint for at least the specified service conditions: to 500-MW power at a maximum nominal head of 1500 m. The feasibility of hydraulic and mechanical design has been demonstrated through the static and dynamic analyses of major components. This machine is the logical extension of the single-stage design.

2.2.3 Multistage, Unregulated Pump-Turbines for Operating Heads of 1000 to 1500 m

Multistage, unregulated pump-turbines offer an economically attractive option for heads of 1000 to 1500 m. Compared with single-stage machines for a given high-head application, multistage units allow more flexibility in choosing both the mechanical and hydraulic design parameters of pump-turbines (Frigo and Pistner 1980).

Multistage, ungated units for operating heads of almost 1300 m are being built. The current experience at very high heads is limited to the Sainte Hélène pump-turbines in France; the units there have operating heads of about 940 m. The capacity of both operating and planned multistage machines is limited to about 150 MW.

The feasibility of developing such machines for capacities up to 500 MW and operating heads up to 1500 m has been evaluated. Preliminary designs have been generated for six multistage pump-turbines. The designs are for nominal capacities of 350 and 500 MW and for operating heads of

1000, 1250, and 1500 m. Mechanical, hydraulic, and economic analyses indicate that these machines will behave according to the criteria used to design them and that they can be built at a reasonable cost with no unsolvable problems. Efficiencies of 85.8% and 88.5% in the generating and pumping modes, respectively, can be expected for the 500-MW, 1500-m unit. Performances of the other five machines are at least comparable, and usually better. Over a 1000 to 1500-m head range, specific \$/kW costs of the pump-turbines in mid-1978 U.S. dollars vary from 19.0 to 23.1 for the 500-MW machines, and from 21.0 to 24.1 for the 350-MW machines.

The machinery is feasible in terms of mechanical, hydraulic, and economic parameters for the specified service conditions. In general, the stress and deflection responses of the 500-MW, 1500-m machine to the various loading conditions, as well as the predicted hydraulic performance, give solid evidence of the integrity of the conceptual design of this unit. They provide equivalent evidence for the other five multistage pump-turbines. The preliminary studies indicate no unresolvable problem. Physical-model studies are needed to confirm these results.

Finally, the efforts made to develop a general multistage pump-turbine concept indicate that, in spite of their inflexible operation, these machines have the advantage of accommodating operating heads at least twice those of current experience. This advance can be accomplished with machines of reasonable size and cost, while at the same time maintaining acceptable efficiency and mechanical reliability. All these factors are essential in considering the feasibility of UPHS projects. The shortcomings that must be weighed when deciding whether or not to use multistage pump-turbines for pumped-storage projects are high-equipment cost and lack of regulating capability.

2.3 POTOMAC ELECTRIC POWER COMPANY STUDY (1981)

Acres American, Inc. performed a preliminary design study of underground pumped hydro and compressed air energy storage in hard rock for Potomac Electric Power Company (PEPCO) of Washington, D.C. (Willett 1981).

The study was sponsored by the Department of Energy and the Electric Power Research Institute. This study is, without a doubt, the definitive design study for UPHS and will provide the baseline against which all UPHS development in the future will be referenced.

The basic requirements stipulated by PEPCO for a UPHS energy storage plant were:

- a generating capacity of 2000 MW
- a level of energy storage that would permit generation at full output for 10 hr
- a capability of load-following, and regulation when generating.

The study established a preference for a "two-step" arrangement with each step consisting of a 1000-MW plant operating at a nominal head of 762 m (2500 ft). This enabled adoption of an overall nominal operating head of 1525 m (5000 ft). The facility was arranged to permit construction in two phases, the first to provide 1333 MW of generating capacity and the second phase to complete the remaining 667 MW of capacity. Two-thirds of the lower reservoir will be excavated during the first phase of construction, with the remainder being completed during the second phase (Willetts 1981).

2.3.1 Site Selection and Investigation

The region considered for selection of potential sites for the PEPCO UPHS plant extended above the northern boundary of their service area and was defined by Maryland's border with Pennsylvania; the southern limit was the Maryland border with Virginia. The eastern boundary was defined by the east edge of the Maryland Piedmont and the western boundary by South Mountain (marking the west edge of the Blue Ridge Province). Topographic features of a site are usually of primary importance for conventional pumped storage plants. In this study the presence of a suitable host rock formation in which to build caverns deep underground was of the utmost importance.

The site selection process was performed to choose a site for the study of the UPHS plant having an installed capacity of 1000 MW and energy storage for 10 hr at full generating output. The site selection was not repeated to evaluate the effects of a subsequent change that increased the capacity of the UPHS facility to 2000 MW, and the chosen site remained the basis for the study of this alternative.

The site selection process adopted for the study involved six distinct steps to allow a systematic selection of a hard rock site. The following primary activities were undertaken:

- definition of the geologic, hydrologic, topographic, and nontechnical factors influencing the siting and operation of a CAES or UPHS facility
- development of technical, economic, and environmental considerations involved in the siting of a CAES and UPHS facility
- data collection, including a detailed literature review, discussion with individuals familiar with the study area and a preliminary reconnaissance to determine an area of study and potential sites for CAES and UPHS
- a comparative review and evaluation of potential sites based on a series of weighted factors as defined by the siting methodology and that relate to primary siting constraints including geology, hydrology, topography, environmental, and economic considerations.

While rock quality and its suitability to accommodate large, deep shafts and caverns of significant dimensions were of prime importance, several other technical and environmental criteria had a significant effect on the site selection. These included the proximity of a site to existing transmission lines and the difficulty and cost of acquiring property for CAES or UPHS facilities, as well as access for exploration.

Environmental factors were also given substantial importance in the site selection process for energy storage facilities. While the location

of UPHS facilities underground diminishes much of their environmental impact, it is essential that due consideration be given to possible ecological and meteorological impacts and the effects of the facility on the neighbors.

A detailed review of the regional geology identified seven rock units as being candidate siting areas. The four most preferred potential siting areas, all within the Sykesville Boulder Gneiss Formation, were identified and subdivided into seven 250-acre siting blocks. One site was selected for further exploration based on the schedule of the exploratory program and site accessibility. It is located at Sunshine, Maryland, southwest of the Triadelphia Reservoir in Montgomery County, approximately 20 mi north of Washington, D.C., and about 20 mi southwest of Baltimore, Maryland. The site covers approximately 500 acres and is crossed by a 500-kV transmission line owned by PEPCO.

The host rock is the Sykesville Boulder Gneiss Formation, a medium-grained, highly foliated, anisotropic gneiss that outcrops in several areas throughout the eastern Maryland Piedmont.

To determine the suitability of the site as a potential location for the UPHS plant, two major investigation activities were undertaken. The first covered topographic features and the shallow subsurface, and the second involved further exploration to gain detailed information on the characteristics of the rock formation at the depths required for the underground reservoirs.

During the first part of the site investigation, geologic mapping was performed. The second part of the investigation involved a deep drilling program, with continuous rock coring together with an in-hole testing program to determine stress conditions and permeability levels and to provide a geophysical log of the formation.

The investigation showed that the bedrock at the site is overlain by residual soils varying in thickness from 6 to 23 m (20 to 75 ft). The

upper 15 to 30 m (50 to 100 ft) of bedrock is locally weathered and fractured. Below 30 m (100 ft) the rock is of good-to-excellent quality. Rock strengths [lower bound of 760 to 844 kg/cm (10,800 to 12,000 psi)] are relatively low strength because of the rock's highly anisotropic nature. Below the upper 30 m (100 ft) of weathering, hydraulic conductivity ranges from 10^{-5} to 10^{-7} cm/s through open fractures and joints.

One of the primary objectives of the second part of the site investigation program was to confirm the existence of the Sykesville Formation to the depth required for cavern construction. Three attempts were made to drill to a depth of 1525 m (5000 ft). In all cases, severe deviation of the drill hole caused termination of drilling. This limited the drilling program to a maximum hole drill length of 1000 m (3274 ft). This hole was terminated at a 52° deviated angle from the vertical. Adjusting for hole deviation, the total maximum vertical depth drilled was 780 m (2556 ft). The drilling program did not confirm suitable rock at the required depths for UPHS, but no evidence was found to suggest that the Sykesville Formation does not exist to sufficient depth.

From the cores taken, the rock quality was found to be high with minimal fractures. Analysis of permeability test data shows the average hydraulic conductivity to be acceptable, with values of less than 10^{-7} cm/s even in the more highly fractured zones. In situ stress determinations by the hydrofracturing method showed that below 400 m (1300 ft) the maximum and minimum horizontal stresses were greater than the overburden stress, and this increased with depth. Calculations showed the maximum stress to be oriented in a NW-SE direction (consistent with other available geologic evidence). This information was then used as the basis for subsequent cavern designs.

2.3.2 Selection of Pump-Turbine Arrangement

2.3.2.1 Comparison of Pump-Turbine Alternatives

At the outset of the study, practice overseas had accepted heads of 610 m (2000 ft) for single-stage reversible-pump-turbines with normal

provision for turbine load regulation by means of wicket gates. Consideration was being given to pump-turbines having more than one stage, with regulation provided on one or more stages. The practice of assigning pumped storage duty to nonregulating multistage pump-turbines designed in accordance with very high head pump practice and accommodating heads of over 1220 m (4000 ft) with four- or five-stage machines has been developed in Europe. Quite apart from the possibilities of improved overall economy arising from adoption of these relatively new designs, the operating head limits for single-stage reversible pump-turbines have been steadily trending upward.

For initial selection purposes, cost comparisons of 2000-MW plants with single-stage reversible pump-turbines in one step (SSRPT-1), single-stage reversible pump-turbines in two steps (SSRPT-2), multistage reversible pump-turbines in one step (MSRPT), unirotational separate pump-turbines with multistage pumps and impulse turbines in one step (USPT), and two-stage reversible pump-turbines with regulating capability in one step (TSRPT) were made. These showed that SSRPT-2 at nominal head of 1400 m (4600 ft) [two steps of 700 m (2300 ft)], MSRPT at nominal head of 1400 m (4600 ft), and TSRPT at nominal head of 1037 m (3400 ft) were the most economic. The costs for SSRPT-1 at nominal head of 700 m (2300 ft) were higher because of the higher volume of lower reservoir excavation involved. Plant designs based on unirotational separate pumps and turbines with Francis turbines and single-stage pumps and on completely separate multistage pumps and motors and impulse turbines with generators were also considered but were eliminated because of cost.

At the time of this study, no TSRPT units had ever been built and therefore, they were not considered further because of lack of design and operating experience with these units. Detailed investigation, including marginal cost-depth studies, of the SSRPT-2 and MSRPT arrangements showed that the estimated costs were similar for both. The studies confirmed the optimal nominal head for MSRPT as 1400 m (4600 ft) but indicated that the corresponding head for SSRPT-2 is 1525 m (5000 ft) [two steps of 762 m

(2500 ft)]. The SSRPT-2 arrangement was preferred to MSRPT in this study because of its load-following ability and greater flexibility. Although designs involve some extrapolations from previous operating practice, it was felt that these lie well within the limits of current technology.

High operating heads require adoption of high rotational speed if efficiency performance is to be sustained at normally accepted levels. The resultant speeds for motor-generator designs are beyond previously proven practice but are not considered beyond present-day design and manufacturing limitations. The high operating speeds favor designs with water-cooled rotors and stators, rather than the more conventional air-cooled units.

The PEPCO study was finally based on an SSRPT-2 arrangement with an overall nominal head of 1525 m (5000 ft). Each step consisted of three pump-turbine/motor-generator sets, each of 333-MW rating and each operating at 720 rpm under a nominal head of 762 m (2500 ft).

However, the future prospects for development of reversible pump-turbine equipment for heads considerably higher than hitherto achieved had a significant impact on the performance of the study. It may well be that, before the time comes to call for bids for pump-turbine and motor-generator equipment, equipment will be available to allow the development of the UPHS concept with plants capable of operating in a single step with heads on the order of 1220 to 1525 m (4000 to 5000 ft).

2.3.2.2 Operational Consideration

The two-step pumped storage facility arrangement generally requires balanced operation of an equal number of units in each of the power plants. The volume of water contained between the operating level limits in the intermediate reservoir allows some measure of unbalanced flow to or from this limited storage. Therefore, three units in one plant could discharge, without compensating operation in the other, for about 15 min; alternatively, one unit could operate alone for about 45 min. In most situations, the UPHS plant would be started up either generating or pumping as a two-unit block of about 660 MW. Load control through wicket-gate adjustment allows

variation over a reasonably wide band of station output. When pumping, the units demand blocks of power of about 690 MW in pairs (345 MW with an unbalanced number of units for short periods of up to 3/4 hr) with actual power determined by the operating head at any particular stage of upper-reservoir filling.

Units would be started in the pumping cycle with the main motor-generator supplied with power through a static converter system. Full station pumping load could be applied in approximately 30 min.

Spherical-type penstock valves located on the high-pressure side of each pump-turbine would be used to isolate the pump-turbines from the penstock system as well as for emergency shutdown in the event of malfunction of the wicket-gate operating mechanism.

Generator-unit circuit breakers would be installed in the underground facilities, and power would be transmitted to and from the transformer banks, motor-generator units, and the surface by SF₆ gas-insulated bus.

A high degree of reliability will be required in all pumping/generating units and supporting equipment located underground. Equal reliability will be required in the shaft hoists, which provide the only access to the deep underground facilities. Special provisions will be made for security of operating personnel below ground.

Normal operation of the pumped facilities will be effected from a system control point remote from the site. A limited number of operating staff will provide the necessary routine services in the underground power plants and at the surface facilities.

Following an initial start-up and proving period, the SSRPT-2 facilities will perform a high standard of overall cycle efficiency of about 76% and provide about 94% availability, if planned outages are not taken into consideration. If both long-term and short-term planned outages are included, availability is estimated to be about 83%.

2.3.3 Pumped Storage Plant Layout

The surface reservoir will be created by a rockfill embankment and lined with asphalt. The hydraulic system will not be dependent on any natural water course and will rely on a pumped-water supply for initial filling and water makeup from an existing nearby reservoir. A single penstock will connect the upper (surface) reservoir to the pump-turbine units located in a powerhouse at the intermediate level. These units will connect to an intermediate-level reservoir from which another single penstock will lead to the pump-turbine units located in a powerhouse at the lower level. Three 333-MW pump-turbine/motor-generator units will be installed in the intermediate powerhouse and three 333-MW units in the lower powerhouse. Step-up transformation from generator voltage to 500 kV will be carried out underground; galleries containing the required equipment will be located directly above and in line with the powerhouse caverns. The SF₆ gas-insulated bus will provide the power circuit connection to the surface. The various excavated powerhouses, reservoirs, and galleries will be accessible only by vertical shafts from the surface.

2.3.3.1 Upper Reservoir

The major feature of the surface works for an UPHS plant will be the asphalt-lined earth and rockfill embankment rising approximately 5 to 35 m (15 to 115 ft) above the original ground surface with outside slopes of 3:1 and a 6-m (20-ft) wide roadway on its crest. The inside reservoir surfaces of semicircular end embankments connected by longitudinal tangent sections will have a slope of 2.5:1 with an asphaltic concrete lining. Drainage will be provided by a system of pipes beneath the reservoir floor leading to a gallery running along the centerline and connecting with the intake structure. Initially the reservoir will be filled with water by pumping from the Triadelphia Reservoir; this supply will continue to be used in operation for makeup water requirements. The intake structure carrying water to the penstock system will be designed to deliver water to and draw water from the reservoir at uniform velocities and minimum head losses.

2.3.3.2 Penstocks and Shafts

In addition to the vertical penstock shaft leading from the upper reservoir intake/outflow structure to the pumped storage plants below, four other shafts will be constructed ranging in depth from 1525 to 1677 m (5000 to 5500 ft). Three of these shafts will contain hoisting conveyances, SF₆ bus for main power transmission, and control cables. The fourth, an air vent shaft, will allow atmospheric air admission to and from the lower and intermediate reservoirs.

The heavy hoist, with its headframe located within the control and administration building, will be a drum-type hoist with two drum and drive units capable of handling loads up to 182 MT (200 tons) with variable speeds up to 76 m/min (250 ft/min). The personnel hoist will also have its headframe located within the control and administration building and will be a friction-type hoist with a double deck conveyance capable of transporting up to 90 men or 18 MT (20 tons) of material at speeds up to 457 m/min (1500 ft/min). In addition, each of the three shafts will have a drum-type inspection hoist used for installation and subsequent inspection of the SF₆ bus, as well as emergency access for personnel. The major portion of rock removal will take place through the shaft ultimately to be used for SF₆ bus and cables. The heavy hoist shaft will provide ventilation air.

The vertical penstocks will have diameters of 5.8 m (19 ft) and be designed for a maximum flow of 153 m³/sec (5400 cfs). Construction of these and other shafts will be accomplished by sinking from the surface using conventional drilling and blasting methods. The penstock walls will have rock bolt support and a permanent concrete lining provided with a drainage system. The penstocks will turn to the horizontal at the powerhouse levels, and concrete-lined manifolds will form three 3.35-m (11-ft) diameter penstocks at each level. An 88-m (290-ft) length of the penstocks upstream from the powerhouses will be lined with 7-cm (2 3/4-in.) thick high-strength steel lines that have flanged connection penstock valves upstream of the pump-turbine spiral cases.

2.3.3.3 Intermediate Reservoir

With the two-step arrangement, the nominal head on each of the two powerhouses will be limited to 762 m (2500 ft). This will provide an intermediate reservoir at the intermediate-powerhouse level with a free hydraulic surface varying over a limited range as required for operation. The two-step facility will normally operate with a balanced number of units in each powerhouse operating at a similar gate opening and flow. This will provide balanced transfer of flow through the intermediate reservoir. Nevertheless, the intermediate reservoir will have sufficient capacity to accept a volume of "storage" equivalent to the full discharge of three pump-turbine units operating for 15 min.

2.3.3.4 Power Generating/Pumping Facilities

The underground powerhouses located respectively at 896 m (2939 ft) and 1647 m (5043 ft) below the crest of the surface reservoir (measured to the centerline of the pump-turbine distributor) will be essentially of identical layout and design. Each will accommodate three 333-MW motor-generator units with associated pump-turbines operating at 720 rpm and equipped with 1.64-m (64.6-in.) diameter spherical penstock valves, governors, and facilities for pump starting with a static frequency converter. Provision will be made for depression of tailwater level in the draft tubes by compressed air during starting. Provision will also be made for bulk-head gate isolation of the 3.5-m (11.5-ft) diameter concrete-lined draft tube outlet tunnels to allow unit unwatering for inspection/maintenance. All auxiliary systems normally required for pumped storage installations will be provided with the special features necessary for operation deep under ground.

2.3.3.5 Lower Reservoir

The economic feasibility of the UPHS concept will depend substantially on the ability to rapidly excavate 5 to 6 million m^3 (7 to 8 million yd^3) of rock from substantial depths. The necessary level of performance

appears to be well within reach of modern construction practice. Excavations of equivalent volumes of rock have been made previously from a variety of host rocks, and integrity with time has been clearly established.

For the UPHS plant, the potential energy will be stored in the upper (surface) reservoir and the lower reservoir will provide simply a holding basin from which water will be pumped at the beginning of the next storage cycle. The lower reservoir will operate at all times at subsurface atmospheric pressure with a free water surface.

The required excavation will be in the form of 12 tunnels of substantial cross section, 26 x 20 m (85 x 65 ft), interconnected by smaller air and water collector tunnels at the extreme ends of the reservoir system. The excavation volume will be 6,012,900 m³ (7,860,000 yd³), which will allow 2.3% for "safety" storage to prevent overflowing of the lower reservoir, and a further 0.3% for freeboard. Two-thirds of this volume will be provided for the first phase, and the remainder will be constructed to complete the plant in Phase 2. The main tunnels in the lower reservoir will be oriented with their axes approximately perpendicular to the strike of the rock foliation, since this will provide more desirable conditions for rock support of the larger spans. The interconnecting tunnels will be of small cross section and can be safely constructed with the less desirable rock conditions in line with the strike of the rock foliation. All of the storage caverns within the lower reservoir will have curved side walls to reduce tensile stress zones. They will be constructed at grades that allow free drainage upon dewatering. Rock support will be provided by patterns of rock bolts in the crown and walls of the tunnels augmented by mesh and shotcrete as required. The final design will depend on future exploratory work and on experience gained in the development of the initial underground facilities. Provision will be made for isolation of any one-third of the reservoir with "stoplogs" to permit reservoir cavern inspection without disrupting plant operation.

2.4 COMMONWEALTH EDISON/HARZA STUDY (1975 to 1981)

Over the years, Commonwealth Edison has investigated numerous alternatives to provide large-scale energy storage to complement the nuclear and coal-fired baseload generating plants in its system. The alternatives include pumped hydro, compressed air energy storage, thermal storage, batteries, and other concepts (Chen and Berman 1981).

Edison's studies led to the selection of UPHS and CAES as being attractive and feasible on a near-term basis. Edison is a participant in the Ludington Pumped Hydro Plant in Michigan and has contracted for the capacity from two units (624 MW) until August 1983 and one unit (312 MW) until August 1988. With the projected termination of operations from Ludington, the anticipated continuation of load growth, and continued reliance on nuclear generation for baseload capacity, Commonwealth Edison undertook a series of studies for a UPHS project within its service territory.

This section summarizes how the site was selected and describes the conceptual project design. Table 2 shows the significant data of the proposed project.

2.4.1 Proposed Site

The first requirement for the site is that the underground power plant and reservoir should be located in a massive, competent, impermeable rock unit of high strength. In the service territory of Commonwealth Edison, the only rock unit that can meet this requirement is the Precambrian granite, which underlies a series of sedimentary rocks (Coates 1982). The Precambrian is closest to the surface in northwestern Illinois, approximately 600 m below the ground surface.

The maximum operating head for reversible single-stage pump-turbines was projected at the time of the siting study in 1975 to be slightly greater than 600 m. Thus, the indicated depth of the Precambrian granite in Illinois would barely meet the requirement at that time. A bore hole

TABLE 2. Commonwealth Edison Underground Pumped Hydroelectric Storage Project Data

General

Maximum pumping input - MW	3,300
Rated output - MW	3,000
Energy storage (generation) - MWh	30,000
Number and size of units - MW	6 - 550
Overall plant efficiency	71%

Operating heads (static)

Number of drops	1
Maximum head - m	1,479
Minimum head - m	1,425

Upper reservoir

Type	Perched
Total storage - million m ³	10.4
Water surface fluctuation - m	15
Water surface area - m ²	740,000

Lower reservoir

Cavern cross section - m	23 x 30.5
Total active storage - million m ³	9.5
Water surface fluctuation - m	30.5

Pump-turbine

Type	Regulating, reversible
Number of stages	2 or 3
Submergence - m	75
Speed - rpm	720

Generator/motor

Type	Water-cooled
Rating - MW	550

Transformers

Number for each unit	3
Type	Single-phase, oil-filled
Rating - MVA	614
Phase to phase voltage - kV	345

was drilled at a location that was expected to be the topographic high for the Precambrian granite. The hole struck granite at 608 m and was taken down another 31 m to confirm that the Precambrian basement rock was reached (Chen and Berman 1981).

In 1978, studies began to select a specific location for the UPHS project in the general vicinity of the stratigraphic hole. An area of some 80 km² was first identified, and a seismic refraction survey was performed to define the topography of the Precambrian as well as the principal overlying rock units. Technical, environmental, cost, and other studies were conducted to identify and then prioritize three alternative sites within the 80 km²-area. Near-surface exploration was conducted to determine feasible locations for the upper reservoir. Two additional deep holes were drilled to provide both stratigraphic and site-specific information of the most favorable site. One hole penetrated to 1659 m and the other to 1608 m. The second hole encountered the Precambrian granite at 665 m and the third at 664 m. Figure 4 summarizes the geologic logs of the three test holes. These holes, together with other investigations and additional near-surface exploration, indicated that the selected site was technically attractive and feasible, with the following characteristics:

- The Precambrian granite is sufficiently deep for either a one-drop or a two-drop UPHS project.
- The terrain is nearly level to very gently rolling. Competent rock is at a shallow depth from the ground surface, allowing the upper reservoir to be created by the construction of an enclosed dike.
- Ample surface or ground water of good quality is available for initial filling and makeup. The ground-water source is preferred.
- There are no major adverse environmental problems.
- There are no access or transmission problems.

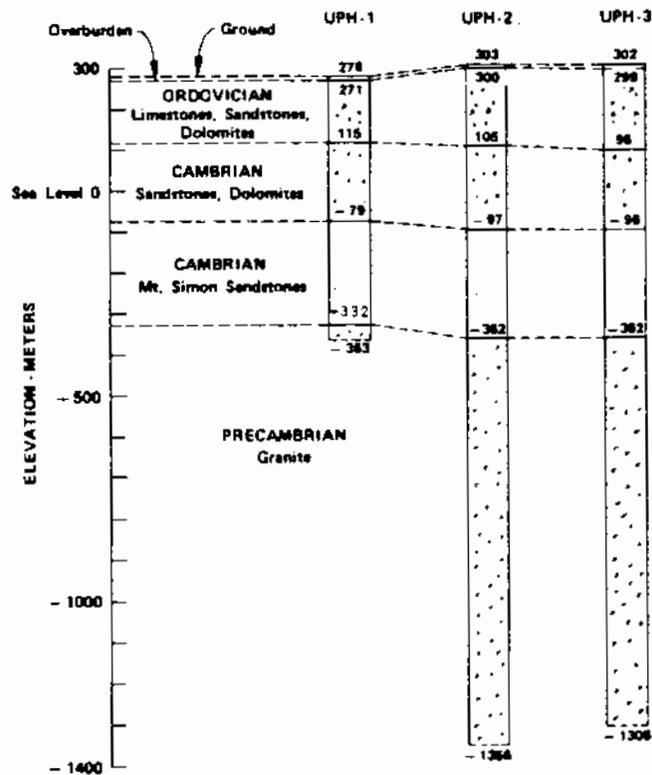


FIGURE 4. Geologic Logs of Commonwealth Edison Project Test Holes

2.4.2 Basic Project Concept

System planning studies were conducted simultaneously with development of the project concept to establish the size of the project. A detailed production cost model, PROMOD III, was used to analyze the performance of the UPHS project in the system expansion through the 1990s. Plant capacities of 2000 and 3000 MW were studied to determine the effect of economies of scale. Because of the economies derived, the 3000-MW plant was used as the design basis. The reservoir size was also studied. It was determined that if energy storage should be less than 8 hr, the full amount of plant generating capacity could not be credited. On this basis, a 10-hr storage pond was selected.

A comprehensive study concurrently performed to establish the basic project concept includes:

- choice between one-drop and two-drop concepts
- determination of total project head
- selection of the type and size of pump-turbine.

For this purpose, the four alternatives in Table 3 were studied with three different head ratings on the pump-turbine, and one-drop and two-drop concepts. Within each alternative, a range of unit sizes from 250 to 500 MW was studied. The relative construction costs shown in Table 3 are for a 3000-MW, 30,000-MWh project.

Alternative 1 had the highest unit cost because of the lowest net head (and correspondingly largest amount of excavation required for the underground reservoir) developed under that alternative. Alternative 3 would develop about the same head as Alternative 2, but had a higher cost because of the cost penalty inherent in a two-drop concept. Alternative 4 has the same minimum construction cost as Alternative 2. However, Alternative 4 poses the greatest geotechnical problems and carries the greatest risks because of the depth below ground surface of the lower reservoir and power station. Fundamental changes in design of some project features, such as the dimensions and shape of the lower reservoir caverns, may be

TABLE 3. Basic Alternatives, Commonwealth Edison Underground Pumped Hydroelectric Storage Project

<u>Alternative</u>	<u>Total Generating Head (m)</u>	<u>Unit Pump Head (m)</u>	<u>Number of Drops</u>	<u>Pump- Turbine</u>	<u>Relative Construction Cost (\$/kW)</u>
1	1043	1100	1	1-stage	390
2	1430	1500	1	2-stage	360
3	1530	811	2	1-stage	380
4	2079	1100	2	1-stage	360

required because of the increased depth. These changes would adversely affect the relative construction cost of Alternative 4.

Alternative 2 was selected because, among other reasons, it had the lowest cost of the three remaining alternatives. The one-drop scheme provides greater flexibility in future design, construction, and operation. It uses two-stage (or possibly three-stage) reversible pump-turbines with a head of 1500 m. These units are beyond the current state of technology, but studies by manufacturers indicate they will be technically feasible at the time they will be needed by the project. The Electric Power Research Institute (EPRI) is sponsoring a development program for an ultra high-head pump-turbine. The reversible pump-turbine selected in this study falls within the range of the EPRI program.

2.4.3 Project Arrangement

Figures 5 and 6 show the plan and cross section of the project. This project arrangement is one of several that were studied to derive a practicable layout with the flexibility to permit changes as detailed information from deep underground exploration became available. The layout was designed to permit construction in a minimum of time and to provide operating flexibility. The functional design of the major features is briefly described.

2.4.3.1 Upper Reservoir

The upper reservoir is created by an enclosed dike, divided into two interconnected halves by a center dike. Splitting the upper reservoir facilitates future maintenance without having to take the entire power plant out of service.

An auxiliary reservoir would be built to provide water for makeup purposes, to provide storage for rapid evacuation of a portion of the water from the upper reservoir, and to regulate the total amount of cycling water contained in the upper-lower reservoir system and thus minimize the risks

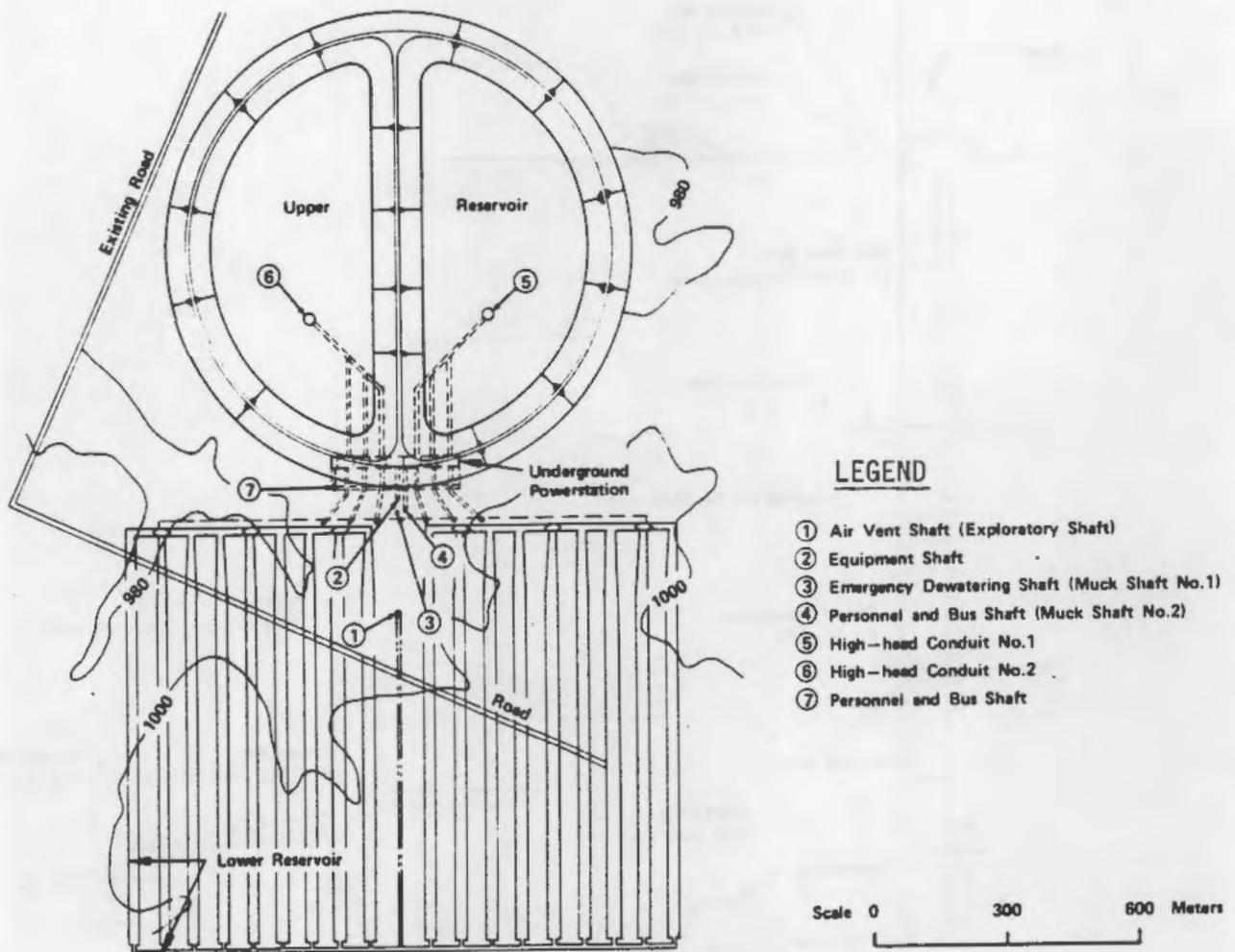


FIGURE 5. General Plan of Upper and Lower Reservoirs, Commonwealth Edison UPHS Project

of overpumping and overgeneration. The auxiliary reservoir is now shown in Figure 5 but can be located anywhere close to the main reservoir.

2.4.3.2 Lower Reservoir

The lower reservoir consists of parallel caverns excavated in the Precambrian granite. The caverns are elliptical in cross section, 23 m

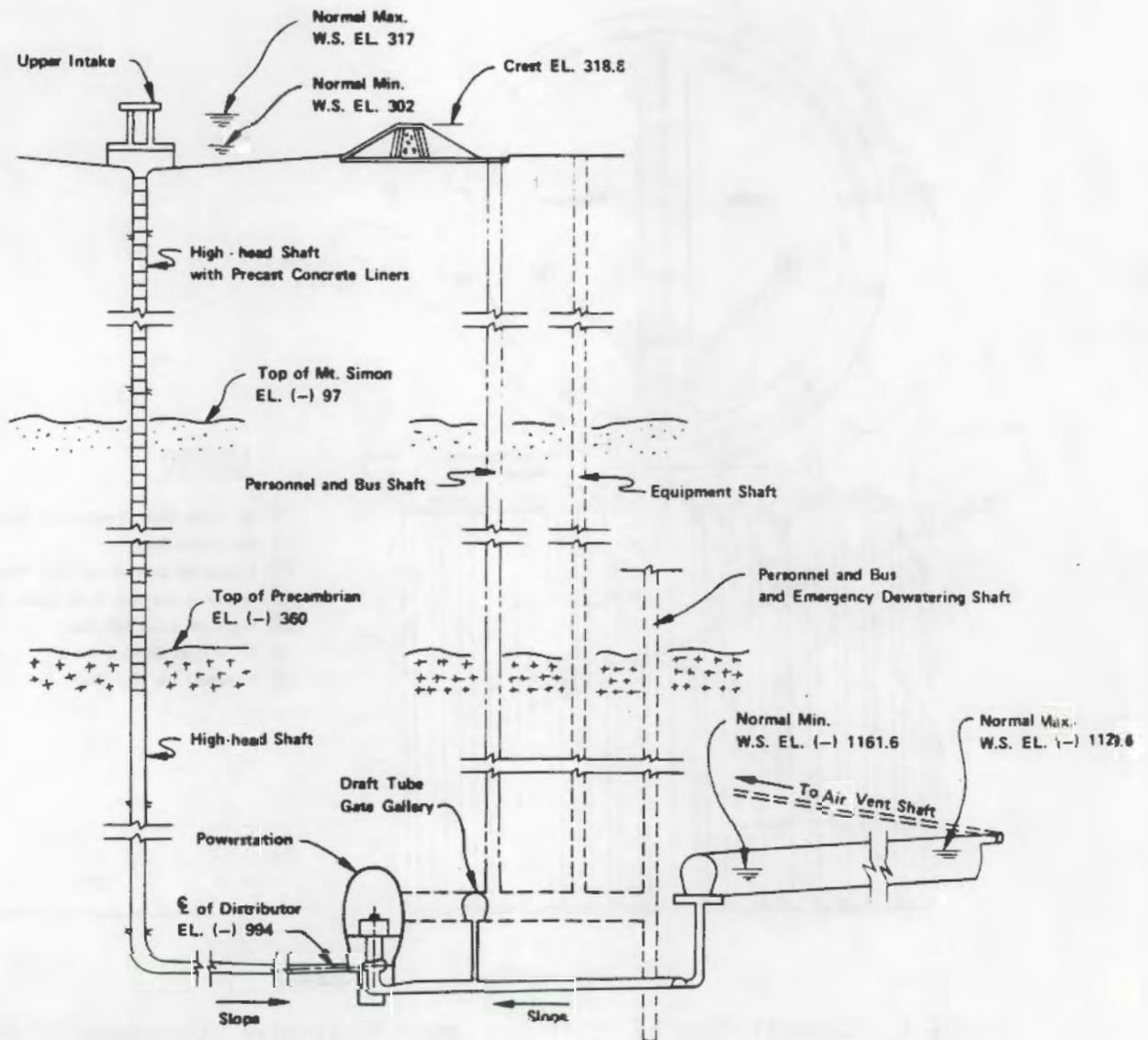


FIGURE 6. Cross Section of Shafts and Plant Subsystems, Commonwealth Edison UPHS Project

wide by 30.5 m high. The caverns will be oriented at a suitable angle to principal stresses to obtain the most favorable stress distribution. Like the upper reservoir, the lower reservoir is also to be divided into two equal interconnected sections. The caverns will be unlined and supported with rock bolts and wire mesh in the center portion of the crown.

The dimensions, spacing and minimal support systems are established on the assumption that the Precambrian granite would be fresh, massive, strong, and moderately to closely jointed. The cavern shape has been established on the basis of a reasonably favorable ratio of horizontal to vertical stresses. The subsurface exploration has generally confirmed the adequacy of the assumptions.

2.4.3.3 Vertical Shafts

Seven vertical shafts extend down to the 1500-m level from the surface, as indicated in Table 4. Two of the shafts would be the high-head conduits, which carry water between the upper reservoir and pump-turbines; each serves three units. The other five would be dry shafts.

The exploratory shaft would be sunk first, constructed by blindface boring from the surface. This shaft would be driven at an early stage to provide information for final design. Experience from boring the small shaft will provide valuable information for sinking the other six larger shafts.

The exploratory shaft was sized to provide room for elevating the muck from raise-shafting the second shaft and possibly the third shaft. Depending on its final location, the exploratory shaft could also serve as the air vent shaft.

TABLE 4. Commonwealth Edison Underground Pumped Hydroelectric Storage Project Shaft Description

<u>Shaft Type</u>	<u>Inside Diameter (m)</u>
Exploratory shaft (air vent shaft)	3.6
Equipment shaft	6.1
Emergency dewatering shaft (muck shaft no. 1)	6.1
Personnel and bus shaft (muck shaft no. 2)	6.1
High-head conduit no. 1	5.2
High-head conduit no. 2	5.2
Personnel and bus shaft	4.9

The upper 670 m of all seven shafts would be in water-bearing dolomite and sandstone. The lower 910 m would be in crystalline granite. The upper 670 m of each of the shafts would be sunk with a boring machine. After this portion of the shaft is lined with precast reinforced high-strength concrete and grouted in the annular space, excavation of the lower portion of the shaft could begin, possibly by raise shafting.

The lower portion of the two high-head conduit shafts would be lined with concrete in place. Drainage adits at suitable depths would be provided around these shafts to prevent excessive buildup of external water pressure. The lower portion of the dry shafts would be unlined.

2.4.3.4. Power Station

The power station is located about 75 m below the lower reservoir to provide submergence for the pump-turbines. The actual location will depend on submergence required by the pump-turbine design. The overall dimensions of a six-unit power station are 293 m long, 23.5 m wide, and 49 m high. Each unit bay is 38 m long with the transformers in a concrete vault adjacent to the generating units. The erection and service bay is located in the center of the power station. Normal personnel access and equipment handling are through shafts connected to the erection bay.

2.4.3.5 Pumping/Generating Equipment

The pump-turbines are reversible, regulating, two-stage machines with a nominal unit rating of 550 MW at 1500 m. Each turbine is provided with a spherical guard valve. The generator/motor is rated to match the output and input of the pump-turbine. The generator/motor will probably be totally water-cooled.

Each generator/motor is connected to three 345-kV single-phase transformers located in a vault in the same unit bay. High-voltage SF₆ insulated buses connect the transformers to the surface. Two sets of buses are required for the six units. Each set is located in a separate shaft.

2.4.4 Conclusions

The site selected by Commonwealth Edison in its service territory is attractive, and has been demonstrated to be technically feasible for a UPHS project. The UPHS project appears to be cost-effective and competitive with oil-fired cycling and peaking generation.

Commonwealth Edison's UPHS study was suspended in January 1980 when revised load growth projections deferred the anticipated service date. This deferral provides an excellent opportunity for further development work on ultra high-head pump-turbines.

The results of subsurface investigations and office studies have provided a firm basis upon which a definite project can be established. A design-level investigation, including the exploratory shaft, can begin when the study resumes. At that time, economic studies to confirm the cost-effectiveness of UPHS will be performed.

2.5 FIFTEEN HUNDRED-METER PUMP-TURBINE STUDY

Economic analyses (C. T. Main, Inc. 1978; Willett 1981) show cost-effective systems at heads of approximately 1500 m, resulting from the inverse relationship between reservoir volume and head. Because excavation of the lower reservoir is a dominant cost factor, high heads are necessary to decrease the required reservoir volume. In addition, economies of scale for UPHS dictate that typical turbomachinery ratings be in the 350- to 700-MW range. Only unregulated multistage reversible pump-turbines and expensive tandem units consisting of multistage pumps and Pelton impulse turbines currently approach the 1500-m capability using a single hydraulic drop. These units are rated at smaller capacities near 100 MW. Single-stage regulating reversible pump-turbines can be used in a double-drop configuration, involving addition of an intermediate level powerhouse and small reservoir, to reach a maximum head of 1250 m. Design and development of regulated two-stage reversible pump-turbines with heads

in excess of 1500 m and capacities in the 350- to 700-m range remain as the optimal choice to achieve the most economic single-drop storage and the flexibility of load-following for UPHS plants.

Pump-turbine equipment in the 350- to 700-MW range, for the heads required, would operate at 500 to 900 rpm, based on specific speed limits. The motor-generators for this capacity-speed range are not within existing practice. Preliminary studies by various manufacturers have indicated that air- or water-cooled motor-generators in this size range appear feasible. Continued development of motor-generators is therefore necessary to confirm that such equipment will be available and matchable to ultra high-head pump-turbines.

The principal design effort on ultra high-head pump-turbines is underway at Hydraulic Turbines, Inc. (1981). The preliminary design was based on Hitachi's accumulated knowledge and experience from previous work in the development of ultra high-head pump-turbines. The design is governed by an Electric Power Research Institute Request for Proposal (RFP) outlined as follows:

- reversible Francis-type pump-turbine
- operating heads in the 1500 m range
- 300- to 600-MW rating
- two stages with regulation on one or both stages.

The double-stage reversible pump-turbine is being designed and sized for 8 to 10 hr daily generation including general mode changes for a 50-yr plant life under normal service in the United States.

The preliminary design embraces several important elements.

First, a decrease in pump specific speed to less than $30 \text{ m-m}^3/\text{sec}$, corresponding to a turbine specific speed of 90 m-kW , causes a decrease in efficiency of more than 2%. Because the specific speed of a 600-rpm machine will be approximately $27 \text{ m-m}^3/\text{sec}$, the efficiency drop will be much

greater than 2%. On the other hand, at a higher speed (e.g., 900 rpm), several problems related to critical speed and vibration may occur. As a compromise, a rated speed of 720 rpm was selected for the baseline machine.

Second, the runner fatigue strength is a critical factor for a high-head pump-turbine due to the high peripheral velocity. The proper material must be selected to withstand the high stress imposed on the runner under high-head conditions. To meet this requirement, cast 5 Ni - 13 Cr stainless steel was found to be the most practical material. The mechanical limitation imposed by the head is expected to be approximately 900 m according to the stress levels computed by the 800-m, single-stage pump-turbine development program. For the double-stage pump-turbine, the pressure will be cancelled out between the action side and the reaction side during operation; therefore, one stage will carry only half of the total head. Considering that the applicable head for each stage would be the same as that of a single-stage machine, the operating total head around 1500 m was selected for this program with some safety margin from the critical stress level. The stress level for the runner of the ultra high-head pump-turbine is well within the safe operating region.

Third, because two runners will share the total head of 1500 m for the double-stage pump-turbine, the submergence of -125 m can also be selected as the same level for the 750-m head, single-stage pump-turbine.

The proposed baseline machine specification, listed in Table 5, was established from the above considerations. The technology developed through this program can readily be transferred to other ultra high-head two-stage machines that are similar to the above baseline machine.

Detailed design will involve stress analysis, fatigue evaluation, manufacturability, assembly/disassembly methods, maintainability and reliability, and motor-generator and auxiliary equipment requirements. Computer programs will be used for hydraulic, stress, natural frequency, and critical speed analyses. A model has been designed and constructed and is undergoing testing to refine and/or verify the detailed design, predict performance characteristics, evaluate efficiencies, verify four-quadrant

TABLE 5. Specifications for 1500-m Pump-Turbine

Type	Vertical shaft Francis-type, double-stage, reversible pump-turbine with movable wicket gates for both the top and bottom stages.
Rated speed	720 rpm
Turbine	
Maximum head	1450 m
Output	655 MW
Discharge	52 m ³ /sec
Minimum head	1390 m
Output	570 MW
Discharge	47.5 m ³ /sec
Specific speed per stage	110 m-kW
Pump	
Maximum total head	1500 m
Minimum total head	1440 m
Maximum discharge	34 m ³ /sec
Pump input	540 MW
Specific speed per stage	33 m-m ³ /sec
Submergence	-125 m
Runner diameter	3250 mm
Main shaft diameter	1370 mm

operation, and optimize cavitation performance. Final design will incorporate refinements from model testing. The program will conclude with confirmatory model testing.

2.6 PROPOSED RESEARCH AREAS

To reduce the uncertainty associated with the geotechnical aspects of deep underground projects, additional research in a few important areas

would improve understanding and execution of excavation (Neff 1982). Some of the more important needs are:

- improved methods to measure in situ stress at depths below 1000 m
- improved analytical tools that utilize nonlinear three-dimensional finite element techniques
- evaluation of new rock support systems that involve prestressing the rock mass
- improved drilling methods enabling extraction of truly representative rock core from very deep holes
- accurate measurement of creep behavior under temperatures and pressures at lower reservoir and powerhouse depths.

3.0 TECHNICAL AND ECONOMIC SUMMARY

Several types of pump-turbines are candidates for use in high-head pumped storage. They have been described by Blomquist, Frigo, and Tam (1979); Rodrique (1979); and Casacci, Roche and Jarriand (1982). The limitations and development prospects of high-speed motor-generators have been examined by Hartmann and Oberer (1982).

This summary addresses the following topics: 1) turbomachinery options, 2) equipment/drop arrangements, 3) site selection, 4) subterranean design, 5) environmental concerns, and 6) economic analysis (Allen et al. 1980).

3.1 TURBOMACHINERY OPTIONS

The various types of pump-turbines considered for high-head pumped storage are briefly described (Blomquist, Frigo and Tam 1979; Rodrique 1979; Casacci, Roche and Jarriand 1982). Limitations and development prospects of large high-speed motor-generators are discussed by Hartmann and Oberer (1982).

3.1.1 Single-Stage, Francis-Type, Reversible Pump-Turbine

This unit, shown in Figure 7, is widely used in the U.S. because of extensive design and operating experience in this country, least equipment cost, high unit capacity, and speed regulation/load-following capability with adjustable wicket gates. Although studies indicate feasibility of heads of 800 to 1000 m, current units do not exceed 625 m.

3.1.2 Unregulated, Multistage, Reversible Pump-Turbine

High operating head (up to 1290 m at present) is the principal advantage of this equipment, which is more expensive than the Francis type and does not have load-following capability. The units, illustrated by Figure B, require less submergence than a single-stage machine. In the pumping mode, most of the machines are started in the watered condition because of the high cost of providing dewatering and priming facilities. Five-stage pump-turbines are under design for a mean head of 1450 m.

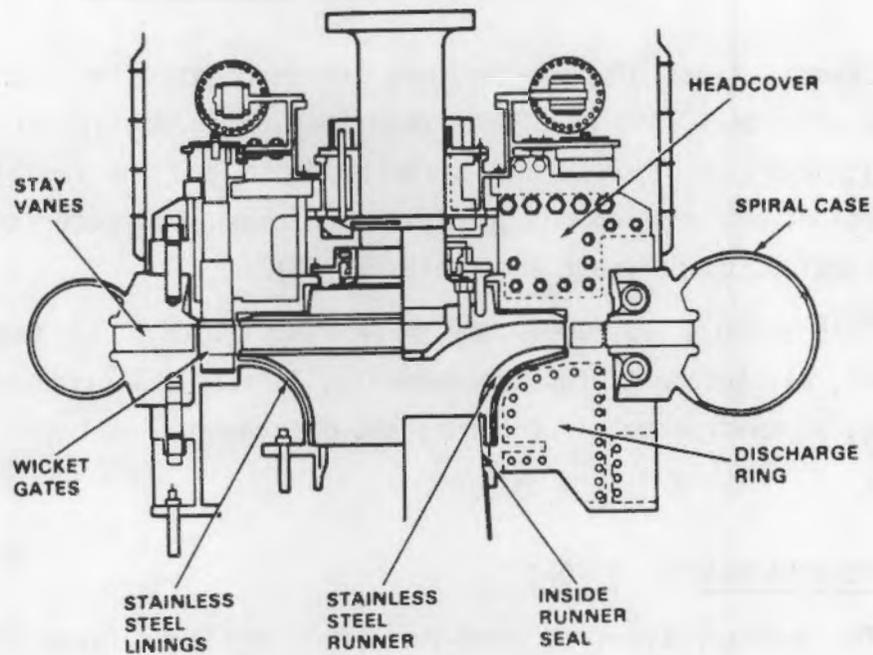


FIGURE 7. Single-Stage, Reversible, Francis-Type Pump-Turbine (Blomquist, Tam and Frigo 1979)

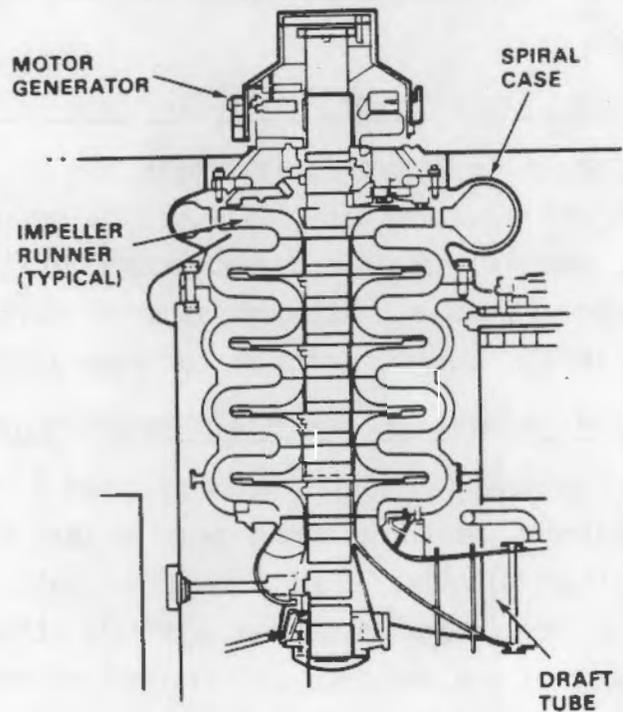


FIGURE 8. Five-Stage, Ungated, Reversible, Francis-Type Pump-Turbine (Ste-Helene Plant in France) (Blomquist, Tam and Frigo 1979)

3.1.3 Two-Stage, Regulated, Reversible Pump-Turbine

This machine, shown in Figure 9, is an extension of the single-stage pump-turbine. It has the potential of providing power regulation for heads above 1000 m. Submergence requirements are less than for single-stage machines at the same head. Current designs include wicket gates in both stages as well as gates in the first stage only with an unregulated second stage.

3.1.4 Separate Multistage Pump and Pelton Impulse Turbine

This machine combination is suited to high heads and quick response time for generating and pumping; it is used in pumped storage plants in Europe for meeting sharp load demands. Disadvantages include required additional water conduits, larger plant space, and a disengageable coupling

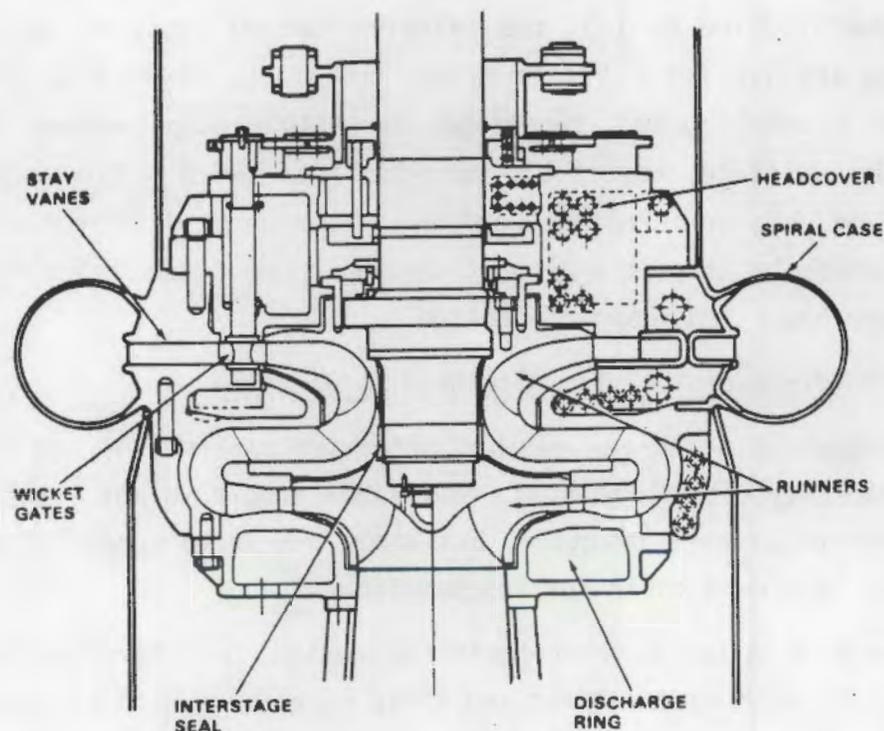


FIGURE 9. Two-Stage, Reversible, Francis-Type Pump-Turbine (Blomquist, Tam and Frigo 1979)

between turbine and pump. This tandem unit is estimated to be much more expensive than a comparably sized two-stage reversible pump-turbine.

3.1.5 Head Cost Comparisons

Studies at Argonne National Laboratory (Blomquist, Tam and Frigo 1979) indicate that the maximum head for single-stage, reversible pump-turbines was 625 m; for tandem units consisting of separate multijet impulse turbines and multistage pumps, 1400 m; and for multistage, reversible, ungated Francis-type pump-turbines, 1290 m. Design studies indicate that heads for the single-stage reversible units could be extended above 1000 m developing over 500 MW output. Reversible pump-turbines, both regulating two-stage units and ungated multistage units, could be developed for power outputs over 500 MW at operating heads up to 1500 m.

Considering the unit equipment capital cost of a single-stage, reversible pump-turbine as 1.0, the relative capital costs of the other turbomachines are 1.7 for a single-gated, two-stage, reversible pump-turbine; 1.8 for a double-gated, two-stage, reversible pump-turbine; 1.6 for an ungated, two-stage, reversible pump-turbine; and 3.3 for a tandem unit, multistage pump and Pelton turbine. These cost differentials may be overshadowed by machine dependent cost considerations relating to subsurface powerhouse and reservoir design.

3.1.6 Motor-Generators for High Head Application

Adequately sized and matched motor-generators (MG) are feasible for large-capacity ultra high-head, reversible pump-turbines. Such MGs are an extension of present practice, but there are large economic incentives of scale to recommend their further development.

Large high-speed motor-generator design is determined by economic comparisons with alternatives and field experience with state-of-the-art MG designs. Experience with hydro plants, pumped storage facilities, and UPHS design studies have determined that increasing MG capacity always has a beneficial economic effect on plant cost.

Precedence experience for large high-speed MG equipment is most easily evaluated by comparing the product of rated capacity and speed (MVA-rpm). The present maximum is a 290 MVA - 600 rpm unit with an MVA-rpm of 174,000. This equipment is at the European Wehr facility. Studies by American utilities indicate that large economic benefit requires MG ratings in the 375 to 500 MVA range with some consideration being given to 750 MVA machinery. This equipment is to be matched to reversible pump-turbine equipment that would operate at speeds between 500 and 900 rpm (514, 600, 720, 900 are available synchronous speeds), for best hydraulic performance. All combinations at the above ranges exceed present experience in the MVA-rpm product. A typical design of 500 MVA at 600 rpm exceeds present experience by 70%.

Preliminary studies have been carried out by Allis Chalmers, Hitachi, and various European manufacturers, and results to date indicate that such designs appear to be feasible.

One approach would be to scale down existing turbogenerators installed in nuclear or conventional steam power plants. The European design of rotor water cooling can also be used at speeds of 600 to 1500 rpm (Hartmann and Oberer 1982).

3.2 EQUIPMENT/RESERVOIR ARRANGEMENTS

The UPHS design is determined by operating head limits on turbomachinery or "drop" and the excavation economics of the lower reservoir(s). Low head turbomachinery may require multiple drops to minimize the cost of excavation. (The storage power capacity is approximately proportional to the total drop at constant storage volume.) Five equipment/hydraulic drop arrangements can reasonably be considered: 1) single drop with high-head single-stage reversible pump-turbine(s); 2) double drop with an intermediate powerhouse and small reservoir and single-stage reversible pump-turbines; 3) single drop with unregulated multistage reversible pump-turbine(s); 4) single drop with multistage pump and Pelton impulse turbine

in tandem units; and 5) single drop with two-stage regulated reversible pump-turbine(s). Equipment development precedents exist for arrangements 1, 2, 3, and 4. Preliminary design studies have been conducted by Allis Chalmers and Hitachi for arrangement 5.

Because primary interest is focused on heads in the 1000- to 2000-m range, arrangement 1 would be venturesome at this time, because experience with the single-stage regulated reversible pump-turbine is limited to a head of 600 to 800 m. When successful designs and tests for high-head machines are realized, however, arrangement 1 will be well suited to UPHS. Arrangement 3 appears to be the state-of-the-art alternative for heads over 1000 m because unregulated multistage reversible pump-turbines are in service and under construction, but the lack of flexibility caused by unregulated operation is a large disadvantage for U.S. users. Five-stage units with fixed stay vanes are scheduled for operation at a maximum head of 1290 m at the Edolo Station of the ENEL in Italy (Meier and Jaquet 1979). Arrangement 5 is the most probable for U.S. implementation. Design and development by Hitachi of an ultra high-head, two-stage, regulating reversible pump-turbine is presently underway, with either single-stage or double-stage gating as options. Arrangement 4, the multistage pump coupled to the Pelton impulse turbine, may continue to be considered in Europe because of its quick response ability and purported ease of maintenance. Arrangement 2 has been favorably regarded (Amblard 1979; Charles T. Main, Inc. 1978; Rodrique 1979) because the double-drop scheme eliminates the need for development of pump-turbines in head ranges beyond the state of the art and allows significant economy in the deepest reservoir. However, it requires two powerhouses which can increase initial cost, construction time, and operating complexity.

Preliminary design studies by Acres American, Inc. (1976) evaluated relative direct cost factors for four of the five arrangements. Multistage unregulated machinery was not considered at the request of Potomac Electric Power Company for operational reasons. Figure 10 gives direct costs for a

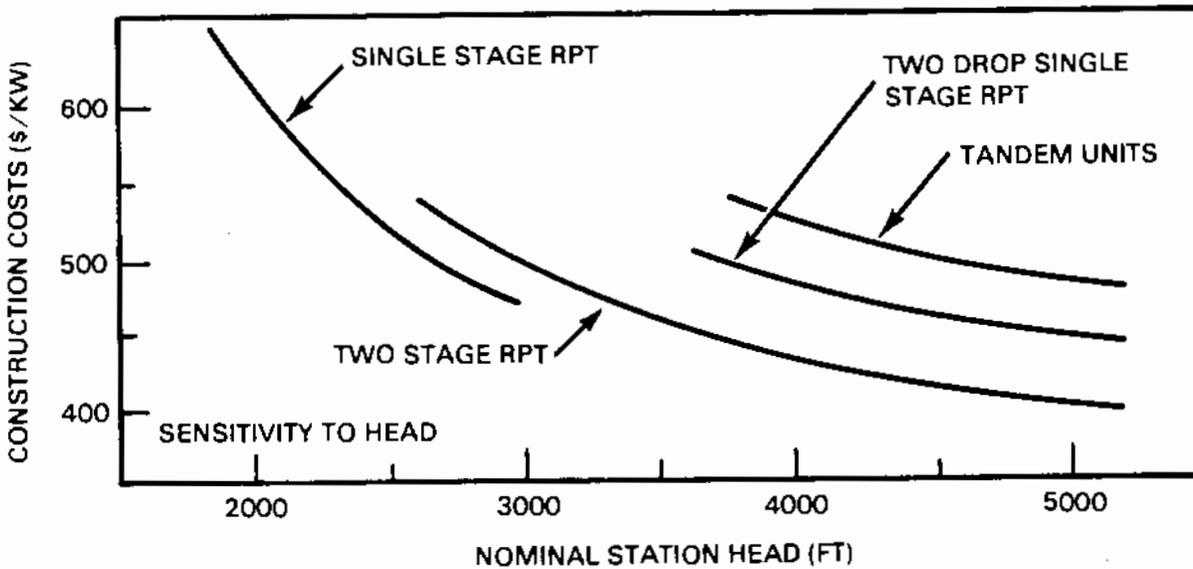


FIGURE 10. The Effect of Operating Head on Plant Construction Costs for Various Turbomachinery/Plant Arrangement Options

2000-MW 10-hr plant design using 300-MW or larger machinery units. The most economical and practical range, from 3500 to 5000 ft of operating head (1100 to 1500 m), indicates two-stage reversible pump-turbines as the preferred machinery. Effects of powerhouse and shaft design, development feasibility, and reservoir design were considered.

3.3 SITE SELECTION

Site selection depends primarily on thorough geologic and hydrologic exploration as well as system transmission and load center factors. For the upper reservoir, initial fill and makeup water must be available from surface sources, shallow aquifers, or other acceptable sources. A relatively impervious reservoir bottom and adequate dike foundation are needed; both conditions imply an impervious overburden above competent rock. The shaft and powerhouse cavern locations require shallow overburden at the shaft head, competent near-surface rock, rock quality at depth adequate for a cavern cross section about 40 m high with a span of 20 m or more, rock formation with minimum structural deformation, and low permeability.

As many as four vertical shafts may be required, although some of the functions (e.g., access and power cables) may be combined in a single shaft.

For the lower reservoir, the host geologic formation must be thick bedded, sedimentary or massive igneous/metamorphic rock, impervious and relatively insoluble over a minimum 50-yr period (Charles T. Main, Inc. 1978). No significant aquifers should be present. (If minor water-bearing formations occur, they should be confined above and below by dense shales or other aquicludes.) The host rock should be essentially homogeneous, for example, a uniform, thick sedimentary formation devoid of permeable interbeds. The roof rock should be of sufficient quality to minimize the need for rock improvement measures, such as bolting. Structurally undisturbed rock, low residual rock stress, and absence of closely spaced or open joints are believed to be necessary conditions. Low seismic risk is essential.

Existing mines in appropriate locations could also be candidates for use as lower reservoirs (Bahadur 1980; Hough and Britton 1982). Depth, geology, mineralogy, age, mining method, and UPHS development approach need to be considered very carefully.

3.4 SUBTERRANEAN DESIGN

Two subterranean reservoir designs have been proposed: room and pillar by Charles T. Main, Inc. (1978) and, more recently, parallel, cross-connected caverns by Acres American, Inc. (Willett 1981). The room and pillar configuration would consist of a grid of tunnels intersecting at right angles, as shown in Figure 2. The Acres American proposed lower reservoir consists of 14 parallel caverns joined at each end by smaller collector tunnels. Drill and blast techniques can take advantage of the cost economies of heading and bench excavation and the schedule advantages inherent in having many working faces during mining. Tunnel boring techniques could be considered based on recent experience, but they have typically been used for linear developments rather than large volumetric development in confined areas typical of present UPHS design.

Where the intact unconfined compressive strength of the rock at a selected UPHS site is less than five times the in situ stress or in the presence of significant jointing or bedding separation, roof support or at least minimum rock bolting will be required. Geologic siting criteria would normally preclude rocks in the lower strength range (e.g., post-Jurassic sandstones and shales).

A penstock design should be developed to accept steady-state and transient water flows in each direction with minimum frictional resistance. Lining of the shaft with concrete or steel-backed-by-concrete will be necessary to prevent high pressure water penetration of adjacent jointed rock for some distance above the powerhouse, where in situ hydrostatic joint pressure may be low due to drainage. The design must also prevent lining collapse caused by stress transients induced by sudden or gradual loss of internal water pressure. Buckling of the liner can occur from flow-pressure transient unloading. The key design problem with respect to buckling is inversely impacted by lining curvature (i.e., a large-diameter penstock increases the wall thickness requirement).

Powerhouse cavern design must provide for variation in host rock lithology, machinery access from the surface, redundant protection from flooding, geologic stability, prevention of hazards from mechanical vibration and resonance, and remote operation with backup controls and failsafe features. The power plant creates particular problems because of its shape and size. Machine assembly will require rooms with heights up to 40 m and spans of 20 m or more. Service bays must be provided for maintenance and storage. Minor site-specific problems can be solved by established techniques such as rock anchoring, rock bolting, grouting, and prestressed concrete lining; but primary integrity depends on uniformly high rock quality at the site. Drainage galleries may be necessary to protect the powerhouse.

3.5 ENVIRONMENTAL CONCERNS

Surface and subterranean environmental concerns primarily center on hydrologic questions related to the movement of large water volumes from deep subterranean chambers to the surface and back. Lower cavern construction will require the excavation of up to 8 million m³ of hard rock. A large fraction may be used as dike-containment (and possibly foundation material) for the surface reservoir. Hydrologic concerns involve the surface drainage and percolation from the excavated rock, ground water impacts, and flow alterations in deep bedrock zones. Water in the surface reservoir may be contaminated with biota that may develop on the walls of the lower reservoir chambers. Seepage through the bottom of the surface reservoir may impact the local water table. Seepage of the penstock's water column into adjacent rock formations may adversely affect aquifer water quality and/or rock structural stability. (Lack of containment within the surface reservoir, penstock or the lower reservoir could result in flooding problems in the powerhouse.) The pumping mode will transfer geothermal and frictional heat to the upper reservoir. Most potential problems can be overcome by careful site selection and proper construction planning. Other environmental concerns involve construction activities, land use, transmission corridors, increased baseload plant use, and atmospheric fogging.

3.6 ECONOMICS

Analysis shows that UPHS can offer substantial savings in total production costs over coal-fired cycling units and gas turbines (Charles T. Main, Inc. 1978). Results are shown in Table 6. Whereas UPHS is more economical than coal cycling units in both systems, the economy of UPHS over gas turbines differs greatly, depending upon the system assumed.

Chiu and colleagues (1979) state that the premium fuel savings by a UPHS plant over an estimated 50-yr life would more than offset the high initial cost. Power system and balance-of-plant costs can be reasonably estimated because the equipment is identical to that used in conventional

TABLE 6. Present Worth Comparisons Among 2000-MW Underground Pumped Hydroelectric Storage, Coal Cycling and Gas Turbine Plants (Charles T. Main, Inc. 1978)

<u>Scenario</u>	<u>Plant Type</u>	<u>Total Present Worth (\$ Millions)</u>	<u>Incremental Present Worth Above UPHS (\$ Millions)</u>
High proportion of baseload generation	UPHS	51,923	--
	Coal cycling	54,036	2,113
	Gas turbines	51,932	9
Low proportion of baseload generation	UPHS	35,345	--
	Coal cycling	36,901	1,556
	Gas turbines	36,011	666

pumped storage. Storage-related costs are more difficult to estimate. However, recent preliminary design studies consider detailed cavern excavation procedures, excavation equipment, and shaft borings and hoists such that a much greater confidence can now be attributed to the cost estimates for these items (Willett 1981; Chen and Berman 1981).

An Acres American report (1976) discussed the relative importance of excavation costs relating to UPHS shafts and caverns. Extremes of geologic conditions would cause only a 5% variation in total plant cost from shaft sinking, but possibly a 50% variation from cavern excavation cost.

Computed capacity costs for various UPHS configurations have been compared to actual costs for existing pumped storage projects. The costs have been adjusted to a July 1, 1978 base. No allowance for interest during construction is included. Table 7 shows that UPHS estimated costs per kW lie between the two highest and the two lowest values for conventional pumped storage.

A recent study (Tam, Frigo and Blomquist 1979) that compared costs for plants with advanced reversible pump-turbines found: 1) advanced

TABLE 7. Comparison of per Kilowatt Costs for Underground Pumped Hydroelectric Storage and Conventional Pumped Storage (Charles T. Main, Inc. 1978)

<u>Configuration or Plant</u>	<u>Cost per Kilowatt</u>	<u>Reference</u>
Bear Swamp, Massachusetts	\$265	Charles T. Main
Ludington, Michigan	319	Charles T. Main
Single-drop, multistage reversible pump-turbine	356 379	Charles T. Main Rodrique
Double-drop, single-stage reversible pump-turbine	378 391	Charles T. Main Rodrique
Single-drop, tandem impulse turbine and multistage pump	398 412	Charles T. Main Rodrique
Single-drop, single-stage reversible pump-turbine	423	Rodrique
Boyd Co., Nebraska	444	Charles T. Main
Bath Co., Virginia	459	Charles T. Main

turbomachinery extends the "least plant cost per MW" to a head greater than 1500 m; 2) the percentage savings in plant costs is relatively insensitive to variation in plant capacity above a certain level (1300 to 2700 MW); 3) for heads above 1000 m, the two-stage, reversible pump-turbine is economically attractive. A significant cost reduction results when a plant with two-stage reversible units is compared with either the two-drop, single-stage, reversible pump-turbine configuration or the single-drop, tandem pump and turbine configuration; and 4) increasing the charge/discharge ratio reduces the relative storage cost, but increases balance-of-plant cost and may reduce turbomachinery efficiency. Overall analysis of capital cost and system performance is essential to selection of turbomachinery options.

4.0 CURRENT AND FUTURE COMMERCIAL STATUS

Despite optimistic forecasts of technical and economic feasibility, so far no utility has committed funds to the design and construction of a UPHS plant. According to a recent survey, some feasibility studies have shown capital cost estimates somewhat greater than for conventional storage (Battelle Columbus Laboratories 1982). Accepting these assessments, even though UPHS has some environmental advantages over conventional pumped storage, higher cost remains an impediment to significant market penetration in the near future.

The following changes in the electricity generating environment are likely to influence organizations toward UPHS commitments:

- increase in the availability of capital and decreased interest rates
- increasing load growth within metropolitan areas
- trend toward joint ownership of large projects
- successful demonstration of advanced high-head reversible pump-turbines
- full utilization of available and environmentally acceptable surface pumped hydro sites
- implementation of regulatory reforms to enable return on capital committed to construction of new facilities
- development of uniform institutional and legal procedures applicable to artificial surface and subsurface reservoirs
- demonstration of complete remote operability of the subterranean powerhouse in all modes of operation.

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