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Preliminary Design Study of Underground Pumped Hydro and Compressed-Air Energy Storage in Hard Rock

Volume 1: Executive Summary

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Prepared by
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Washington, D.C.

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Preliminary Design Study of Underground Pumped Hydro and Compressed-Air Energy Storage in Hard Rock

Volume 1: Executive Summary

EM-1589, Volume 1
Research Project 1081-1
DOE/ET 5047-1

Final Report, May 1981

MASTER

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Buffalo, New York
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Washington, D.C.

ABSTRACT

Potomac Electric Power Company (PEPCO) and Acres American Incorporated (AAI) have carried out a preliminary design study of water-compensated Compressed Air Energy Storage (CAES) and Underground Pumped Hydroelectric (UPH) plants for siting in geological conditions suitable for hard rock excavations. The work was carried out over a period of three years and was sponsored by the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI) and PEPCO.

The study was divided into five primary tasks as follows:

- Establishment of design criteria and analysis of impact on power system;
- Selection of site and establishment of site characteristics;
- Formulation of design approaches;
- Assessment of environmental and safety aspects; and
- Preparation of preliminary design of plant.

The salient aspects considered and the conclusions reached during the consideration of the five primary tasks for both CAES and UPH are presented in this Executive Summary, which forms Volume 1 of the series of reports prepared during the study. The investigations and analyses carried out, together with the results and conclusions reached, are described in detail in Volumes 2 through 13 and ten appendices.

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PERSPECTIVE

PROJECT DESCRIPTION

This project, RP1081-1, is an integral part of the energy storage programs of EPRI and the U.S. Department of Energy (DOE). It follows and expands upon studies completed in 1976 that indicated that the most viable near-term utility energy storage alternatives are (1) compressed-air energy storage (CAES) and (2) underground pumped hydro (UPH). This project was initiated to determine the design criteria and develop preliminary engineering designs for both of these storage concepts where underground caverns are excavated out of competent rock. A comprehensive site-selection process identified a site suitable for either CAES or UPH based on considerations of geology, distances of electrical transmission, access to transportation, and environmental impact.

Cost estimates were prepared for each of the studied generation facilities based on the design details and the projected construction schedules. Licensing and environmental and safety aspects were also assessed.

This project included a detailed study of the potential impact of these energy storage technologies on the power system of the Potomac Electric Power Company (PEPCo) and a comparison of the system costs and benefits attributable to the proposed plants with those obtainable from conventional oil-fired peaking facilities. The study also identified R&D topics that could minimize capital as well as operation and maintenance costs and could promote utility acceptance of the technologies investigated.

PROJECT OBJECTIVES

The prime objective of this project was to develop sufficiently detailed engineering designs for each of the facilities to establish several important factors:

1. Construction costs and schedules
2. Performance and operating characteristics

3. Potential construction and operating risks associated with UPH and CAES technologies
4. Environmental, social, and licensing issues

The second objective of the study was to determine the economic benefits that could accrue to a specific utility system from these technologies, due to enhanced flexibility in meeting electrical load demands. The results, although developed for a specific system, are intended to be sufficiently generic for other utilities to determine the potential benefits and costs appropriate to their systems.

PROJECT RESULTS

The project started in the fall of 1977 and was completed in mid-1980. Acres American, Inc. (AAI), as the prime contractor, formulated the design criteria with inputs of system and siting requirements from PEPCo, performed the detailed technical designs and evaluations of machinery and plant component configurations, and produced the project reports. Supportive subcontract work by consulting specialists for the shafts, caverns, hoisting equipment, and other geotechnical aspects was led by AAI. Brown Boveri Corporation and Boving and Company provided, respectively, CAES and UPH machinery inputs.

The results are published as thirteen separately bound topical reports and ten appendices that present the information developed in the principal tasks. A list of the reports and appendices follows this Perspective.

These reports provide information, data, and methodology that utilities will find valuable in evaluating peaking and intermediate options for generation expansion. Specifically, the major products of this CAES and UPH preliminary design project are as follows:

- An evaluation was completed indicating that either technology offers a technically feasible and economically attractive alternative. PEPCo planning studies indicate a total savings (present unit) of greater than $1 billion for a 670 MW, 10 hr UPH or CAES plant when compared with combustion turbines. A net savings of one million bbls/yr of fuel oil was projected.
- A methodology was developed for site selection and subsequently used to select a site in the PEPCo system.
- The mechanical machinery train for the CAES plant was designed and costed utilizing state-of-the-art compressors, expansion turbines, and supporting interstage coolers and recuperators.
- The two-drop concept (utilizing an intermediate reservoir) was determined to be the current state-of-the-art option for UPH, making

best use of the currently available single-stage reversible pump-turbine technology while providing the hydraulic heads necessary for economic viability and the power output regulations deemed necessary by PEPCo. (It appears to be the desired option by U.S. utilities interested in pumped storage.)

- Cost estimates were prepared for CAES and UPH in sufficient detail so as to provide reasonable confidence for their use in utility generation expansion system studies.
- A comprehensive technical guide was produced that can be used by utilities in the preparation and performance of their own site-specific studies.
- Project components and systems requiring or benefiting from additional R&D were identified, e.g., development of an ultrahigh-head regulatable reversible pump turbine; development of a CAES recuperator for high-pressure cycling systems; and improvements in excavation and construction approaches for the subterranean facilities to reduce construction time and costs and to increase confidence in the cost estimates. Again, these results are expected to expedite utility decisions on CAES and UPH projects and to guide future R&D.

The conclusions to be derived by the industry from this project study are that both UPH and CAES are near-term, practical, and economical peaking and/or intermediate generation alternatives. The PEPCo studies showed that either technology would be economically viable for their system at this time, with final judgments and decisions on selection to be based upon other system-specific parameters. Licensing of the projects is unlikely to be a major impediment because these technologies impact the environment to a lesser degree than other alternatives.

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Charles P. Demos
U.S. Department of Energy

LIST OF REPORTS

TO

Preliminary Design Study of Underground Pumped Hydro and Compressed-Air Energy Storage in Hard Rock

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Volume 6: Site Investigation--Shallow Drilling
Volume 7: Site Investigation--Deep Drilling
Volume 8: Design Approaches--UPH
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Volume 13: CAUPH Preliminary Licensing Documentation

ACKNOWLEDGMENTS

The study program presented in this series of reports has benefited from contributions from many organizations and individuals. The Potomac Electric Power Company and Acres American Incorporated wish to acknowledge the valuable input provided by:

Subcontractors to Acres American Incorporated:

Boving and Company:	Single Stage Reversible Pump-Turbines
Boyles Brothers Drilling Company:	Deep Drilling
Brown Boveri Company:	UPH Motor-Generators and CAES Turbo-Machinery
C-E Lummus:	Intercoolers/Aftercoolers
Cementation Company of America:	Shafts
Coaltech Incorporated:	Recuperators
Foster Wheeler Canada Limited:	Recuperators
GEA Limited:	Recuperators
Warren George Company:	Shallow Drilling
Jacobs Associates:	Underground Construction Costs
Lynes Incorporated:	Permeability Testing
Mechanical Technology Incorporated:	Turbomachinery Design
Neyrpic S.A.:	Multi-Stage Reversible Pump-Turbines
NUS Corporation:	Environmental
Rowe and Associates:	Champagne Effect
SSS Clutch Company:	Synchronous Clutches
Terra Tek Incorporated:	Geotechnical Testing
G. L. Tiley and Associates:	Hoists

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Mr. J. Parmakian	Hydromachinery Consultant
Dr. J. Roen	U.S. Geological Survey
Dr. J-C Roegiers	University of Toronto
Dr. D. S. Rowe	Rowe and Associates
Mr. P.O. Sandstrom*	Shafts Consultant
Mr. P. Wickland	Drilling Consultant

*Deceased

PROJECT MANAGEMENT

This project was originally planned and the RFP issued by J. Pepper and T. R. Schneider of EPRI and J. Edmonds and J. C. Smith of DOE. The project management was assumed by A. Ferreira for EPRI in 1977. B. J. Mueller of DOE succeeded J. Edmonds in late 1979, with C. P. Demos succeeding B. J. Mueller in late 1980. W. A. Stevens and H. Balzan provided substantial consulting inputs for EPRI and DOE, respectively.

Parallel preliminary design projects for CAES, utilizing a salt dome geologic media for the storage cavern and its storage of pressurized air in a porous aquifer, were also investigated. The salt geology project headed by Middle South Services, Inc., is complete, and the final report is expected to be available in mid-1981. The porous aquifer project, managed by R. B. Schainker of EPRI, is headed by Public Service Co. of Indiana and is still in progress, with a publication date expected in 1982.

AVAILABILITY OF REPORTS

Due to the joint EPRI-DOE funding of the project, each of the reports documenting the project results is available from both EPRI and DOE publication services. The EPRI service can be reached at:

EPRI, Research Reports Center
P.O. Box 50490
Palo Alto, CA 94303
(415) 855-2890
(415) 965-4081

The DOE service can be reached at:

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SUMMARY

THE STUDY

Large scale energy storage for electrical power systems has traditionally been provided by hydroelectric pumped storage plants where potential energy is stored by water pumped from a lower to an upper reservoir (both reservoirs being above ground). These pumped storage plants require natural topographic features and adequate sites for reservoirs, and in many instances have raised environmental opposition. It has become increasingly difficult to secure the necessary permits and licenses from the Federal Energy Regulatory Commission to allow construction to proceed.

In the early 1970's, two alternative approaches to the provision of large scale energy storage came under review. The first followed hydroelectric pumped storage practice but provided the potential head difference by locating the lower reservoir, from which water was pumped, deep underground. The second approach also involved an underground cavern, which was used to store air under pressure. The compressed air stored during periods of reduced system demand would be used as input to expansion turbines with added fuel energy provided by oil or gas combustion.

By 1977 the concepts were sufficiently advanced to justify preliminary design studies. While no pumped storage plant with an underground lower reservoir (UPH) has been built, both the equipment and the facilities required are all well supported by existing technology. Compressed air energy storage (CAES) is, at this time, being proven in a facility located in West Germany which came into service in 1979 using caverns leached in salt. Siting and system studies have shown that both UPH and CAES provide potentially viable options for U.S. power utilities.

The study undertaken by Potomac Electric Power Company (PEPCO) for the Department of Energy (DOE) and Electric Power Research Institute (EPRI) considered the application of either concept to an actual system and site with hard rock formations deep underground suitable to accommodate the large excavated caverns. The objective was to carry out sufficient engineering design to provide estimates of cost, schedule and risk upon which a decision could be made to proceed to construction. Acres American Incorporated (AAI) undertook the technical studies, estimating and scheduling work as the architect/engineer.

REPORTS

This Executive Summary forms Volume I of a series of thirteen reports which document the results of the DOE/EPRI energy storage study. The other volumes are:

- Volume 2, Project Design Criteria - UPH: This presents the criteria used in the development of the selected UPH plant design;
- Volume 3, Project Design Criteria - CAES: This presents the criteria used in the development of the selected CAES plant design;
- Volume 4, System Planning Studies: This presents the methodology used in and the results obtained from the economic evaluations of CAES and UPH performed for the PEPCO system;
- Volume 5, Site Selection: This documents the selection process undertaken to identify and rank sites potentially suitable for CAES or UPH;
- Volume 6, Site Investigation - Shallow Drilling: This describes the results of the shallow drilling (up to 500 ft) program to define the surficial geological conditions and the nature of the overburden and of the bedrock at shallow depths;
- Volume 7, Site Investigation - Deep Drilling: This describes the deep drilling and testing program. Maximum depth achieved, measured vertically from the surface, was 2556 ft;
- Volume 8, Design Approaches - UPH: This presents the alternative arrangements considered for the UPH facility and the results of the studies performed to select a preferred arrangement. Five appendices to this volume are bound separately as follows:

  -- Appendix A: Upper Reservoir
  -- Appendix B: Shafts
  -- Appendix C: Heavy Hoist
  -- Appendix D: Power Plant (SSRPT-2 and MSRPT)
  -- Appendix E: Lower Reservoir

- Volume 9, Design Approaches - CAES: This presents the alternative designs considered for the CAES facility and the results of the studies performed to select a preferred design approach. Five appendices to this volume are bound separately as follows:

  -- Appendix A: Air Storage System
  -- Appendix B: Champagne Effect
  -- Appendix C: Major Mechanical Equipment
  -- Appendix D: Mechanical Systems
  -- Appendix E: Electrical Systems

- Volume 10, Environmental Studies: This presents the results of a preliminary environmental assessment of the proposed CAES and UPH facilities.

- Volume 11, Plant Design - UPH: This documents the plant design of the preferred UPH arrangement, including construction schedule and cost estimate.

- Volume 12, Plant Design - CAES: This documents the plant design of the preferred CAES arrangement, including construction schedule and cost estimate.

- Volume 13, CAUPH Preliminary Licensing Documentation: This provides a review of the regulatory and licensing considerations for both the CAES and UPH facilities.

OUTPUT AND STORAGE CAPACITIES

Following system studies by PEPCO and a systematic siting study, a location for either UPH or CAES facilities in the range of 1000 to 2000 MW was selected in Maryland, close to Washington, D.C. and to PEPCO's 500 kV transmission system. Surveys and subsurface investigations carried out included exploration drilling of several holes a few hundred ft deep and one to over 2500 ft. The gneiss bedrock was found to be suitable for the underground caverns. These caverns involve tunnels 85 ft high and 66 ft wide in rock, requiring only limited permanent roof support. The 1000 MW CAES plant capable of storing 10 million kWh suitable for the PEPCO system would involve a cavern volume of about 800,000 yd^3; the larger 2000 MW UPH plant for storage of 20 million kWh (the larger capacity adopted to achieve the economy of scale) would involve excavation of about 7.9 million yd^3 to create the lower reservoir.

Design criteria were established for both UPH and CAES plants and the approach to the design of facilities suitable for utility use was established in close consultation with PEPCO. Environmental and safety aspects of the plants were assessed. Preliminary designs, adequate for reliable estimates to be made of capital costs and construction schedules, were prepared.

THE UPH PLANT

In the case of UPH it was recognized that the economics of development were strongly influenced by the difference in level between the underground storage and the upper reservoir. For a simple single step UPH facility, previous pump-turbine design experience suggests a difference in level or "head" of about 2000 ft; two steps (i.e. two power plants in series) with a small intermediate balancing reservoir allows 4000 ft to be developed. The studies, in fact, led to the selection of 2500 ft per step (5000 ft total head) based on reliable predictions of an appreciable advance in reversible pump-turbine technology. Six 333 MW pumped storage units operating at 720 rpm were selected, three each in the upper and lower power plants, providing 2000 MW total capacity.

Other aspects of UPH which received particular design attention included several shafts required for access, equipment handling and the high pressure water conduits. Electrical systems were studied and an arrangement with transformation step-up to 500 kV underground was adopted. Motor-generator designs were examined and the high speed, high powered units with water-cooled rotors and stators were found to be within acceptable limits of technology. Static converter starting equipment was recommended. In summary it was concluded that all aspects of the UPH design could be covered without utilizing unproven practices.

THE CAES PLANT

The CAES plant has precedent in the plant designed and under construction at Huntorf, West Germany. During the study period, this plant became operational and provided confirmation of the capability of the various elements of equipment. In the PEPCO studies certain specific requirements differed from Huntorf experience. First, CAES in hard rock caverns allows hydraulic compensation to maintain near constant air pressure. This requires a surface compensating reservoir, a water shaft and facilities arranged to avoid accidental release of air bubbles through the hydraulic shaft system (leading to a phenomenon known as the "champagne effect"). Second, the original Huntorf installation was designed without particular recognition of energy economics appropriate to the increasing cost trends in fuels. The application of CAES to the PEPCO system involved careful study of the benefits and costs of more advanced designs of heat recuperators, some involving application of new technology. In general, however, the CAES designs adopted for the study were based on precedent experience.

COSTS AND SAVINGS

The UPH and CAES study established that either approach offered a technically feasible and economically attractive alternative. A 1000 MW CAES plant involved a direct cost in mid-1979 dollars of $376/kW; a 2000 MW UPH facility involved a direct cost in mid-1979 dollars of $416/kW. The CAES plant could be licensed and built to commercial operation of the first unit in 8-3/4 years while the UPH plant would require 11-3/4 years to commercial operation of the first unit. A reduction of over $1 billion in system costs (cumulative present worth of minimum revenue requirements) between the years 1990 and 2007 was predicted to result from the incorporation of PEPCO's share (667 MW) of either energy storage plant into PEPCO's generation expansion plans compared with the use of an equivalent capacity of combustion turbines. The savings in oil consumption were estimated to be 1 to 2 million barrels per year in either case. From an environmental standpoint either alternative would lead to impacts which are believed to be acceptable.

CONCLUSIONS

The conclusions reached from the study provide specific direction for the future effort required to reach a point at which UPH and/or CAES plants may be adopted by power utilities for additions to generating plant construction. Basically, equipment development should progress with the objective of achieving even better capital cost and operating performance. In the case of UPH this involves increasing operating head, preferably to a point where single step development in the range of 4000 ft to 5000 ft can be achieved in a plant capable of load regulation. A two-stage pump-turbine with controllable wicket gates offers significant opportunity in this direction. In the case of CAES, recuperator design for the high system pressures required deserves attention. Further study of specific aspects of the hydraulically-compensated, hard rock cavity storage systems would be beneficial to augment the operating experience being gained year by year at Huntorf. For both UPH and CAES, the construction approaches to the underground facilities demand further and continuing study with the aim at reducing estimated costs while at the same time increasing confidence in the estimates.

It may be concluded that UPH and CAES offer attractive and economic options to power utilities. For those with access to locations over geologically suitable rock masses and convenient to transmission routes, the possibility exists that siting problems for energy storage facilities experienced in the past will be significantly lessened. A step has been taken towards the introduction of a new form of power generation which can well serve system needs of the future.

Section 1

THE ALTERNATIVES FOR POWER SYSTEM ENERGY STORAGE

INTRODUCTION

During the past thirty years or more, power utilities have built thermal generating plants with units of gradually increasing size. Outputs of individual units in the 500 MW to 1300 MW range have been adopted as technology advanced and the favorable economics of scale became evident. These large units carry the base load with relatively high efficiency leaving the mid-range cyclical loads to be supplied by older, smaller turbine generators with predominantly oil-fired boiler plants.

Peak loads occurring over relatively short periods are typically served by gas-turbine and diesel-powered plant. In addition, conventional hydroelectric plants and pumped storage hydroelectric plants have been installed to satisfy some of the peaking and mid-range requirements.

Even with substantial mid-range and peaking capacity installed, it may often be necessary to cycle large base load units to meet varying customer demand. Cyclic operation of steam units, however, can result in increased maintenance costs and shorter unit life due to thermal stressing and also increased fuel usage per unit of energy produced due to less efficient operation on partial loads.

Energy storage is now being considered by many utilities as a means of reducing the problems of unit cycling and equipment loading, of achieving significant savings in oil consumption and in plant investment, and of allowing a more effective use of thermal power generating plant. In the absence of effective load management control, energy storage allows a utility to use supply management to achieve a relatively stable load on its large units as indicated on Figure 1-1.

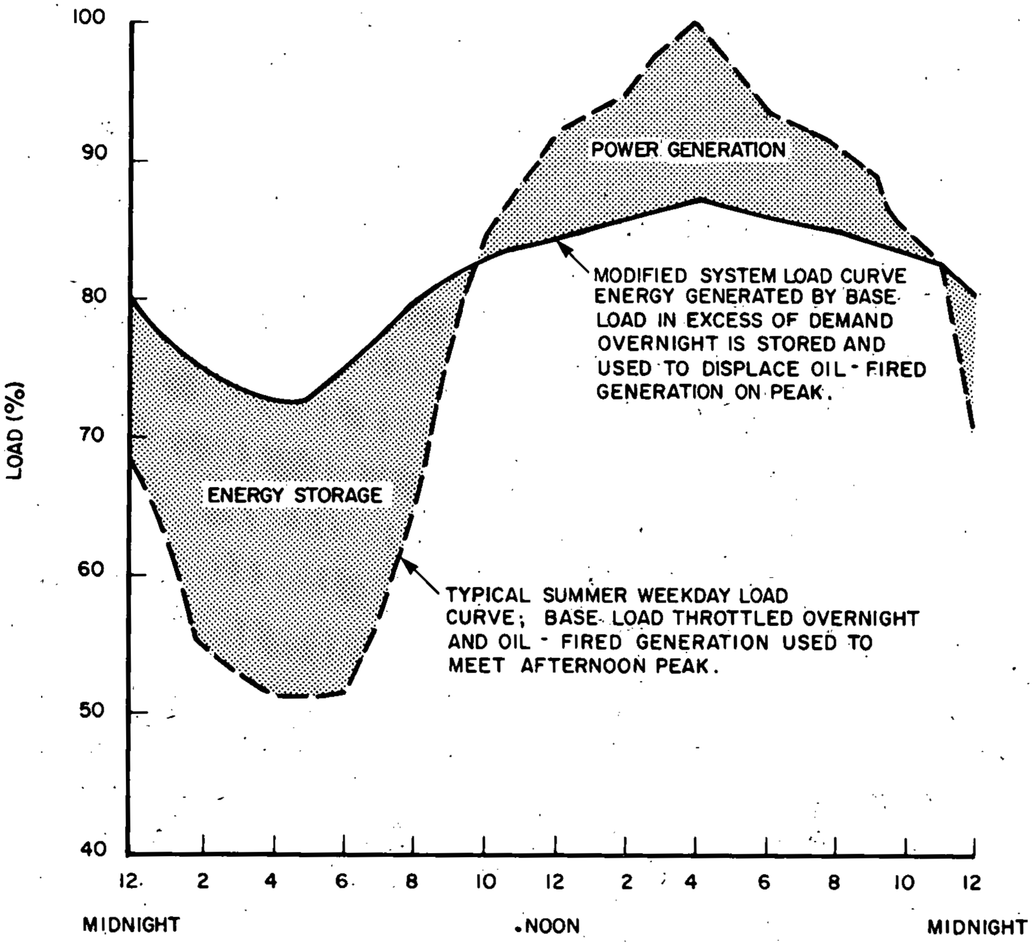

Figure I-1 Modified System "Base" Load

Large scale energy storage has traditionally been provided by hydroelectric pumped storage plants developing the potential head between surface reservoirs at different topographic levels. However, few sites for large conventional pumped storage hydroelectric plants are now available, and the siting of these plants has proved to be increasingly difficult due to constraints on large man-made reservoirs in areas of environmental sensitivity. Where conventional pumped storage sites are unavailable, utilities are considering new technologies such as underground pumped hydro and, as lately proven in a commercial application at Huntorf, West Germany, compressed air energy storage.

The particular study and preliminary designs dealt with in these reports cover concepts for compressed air energy storage (CAES) and underground pumped hydroelectric storage (UPH) facilities employing large-scale caverns and reservoirs excavated in hard rock.

BENEFITS OF ENERGY STORAGE

For utilities having sufficient coal and nuclear generating capability and presently using gas turbines and small oil-fired plants to meet peak power requirements, underground hydroelectric storage (UPH) or compressed air energy storage (CAES) can provide a means of reducing oil consumption. The potential oil savings are large enough that CAES concepts, which require supplemental oil-firing during power generation, can still provide significant system-wide economy in oil use.

Energy storage plants can improve the system's response to sudden load changes. System load change or tripout of a large generating unit or transmission link can be balanced by allowing energy storage plants either to absorb or generate power as required. The quick response characteristic provides improved system reliability. Energy storage plants can provide synchronous condenser service, spinning reserve, and can operate in a variety of standby roles.

ENERGY STORAGE ALTERNATIVES STUDIED

Until recently, the only proven technology available for large-scale energy storage was hydroelectric pumped storage. However, the difficulty of providing large man-made surface reservoirs has led to the development of the UPH and CAES concepts.

UPH, as presented in Figure 1-2, is basically similar to conventional pumped hydroelectric storage. In both cases, energy is stored by pumping water from a lower level to an upper reservoir. The stored energy is then returned to the power system when the water is allowed to flow back through the hydraulic turbine powering the generator. Use of an underground cavern excavated at depth for the lower reservoir allows a degree of freedom in selecting the operating head for pumping and generating. It usually offers the advantage of operation at a considerably higher head than otherwise possible with pumped storage plants relying on natural topography on the surface. The higher head allows a proportional reduction in the volume of storage reservoirs. Enhanced siting opportunities arise from the reduced environmental impact offered by location of facilities underground and by the reduced volume of water handled.

CAES, as presented in Figure 1-3, is basically a split Brayton or "gas turbine" cycle using an underground reservoir for storage of air compressed during periods of off-peak system load demand. Power is then generated during peak load periods by the released compressed air which is heated by oil or gas firing and then expanded through a combustion turbine. Like UPH, a CAES plant offers enhanced siting opportunities arising from the relatively compact site arrangement which can be attained.

While no UPH plant has yet been constructed, the hydraulic system involved is based on well proven designs, and there is little concern regarding the applicability of existing technology. A single 290 MW CAES plant has so far been constructed utilizing two caverns solution-mined in a salt dome for air storage. This plant has operated successfully for two years at Huntorf, West Germany, and has demonstrated the practicability of the technology involved.

CRITERIA FOR ENERGY STORAGE

Centralized energy storage employing UPH or CAES design concepts is worthy of consideration in electric utility system planning where the following criteria exist:

- A relatively low system load factor or large differential between minimum and maximum daily loads;
- Available coal-fired or nuclear base load pumping power;

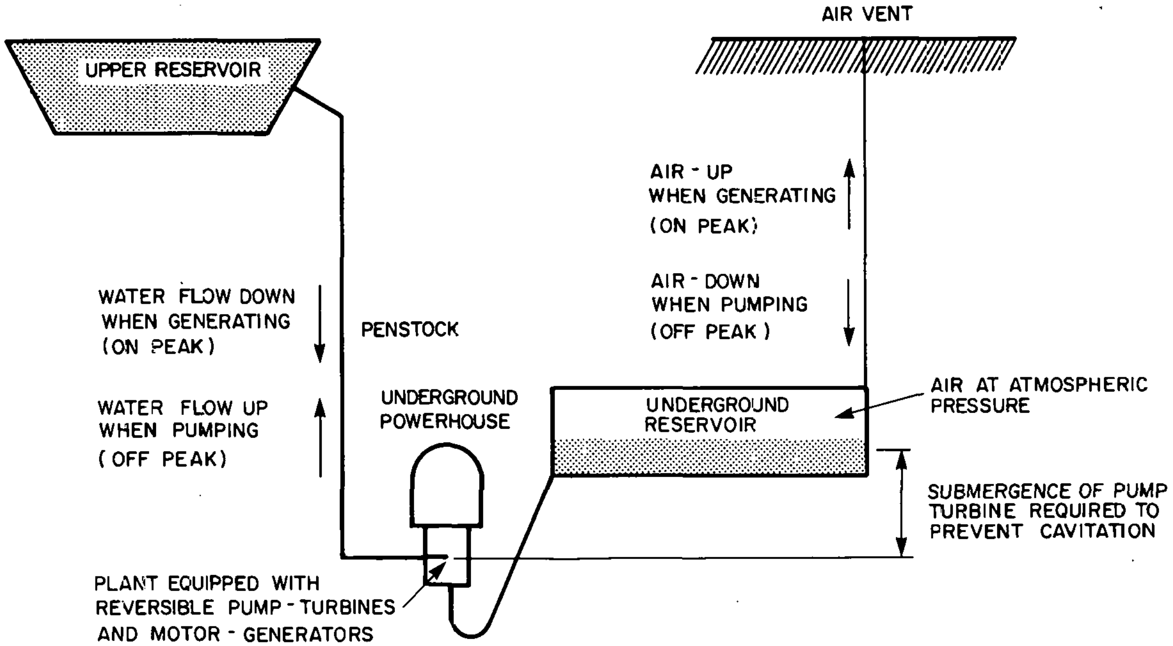

Figure 1-2 Underground Pumped Hydroelectric Storage System

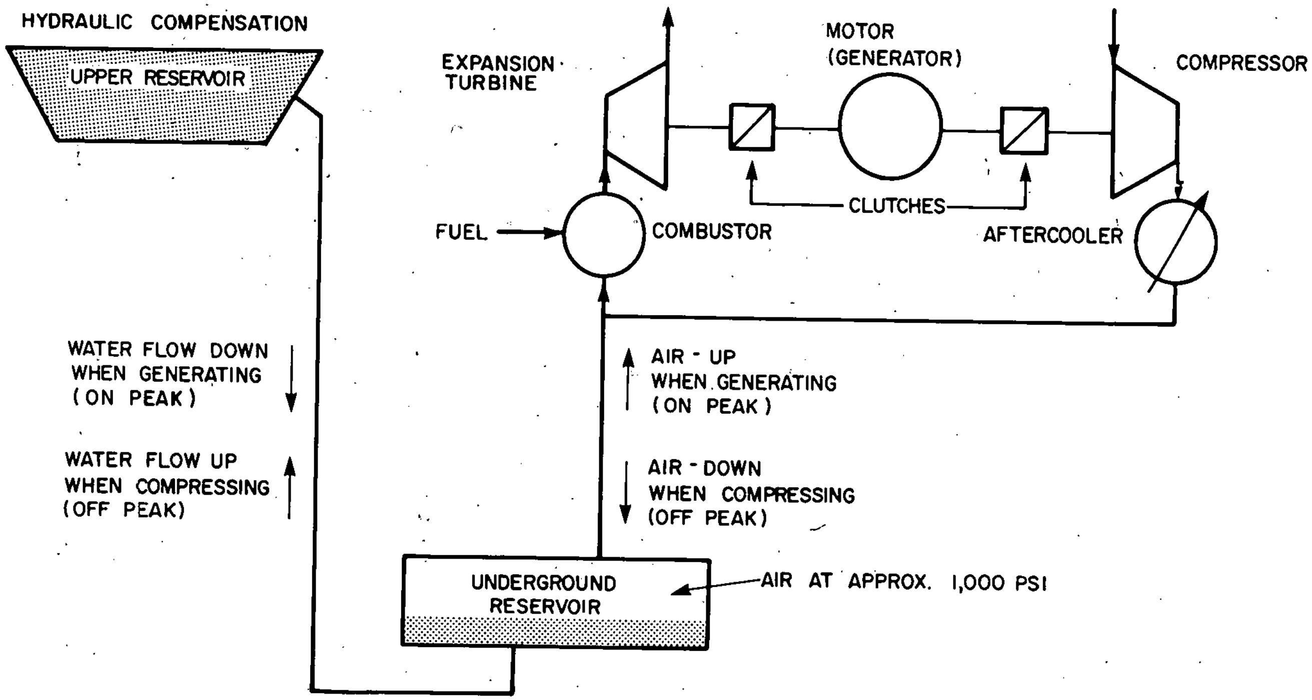

Figure 1-3 Compressed Air Energy Storage System

- A need for new generation due to load growth or retirement of old plants; and
- A site with an acceptable geologic formation at depth and reasonably close to major system transmission line routes.

These criteria apply in varying degrees to a number of electric utilities in the United States, including the Potomac Electric Power Company (PEPCO). Preliminary generation planning studies carried out by PEPCO have shown that 670 MW of energy storage installed in the 1990's could provide significant system economic benefits. A siting study of the PEPCO service area and surrounding regions has revealed suitable hard rock and a competent formation at depth for underground energy storage facilities.

ENERGY STORAGE IN SYSTEM PLANNING

While many factors directly affect utility need to add to present generating capability, the ultimate decision on what type of unit to add is based on necessity and economics.

When the requirement for power generation plant operation is less than a few hundred hours per year (i.e. low capacity factor), combustion turbines with their low capital costs appear attractive. At the other end of the capacity factor scale, coal plants appear most attractive when they can be used in excess of several thousands of hours per year.

From 500 to 3500 hours of operation per year at rated load (equivalent to capacity factors of 5 percent to 40 percent), energy storage plants and existing oil-fired cycling units appear to be the economic choice. The portion of this mid-range load which can be economically carried by an energy storage plant can be significant. In the case of the CAES and UPH plants covered in the study, capacity factors of approximately 21 percent and 16 percent respectively were predicted by the PEPCO system planning studies.

PURPOSE OF STUDY

In 1976, when the Energy Research and Development Administration (now DOE) and EPRI issued a request for proposals for the investigation of energy storage concepts, it was felt that the technology needed for UPH and CAES was not yet at a level at which any U.S. utility would make a commitment leading to construction without further study. The DOE/EPRI investigations were therefore structured to develop preliminary engineering designs to the degree which decisions could be made with confidence based on a detailed assessment of the following:

- Capital cost and overall licensing and construction schedules;
- Performance and operating characteristics;
- Environmental impact and licensing issues;
- Potential risks associated with UPH and CAES technologies; and
- Benefits accruing to the utility system.

EXECUTION OF THE STUDY

In late 1977, PEPCO, with Acres American Incorporated (AAI) as engineering consultant, began the detailed study of the CAES and UPH concepts based on underground caverns excavated in hard rock.

Several potential sites for either a CAES or an UPH plant were located near the PEPCO service area, with no one site showing a distinct technical advantage over the others. Based on several non-technical issues, including ease of access for preliminary investigations, a site near Sunshine, Maryland, was selected. While the results of the site investigation program were not conclusive in establishing the prime suitability of the site from a geotechnical viewpoint, reasonable confidence in its potential remains.

Both CAES and UPH were found to be feasible and to be economically attractive when applied to the PEPCO system. Application of either concept provides for a significant reduction in oil usage. No particular constraints were found regarding either CAES or UPH from an environmental and licensing point of view. It is believed that an exemption from the Fuel Use Act legislation based on the fuel mix provisions will permit oil burning in a CAES plant designed for the selected capacity factor.

The UPH plant configuration developed during the study was based on a capacity of 2000 MW with 10 hours of storage and on a two-step design, each involving 2500 ft head. The CAES plant would have a capacity of 1000 MW with 10 hours of storage with a No. 2 oil-fired turbine system. The difference in capacity selected arises from the economy/scale effect which has a more marked influence on the UPH plant. If PEPCO were to build an UPH facility a proportion of its capacity would be available for joint use on the Pennsylvania-New Jersey-Maryland (PJM) power pool system.

Direct capital costs in July 1979 dollars were estimated to be $375.5/kW for CAES and $415.7/kW for UPH. The times required from start of construction to commercial operation of the first unit were estimated to be 5 years and 8 years respectively. The licensing process would require 3 years and 9 months in both cases.

Section 2

SITE SELECTION

INTRODUCTION

The region considered in this study for the selection of potential sites for a CAES or UPH plant is shown on Figure 2-1. The northern boundary of the area extended well beyond PEPCO's 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 Provinces).

While the topographic features of a site are of primary importance for conventional pumped storage plants, they are of less concern for CAES and UPH. For CAES and UPH site selection, the presence of a suitable host rock formation in which to build caverns deep underground is of the utmost importance.

The site selection process was performed to choose a common site for the study of both UPH and CAES plants having an installed capacity of 1000 MW and energy storage for 10 hours at full generating output. The site selection was not repeated to evaluate the effects of a subsequent change which increased the capacity of the UPH facility to 2000 MW, and the chosen site remained the basis for the study of this alternative.

METHODOLOGY

The site selection process adopted for the study involved six distinct steps to allow a systematic selection of a hard rock site suitable for both CAES and UPH. The methodology presented in the Site Selection Flow Chart (Figure 2-2) utilized the site specific technical and environmental conditions that have the greatest impact on plant siting. The following primary activities were undertaken:

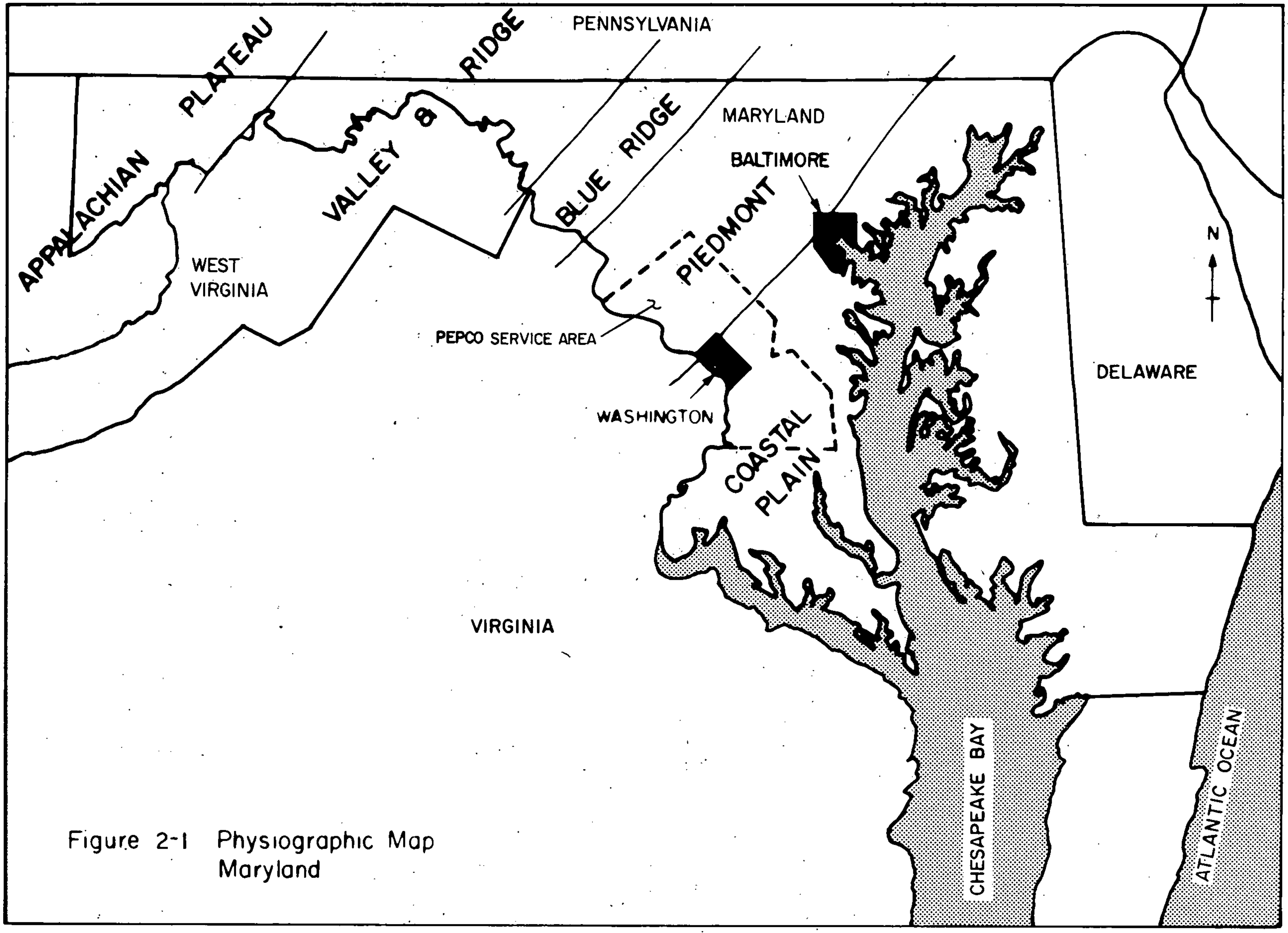

Figure 2-1 Physiographic Map
Maryland

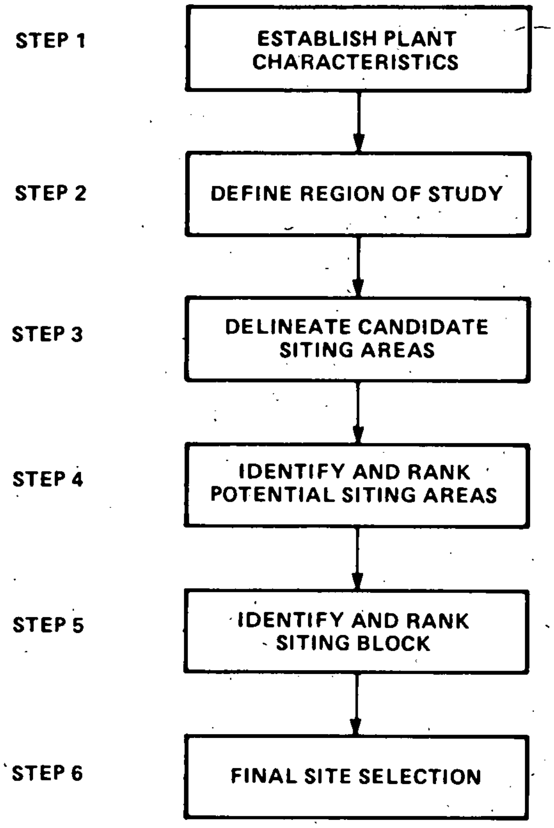

Figure 2-2 Site Selection Flow Chart

- Definition of the geologic, hydrologic, topographic, environmental and nontechnical factors influencing the siting and operation of a CAES or UPH facility;
- Development of technical, economic and environmental considerations involved in the siting of a CAES and UPH 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 UPH; and
- A comparative review and evaluation of potential sites based on a series of weighted factors as defined by the siting methodology and which 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 UPH facilities, as well as access for exploration.

The site selection process involved attributing cost penalty values to the following technical and physical property factors associated with specific siting blocks (i.e. zones capable of accommodating the proposed facilities) within the potential siting areas (i.e. regions in which several siting blocks were located):

- Topography;
- Site access roads;
- Property acquisition;
- Length of required water line for filling;
- Distance to transmission system interconnection; and
- Length of fuel pipeline (CAES only).

Environmental factors were also given substantial importance in the site selection process for energy storage facilities. While the location of much of the CAES and UPH facilities underground diminishes their environmental impact, it is essential that due consideration be given to:

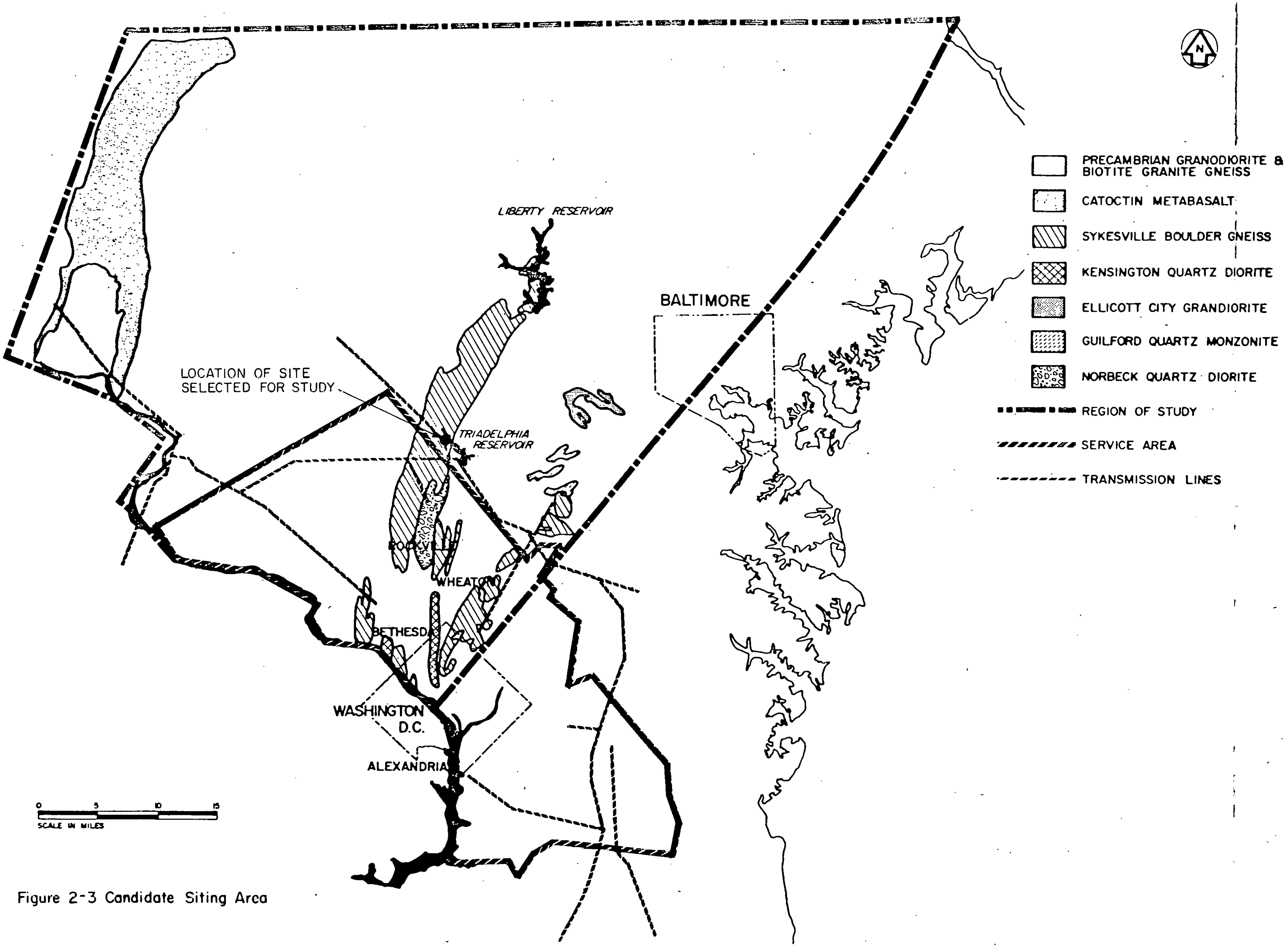

Figure 2-3 Candidate Siting Area

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- Terrestrial ecology;
- Aquatic ecology;
- Historical and archaeological sites;
- Existing and planned land uses;
- Visual aesthetics;
- Transportation access;
- Noise; and
- Meteorology and air quality.

RESULTS

A detailed review of all the rock units within the region of study was made and a total of seven rock units, shown on Figure 2-3, were identified as being candidate siting areas. A gross screening process was carried out and those candidate siting areas (or portions thereof) that were considered unacceptable for plant location because of environmental and/or socio-economic restraints were eliminated. Of the remaining areas, the four most preferred potential siting areas, all within the Sykesville Boulder Gneiss Formation, were identified and then further subdivided into a total of seven 250-acre siting blocks. All of these seven siting blocks were found to be both technically and environmentally acceptable for the construction and operation of a CAES or an UPH facility, with no one site showing distinct advantage over another.

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 miles north of Washington, D.C. and about 20 miles southwest of Baltimore, Maryland. The site is on the Sykesville Boulder Gneiss Formation and covers approximately 500 acres. It is bordered on the west by Route 97 and on the south by Route 650. It has moderate relief with elevations ranging from 510 ft MSL in the southwest to 375 ft MSL in the east and is crossed by a 500 kV transmission line owned by PEPCO.

Section 3

SITE INVESTIGATION

GENERAL

The site selected for the study is located in the Sykesville Boulder Gneiss Formation, a medium-grained, highly foliated, anisotropic gneiss which outcrops in several areas throughout the eastern Maryland Piedmont. Regional geologic interpretation in the vicinity of the site suggests that the Sykesville Formation is underlain by the Wissachickon Formation, a highly schistose and possibly weaker rock than the Sykesville. The Wissachickon Formation is probably unsuitable for construction of a CAES or UPH facility.

To determine the suitability of the site as a potential location for a CAES or UPH 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 for both CAES and UPH.

During the first part of the site investigation, geologic mapping was performed. Samples of the soil and rock were obtained and tested from ten boreholes sunk to a depth of 100 ft and from two boreholes sunk to a depth of 500 ft. 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.

SHALLOW DRILLING RESULTS

The investigation showed that the bedrock at the site is overlain by residual soils varying in thickness from 20 to 75 ft. These residual soils are in two zones. The upper zone, generally ranging from 5 to 15 ft in thickness, consists of a medium-grained, sandy silt and/or silty sand which grades into a lower zone of saprolitic soil, generally ranging from 5 to 75 ft in thickness and consisting of a totally decomposed granitic gneiss material. The lower soil zone forms a gradational contact with the underlying bedrock.

The upper 50 to 100 ft of bedrock is locally weathered and fractured. Below 100 ft the rock is of good-to-excellent quality. Unconfined rock strengths range between 10,800 to 12,000 psi. This relatively low strength is attributed to the rock's highly anisotropic strength characteristics introduced by the angular orientation of the foliation planes to the tested core. These measured strengths are considered to represent the lower strength bounds, however, since the angle of the foliation to the vertical core axis of the samples was in the critical range (30-50°).

The site groundwater table is a subdued replica of the surface topography with depths to the water table ranging from 30 to 50 ft in the higher elevations to near surface in the valley floors. Groundwater flows are generally restricted to the upper soil horizons and to open fractures and joints within the bedrock. Below the upper 100 ft of weathering, hydraulic conductivity ranges from 10^{-5} to 10^{-7} cm/s.

DEEP DRILLING RESULTS

The actual depth to the Sykesville/Wissachickon contact beneath the site is unknown. Therefore, 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 (approximately 5000 ft below ground surface for UPH and 2500 ft for CAES).

The results of the deep drilling program established the presence of rock at the required depth for CAES but did not establish the presence of suitable rock at the required depths for UPH.

However, no evidence has so far been found to suggest that the Sykesville Formation does not exist at the depth required for UPH. Three attempts were made to drill to a depth of 5000 ft. In all cases, due to the anisotropic nature of the rock, severe deviation of the drill hole resulting in excessive torque on the drill rods caused termination of drilling. A wide range of modern drilling techniques and equipment were employed in an attempt to maintain hole verticality without success. This limited the drilling program to a maximum hole drill length of 3274 ft where it was terminated at a 52° deviated angle from the vertical. Adjusting for hole deviation, the total maximum vertical depth drilled was 2556 ft.

From the cores taken, the rock quality was found to be high. Most fractures in the core fell into two categories: smooth, planar, clean fractures along the foliation; and slightly rough, irregular planes across the foliation (often rehealed). The temperature at the bottom of the hole (2556 ft vertical distance) was measured as 73°F, giving a thermal gradient of approximately 1°F/100 ft. Permeability tests, using the water injection method, were performed using both a single and double packer test zone. Analysis of the test data shows the average hydraulic conductivity to be acceptable for CAES, with values of less than 10^{-7} cm/s even in the more highly fractured zones.

In situ stress determinations were made in three test zones in the borehole by the hydrofracturing method. The results of the testing showed that, at depths below 1300 ft, the maximum and minimum horizontal stresses were greater than the overburden stress and increased with depth. Calculations showed the maximum stress to be oriented in a NW-SE direction (consistent with other available geologic evidence), and this was then used as the basis for subsequent cavern designs.

Section 4

SYSTEM PLANNING STUDIES

GENERAL

With the identification of suitable sites for an energy storage facility within or near the PEPCO service area, it was necessary to determine the contribution to the PEPCO electrical power system which could usefully be made by an energy storage facility. A review of PEPCO's typical summer daily load profiles (Figure 4-1) indicated that energy storage could be a beneficial addition to the system. PEPCO's service area, primarily the Washington, D.C. metropolitan area, is characterized by a low annual system load factor (47 percent in 1979) reflecting the daytime energy consumption by governmental and commercial offices and the lack of second- and third-shift industry. Although the PEPCO system does not include any nuclear plants, the utility has a relatively large coal-fired base load generating capacity.

Previous studies indicated that PEPCO should consider energy storage as a part of its future expansion plans. To evaluate and quantify the benefits associated with CAES and UPH, a detailed system planning analysis was performed by PEPCO as part of this study to determine:

- When additional capacity would be required by PEPCO's load growth;
- To what extent energy storage can supply the system's needs; and
- Whether energy storage would be an economic plant type for PEPCO.

METHODOLOGY

A primary criterion applied by utilities for evaluating alternative generation plans is the minimization of the total cost of power generation. PEPCO evaluates capital project alternatives on the basis of the cumulative present worth of the minimum annual revenue requirements (CPWMRR) over the life of the project. To determine this, a probabilistic production costing computer program (PROMOD) is used in conjunction with a program for economic evaluation (ECON).

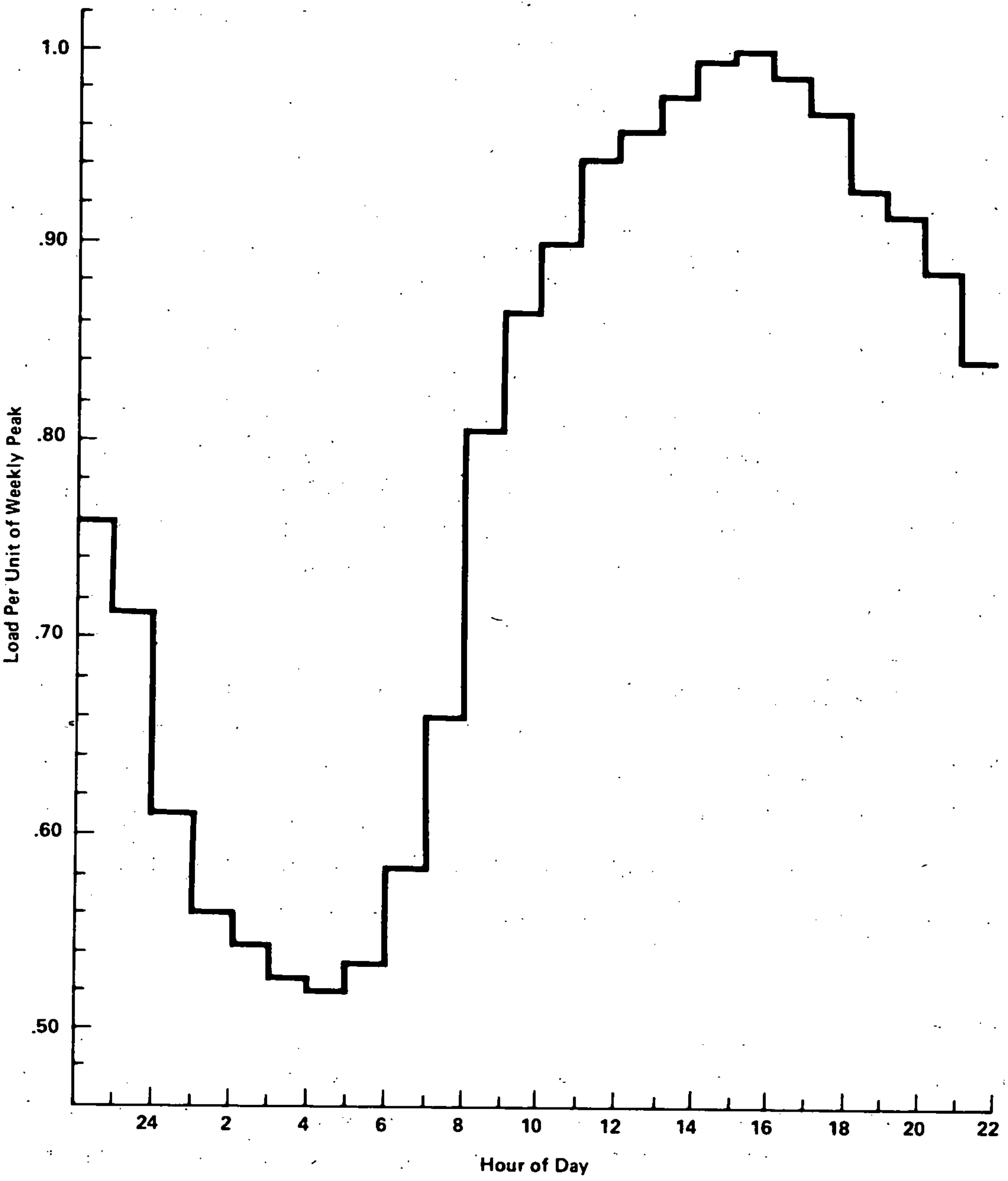

Figure 4-1 Summer Daily Load Shape
(1988 - 2006)

System load growth projections made in late 1978, indicating that PEPCO's peak demand will be approximately 4000 MW in 1980 and will grow to 6500 MW in 2008, were used as the study basis for developing alternative expansion plans. These utilized:

- Coal-fired and nuclear plant additions to the base load capacity; and
- Combustion turbines, UPH or CAES to provide peaking power.

No requirements were identified for any additional mid-range fossil-fueled plants beyond those presently included in the PEPCO system or in construction.

Operating costs were based upon presently contracted and projected fuel prices, with several price escalation rates used to determine the sensitivity of the results to fuel costs. The sensitivity of the CPWMRR was also investigated for changes in capital cost, unit forced outage rates, cost of capital and cycle efficiency. The basic plant input data and the range of parameters considered are shown on Tables 4-1 and 4-2.

RESULTS

The results of the analysis as presented on Tables 4-3 and 4-4 indicate that both CAES and UPH provide a means for PEPCO to meet its future needs for electric generating capacity with significant savings in both required revenues and oil consumption compared with the use of equivalent capacity combustion turbines. The most economic approach for both CAES and UPH involves ten hours of storage with a total PEPCO-owned generating capacity of approximately 675 MW, with three equal increments coming into operation sequentially in 1990, 1993 and 1995. It was assumed for this study that each UPH increment would be 666 MW with the PEPCO share approximately 1/3 of each.

The most favorable CAES-based expansion plan reduced the present worth of future revenue requirements by $1,358,000,000 from that of the most favorable combustion turbine based expansion plan. The comparable revenue saving for UPH was $1,246,000,000.

The reduction of oil consumption in the PEPCO system due to energy storage was significant and nearly equal for both CAES and UPH. CAES was projected to save 19 million barrels over the period 1990 through 2007, in spite of the oil

Table 4-1

PLANT INPUT DATA

Parameter	CAES	UPH	CT
Variable O&M Costs	0.25 mill/kWh (1980$)	0.16 mill/kWh (1980$)	$100/hr (1980$)
Fixed O&M Costs	$3.75/kW-yr (1980$)	$39.25/kW-yr (1980$)	$7,200/yr (1980$)
Turnaround efficiency, $\frac{\text{kWh output}}{\text{kWh input}}$	---	0.72	---
Electric Energy Ratio $\frac{\text{kWh input}}{\text{kWh output}}$	0.75	---	---
Fuel Heat Rate	4250 Btu/kWh	---	12,800 Btu/kWh
Storage Energy	10-hour x Inst. Cap.	10-hours x Inst. Cap.	---
Generation Output, MW/unit	225	333/666*	50
Planned Outage Rate	2 wk/yr	4 wk/yr	2 wk/yr
Forced Outage Rate	10%	4%**	16%

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* Two-step system, two 333 MW units operating in series.
** Combined outage rate for two units in series operation.

Table 4-2

RANGE OF PARAMETERS
FOR SENSITIVITY ANALYSIS

Parameter	Range
Storage Capacity	5 to 13 hours
Capital Cost	Base Est. to 1.1 x Base Est.
Minimum Acceptable Return	10.78% to 12.5%
Fuel Cost Escalation, Coal	7% to 9%
Fuel Cost Escalation, No. 2 Oil	9% to 11%
Forced Outage Rate, UPH	4% to 8%
Forced Outage Rate, CAES	10% to 20%
UPH Cycle Efficiency	68% to 72%

Table 4-3

EVALUATION OF ALTERNATIVES BASED ON CUMULATIVE PRESENT WORTH OF MINIMUM REVENUE REQUIREMENTS (CPWMRR)

PLAN NAME	DESCRIPTION[2]	CPWMRR[1] (\$ x 10^6)	INCREASE OVER CAES 31
CAES 31	225 MW - 1990, 1993, 1995	15,003	0
UPH 5	222 MW - 1990, 1993, 223 MW - 1995	15,115	112
UPH 6	444 MW - 1990, 223 MW - 1995	15,116	113
UPH 7	223 MW - 1990, 444 MW - 1993	15,116	113
CAES 34	225 MW - 1990, 1993, 1999	16,058	1,055
UPH 8	333 MW - 1990, 1994, 334 MW - 2001	16,247	1,244
UPH 9	666 MW - 1990, 334 MW - 2001	16,249	1,246
CT 21	300 MW - 1990, 1994	16,361	1,358
CAES 41	450 MW - 1990, 1995	16,377	1,374
CAES 42	225 MW - 1990, 1993, 1995, 1998	16,387	1,384
UPH 2	666 MW - 1990, 334 MW - 1997	16,428	1,425
UPH 1	333 MW - 1990, 1994, 334 MW - 1997	16,433	1,430
UPH 3	334 MW - 1990, 666 MW - 1994	16,458	1,455
CT 31	300 MW - 1990, 1994, 1997	16,843	1,840
UPH 10	334 MW - 1990, 666 MW - 1998	17,688	2,685
CAES 43	225 MW - 1990, 1993, 1999, 2002	17,699	2,696
CAES 56	225 MW - 1990, 1993, 1995, 2002, 2004	18,033	3,030
CT 42	300 MW - 1990, 1994, 2001	18,117	3,114
CAES 51	225 MW - 1990, 1993, 1995, 1998, 2000	18,120	3,117
CT 41	300 MW - 1990, 1994, 1997, 2000	18,552	3,549
CT 43	300 MW - 1990, 1994, 2001, 2004	19,868	4,865
UPH 4	444 MW - 1990, 1995, 445 MW - 2000	23,565	8,562

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[1] Cumulative present worth of minimum revenue requirements in millions of 1980 dollars.

[2] All energy storage alternatives include 10 hours of storage.

Table 4-4

COMPARISON OF PEPCO SYSTEM FUEL AND ENERGY STORAGE PLANT USAGE

	COAL, 10^3 TONS			NO. 6 OIL, 10^3 BBL			NO. 2 OIL, 10^3 BBL			ENERGY STORAGE GENERATION, GWH		ENERGY STORAGE CAPACITY FACTOR, %	
Year	CAES 31	UPH 5	CT21	CAES 31	UPH 5	CT 21	CAES 31	UPH 5	CT 21	CAES 31	UPH 5	CAES 31	UPH 5
1990	6,825	6,863	6,647	5,349	5,580	6,190	1,143	1,171	1,461	466	373	23.6	19.2
1991	6,684	6,805	6,614	6,697	6,511	6,941	1,296	1,262	1,546	470	353	23.9	18.2
1992	6,886	6,934	6,726	6,419	6,546	7,199	1,289	1,315	1,582	473	357	24.0	18.4
1993	6,887	7,094	6,756	7,163	6,958	7,734	1,294	1,291	1,691	808	673	20.5	17.3
1994	7,036	7,124	6,752	6,959	7,339	8,230	1,498	1,439	2,035	832	586	21.1	15.1
1995	7,086	7,232	6,935	7,613	7,778	8,108	1,409	1,494	2,073	1,129	806	19.1	13.8
1996	7,260	7,386	7,018	7,476	7,868	8,409	1,566	1,554	2,258	1,163	867	19.7	14.8
1997	7,251	7,297	7,467	8,228	8,797	7,306	1,732	1,876	2,088	1,129	673	19.1	11.5
1998	7,775	7,973	7,609	6,728	6,750	7,372	1,554	1,650	2,155	1,156	893	19.6	15.3
1999	7,860	7,925	7,810	7,063	7,737	7,297	1,792	1,793	2,224	1,222	831	20.7	14.2
2000	8,075	8,198	7,763	6,720	7,170	8,049	1,887	2,035	2,596	1,194	862	20.2	14.8
2001	8,268	7,580	7,282	6,782	5,341	5,791	1,804	1,358	1,800	1,297	975	21.9	16.7
2002	7,529	7,664	7,380	5,353	5,856	6,675	1,435	1,408	1,951	1,177	973	19.9	16.7
2003	7,601	7,555	7,312	5,796	5,183	6,136	1,705	1,521	1,952	1,237	904	20.9	15.5
2004	7,562	7,755	7,631	4,931	5,151	6,411	1,616	1,537	2,057	1,123	961	19.0	16.4
2005	7,612	7,754	7,512	5,603	6,021	6,878	1,738	1,715	2,197	1,238	948	20.9	16.2
2006	7,698	7,724	7,816	5,937	6,778	5,754	1,957	1,997	2,156	1,165	929	19.7	15.9
2007	8,135	8,521	8,213	5,046	6,032	6,609	1,756	1,876	2,255	1,140	959	19.3	16.4

requirement for CAES during power generation. This is a result of the higher capacity factor obtained for CAES. UPH was projected to save 16 million over the same period. Oil savings for both types of plants are expected to continue at a rate of 2 million barrels per year thereafter.

The foregoing results reflect only the benefits obtained directly from the PEPCO system. With operation of the CAES and UPH plants as part of the Pennsylvania-Jersey-Maryland (PJM) system:

- The energy output obtained from both systems increases, with UPH showing a more significant increase from 75 percent of the CAES output for service to the PEPCO system alone to 91 percent of the CAES output on the PJM system; and
- Both systems are cost effective.

CONCLUSIONS

The analyses indicate that either UPH or CAES can provide significant benefits to the operation of the PEPCO system. Both produce reductions in revenue requirements; both provide savings of oil-based fuels and allow increased utilization of coal-fired (and nuclear) capacity; and both serve substantial portions of PEPCO's peak energy needs.

Improved operating schedules and reduced maintenance due to reduced thermal cycling of base load plants were not evaluated as part of this analysis, but are expected to provide added benefits arising from the installation of energy storage facilities.

Section 5

ENVIRONMENTAL ISSUES

GENERAL

A careful assessment of environmental issues which could arise from the construction and operation of UPH or CAES facilities on the site near the rural community of Sunshine in Montgomery County, Maryland, was made during this study.

The approach adopted in the environmental assessment included a characterization of the existing environment with emphasis on potentially sensitive areas, i.e., those components which are considered unique, vulnerable or valuable. Consideration was then focused on those elements of the existing environment which would have an impact on the proposed facilities or which would adversely interact with them. This was followed by an assessment of environmental and public safety concerns arising from the proposed facilities.

RESULTS

Features of the facilities and elements of the environment which have been reviewed are summarized in Table 5-1 for UPH and in Table 5-2 for CAES. Comprehensive tabulations of the nature of environmental impacts have been compiled, and those which have significance have been identified.

In the case of UPH, the impacts judged to be significant were the alteration or loss of prime farmland and farmland of statewide importance, changes in the existing land use, conflict with present surrounding land use, and changes in the existing and planned zoning.

In the category of impacts arising from accidental events, the highly unlikely release of water from the facility reservoirs into the Triadelphia Reservoir was judged to be of high significance but amenable to reduction in risk by appropriate design.

TABLE 5-1

POTENTIAL INTERACTION BETWEEN THE UPH FACILITY AND ELEMENTS OF THE ENVIRONMENT

UPH Facility Elements Associated Actions[a]	Elements of the Environment																													
	Meteorology	Air Quality	Noise and Vibration	Topography	Active Geomorphic Processes	Soil	Geology	Energy & Mineral Resources	Geologic Areas of Special Interest	Drainage & Surface Water Bodies	Surface Water Availability	Surface Water Quality	Surface Water Use	Aquifers	Groundwater Availability	Groundwater Quality	Groundwater Use	Terrestrial Vegetation	Terrestrial Wildlife	Special Status Terrestrial Species	Aquatic Fauna	Aquatic Habitats	Special Status Aquatic Species	Economy	Demography	Infrastructure	Land Use	Aesthetics	Cultural	Social
CONSTRUCTION		●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
SITE DEVELOPMENT		●	●	●	●	●	●			●	●	●		●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
Clearing, Grading, Near Surface Excavation, Building Structures, Lay Down, Constructing Roads, etc.		●	●	●	●	●	●			●	●	●		●	●	●	●	●	●		●	●					●	●	●	
Excavation of Shafts and Underground Cavern		●	●				●							●	●	●	●													
Disposal of Excavated Rock in Reservoir Dike and Stock Piles		●	●	●		●					●	●		●	●	●		●	●		●	●					●	●		
Lining Reservoir with Asphalt		●	●																											
Ventilating Exhaust from Cavern		●	●																											
Discharge of Runoff					●	●						●									●	●								
Use of Workers																								●	●	●				●
SITE ACCESSIBILITY			●																							●				
Road Transportation of Personnel, Material, Equipment, and Services			●																							●				
OPERATION	●		●	●		●	●			●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
HEAVY HOIST			●																											
Hoist Operation			●																											
UPPER RESERVOIR (Surface)	●				●	●				●	●	●	●			●		●	●		●	●		●		●	●	●		●
Impoundment of Heated Surface Water										●									●											
Evaporation and Fogging	●																											●		
Icing Resulting From Fogging	●																	●								●		●		
Discharge of Heat	●																													
Initial Use of Surface Water to Fill											●		●																	
Intake of Water From Triadelphia Reservoir																					●	●								
Normal Daily Use of Surface Water											●		●																	
Impounding Water in Auxiliary Reservoir										●									●											
Leakage																●														
Dike Failure and Resulting Flooding (accident)[b]					●	●						●	●					●	●		●	●		●			●			
POWER FACILITIES			●																											
Switchyard Operations			●																											
LOWER RESERVOIR (Underground)				●	●	●	●			●	●		●	●	●	●	●	●	●					●			●	●	●	●
Existence of Cavern							●																							
Major Cavern Collapse and Subsidence (accident)[b]				●	●	●	●			●	●		●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
Water Leakage														●	●	●	●													
SHAFTS							●							●	●	●	●													
Existence of Shafts							●							●	●	●	●													
OTHER OPERATION			●			●	●					●	●			●	●	●	●		●	●		●	●	●				●
Use of Workers																								●	●	●				
Flow of Water to Lower Reservoir Through Penstock			●				●																							
Discharge of Runoff During Operation												●									●	●								
Treatment of Waste Water Effluent			●																											
Disposal of Solid Refuse and Sludges Off-Site																														
Malfunction and Discharge of Untreated Waste Water (accident)[b]						●					●	●	●			●	●	●	●		●	●								
SITE STRUCTURES AND ARRANGEMENT				●		●				●	●				●			●	●		●	●					●	●	●	●
Existence of Upper Reservoir				●		●				●	●				●			●	●		●	●					●	●		
Existence of Site Roadway System				●		●				●	●				●			●	●		●	●					●	●		
Security Fencing						●																					●	●		
Existence of Rock Stockpiles				●		●				●	●				●			●	●								●	●		
Existence of Heavy Hoist Headframe Building						●					●				●			●	●								●	●		
Existence of Other Buildings						●					●				●			●	●								●	●		
SITE ACCESSIBILITY			●																							●				
Road Transportation of Personnel and Services			●																							●				

[a] Only those actions with potential environmental interaction are listed

[b] Very unlikely accident

● Indicates potential interaction

TABLE 5-2

POTENTIAL INTERACTION BETWEEN THE CAES FACILITY AND ELEMENTS OF THE ENVIRONMENT

	Elements of the Environment																													
CAES Facility Elements Associated Actions[a]	Meteorology	Air Quality	Noise and Vibration	Topography	Active Geomorphic Processes	Soil	Geology	Energy & Mineral Resources	Geologic Areas of Special Interest	Drainage & Surface Water Bodies	Surface Water Availability	Surface Water Quality	Surface Water Use	Aquifers	Groundwater Availability	Groundwater Quality	Groundwater Use	Terrestrial Vegetation	Terrestrial Wildlife	Special Status Terrestrial Species	Aquatic Fauna	Aquatic Habitats	Special Status Aquatic Species	Economy	Demography	Infrastructure	Land Use	Aesthetics	Cultural	Social
CONSTRUCTION		●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
SITE DEVELOPMENT		●	●	●	●	●	●			●	●	●		●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
Clearing, Grading, Near Surface Excavation, Building Structures, Laydown and Constructing Roads, etc.		●	●	●	●	●	●			●	●	●		●	●	●	●	●	●		●	●					●	●	●	
Excavation of Shafts and Underground Cavern		●	●				●							●	●	●	●													
Disposal of Excavated Rock in Reservoir Dike		●	●	●		●					●	●		●	●	●		●	●		●	●					●	●		
Lining Reservoir Dike with Asphalt		●	●																											
Ventilating Exhaust for Cavern		●	●																											
Discharge of Runoff					●	●						●									●	●								
Filling of Compensating Reservoir and Impoundment											●		●																	
Use of Workers																								●	●	●				●
SITE ACCESSIBILITY		●	●	●	●	●	●			●	●	●			●	●		●	●		●	●				●	●	●	●	●
Road Transportation of Personnel, Material, Equipment, & Services to Site			●																											
Fuel Oil Delivery by Pipeline		●	●	●	●	●	●			●	●	●			●	●		●	●		●	●					●	●	●	●
OPERATION	●	●	●	●	●	●	●			●	●	●	●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
FUEL SYSTEM		●	●			●						●	●			●	●	●	●		●	●								
Fuel Oil Delivery (see SITE ACCESSIBILITY)																														
Fuel Oil Unloading and Storage		●																												
Fuel Oil Treatment and Transferring by Pumping			●																											
High Pressure Fuel Oil Boost Pumping			●																											
Use of ASTM No. 2 Fuel Oil		●																												
Abnormally Large Spills (accident)[b]						●						●	●			●	●	●	●		●	●								
See WATER TREATMENT SYSTEM for Disposal of Waste & Normal Spills																														
SAFETY AND FIRE PROTECTION																										●				
Large Facility Fire (accident)[b]																										●				
HIGH PRESSURE RECUPERATOR																														
TURBINE-MOTOR/GENERATOR SYSTEM		●	●																									●	●	
Fuel Combustion																														
Turbine Operation			●																									●	●	
Motor Operation			●																									●	●	
Generator Operation			●																									●	●	
Exhaust		●	●																									●	●	
COMPRESSOR			●																									●	●	
Compress Air (Compressor Air Inlet System Operation)			●																									●	●	
INTERCOOLERS/AFTER COOLER & MOISTURE SEPARATORS	●		●																									●	●	
Removes and Discharges Heat	●																													
Air Cooling Tower Fan Operation			●																									●	●	
PLANT POWER SYSTEM			●																									●	●	
Operation of Generator Setup Transformer			●																									●	●	
WATER SUPPLY SYSTEM											●		●		●	●	●				●	●								
Initial Fill of Compensating Reservoir and Impoundment											●		●																	
Normal Daily Use of Surface Water											●		●																	
Normal Daily Use of Groundwater															●		●													
Leakage															●	●	●													
Triadedelphia Reservoir Intake Operation																					●	●								
WASTE TREATMENT SYSTEM			●								●	●	●		●	●	●	●	●		●	●								
Disposal of Sanitary Wastes by On-Site Septic System																●														
Disposal of Solid Refuse and Sludges Off-Site																														
Treatment of Waste Water Effluent			●																											
Discharge of Treated Waste Water to On-Site Stream											●	●	●																	
Malfunction and Discharge of Untreated Waste Water (accident)[b]											●	●	●		●	●	●	●	●		●	●								

[a] Only those actions with potential environmental interaction are listed

[b] Very unlikely accident

● Indicates potential interaction

TABLE 5-2

POTENTIAL INTERACTION BETWEEN THE CAES FACILITY AND ELEMENTS OF THE ENVIRONMENT (Continued)

CAES Facility Elements Associated Actions[a]	Elements of the Environment																													
	Meteorology	Air Quality	Noise and Vibration	Topography	Active Geomorphic Processes	Soil	Geology	Energy & Mineral Resources	Geologic Areas of Special Interest	Drainage & Surface Water Bodies	Surface Water Availability	Surface Water Quality	Surface Water Use	Aquifers	Groundwater Availability	Groundwater Quality	Groundwater Use	Terrestrial Vegetation	Terrestrial Wildlife	Special Status Terrestrial Species	Aquatic Fauna	Aquatic Habitats	Special Status Aquatic Species	Economy	Demography	Infrastructure	Land Use	Aesthetics	Cultural	Social
SURFACE RESERVOIR (Compensating Reservoir, see also WATER SUPPLY SYSTEM)	●				●	●				●		●	●			●		●	●		●	●		●		●	●	●		
Impounding Heated Surface Water										●									●											
Evaporating & Fogging	●																											●		
Icing Resulting From Fogging	●																	●								●		●		
Discharge of Heat	●																													
Leakage																●														
Dike Failure and Resulting Flooding (accident)[b]					●	●						●	●					●	●		●	●		●			●			
AIR AND WATER SHAFT							●							●	●	●	●													
Existence of Shaft Cavity							●							●	●	●	●													
UNDERGROUND CAVERN				●	●	●	●			●	●		●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
Existence of Cavern							●																							
Air Leakage						●								●	●		●	●									●			
Major Cavern Collapse and Subsidence (accident)[b]				●	●	●	●			●	●		●	●	●	●	●	●	●		●	●		●	●	●	●	●	●	●
PIPING SYSTEM																														
MISCELLANEOUS PLANT SERVICES																														
SWITCHYARD			●																											
Switchyard Operation			●																											
SITE STRUCTURES AND ARRANGEMENT				●		●				●	●				●			●	●		●	●					●	●		
Existence of Turbo Machinery and Auxiliary Buildings and Other Structures						●				●	●				●			●	●								●	●		
Existence of Surface Reservoirs (Compensating and Impoundment)				●		●				●	●				●			●	●								●	●		
Existence of Site Roadway System				●		●				●	●				●			●	●		●	●					●	●		
Security Fencing						●																					●	●		
OTHER OPERATIONS			●																					●	●	●				
Use of Workers																								●	●	●				
Champagne Effect (accident)[b]			●																											
SITE ACCESSIBILITY			●																							●				
Road Transportation of Personnel and Services			●																							●				

[a] Only those actions with potential environmental interaction are listed

[b] Very unlikely accident

● Indicates potential interaction

These impacts were also judged to be significant for CAES facilities. Some additional issues and elements were evident for CAES systems; they included the potential decrease in air quality arising from turbine exhaust NO_x emissions and an increase in ambient noise levels from compressor air inlet and cooling tower plant during operation.

In regard to cultural and historic resources, it has been noted that two structures listed in the Locational Atlas and Index of Historic Sites published by the Maryland National Park and Planning Commission are located within the boundaries of the site at Sunshine. These buildings will require evaluation by the Planning Board to determine their suitabilty for inclusion in the historic preservation master plan. Issue of a demolition or alteration permit could involve a time delay while the historical value of the structure is ascertained.

Because the site is adjacent to the Triadelphia Reservoir, the plant's impact on a variety of public recreational features nearby must be considered. The Patuxent River, because of its scenic, recreational, and related resources, has been designated a State Wild and Scenic River. This designation covers the river and all of its tributaries but does not preclude construction of the planned UPH or CAES facilities.

Two series of environmental impacts specifically associated with UPH and, to a lesser extent because of smaller size, with CAES facilities are those pertaining to the removal, stockpiling and the possible later handling and transportation of large volumes of excavated rock, and those arising from somewhat elevated temperatures of the water in the surface reservoirs. Special measures will reduce the aesthetic impact of stockpiled rock, which will be limited to 40 to 85 ft above existing land surface with provisions for landscaping and run-off control. Fogging at the water-air interface, due to higher-than-ambient water temperatures which may be expected during about one-third of the winter mornings, is expected to have only a limited impact on traffic movement and other activities in the site area.

Safety assessments identified safety hazards to the public in the vicinity of the site. The consequences of potential hazards were examined using published data, assessed in some cases by comparison with existing and similar facilities elsewhere. These assessments identified features that represented potential new and unusual risks and demonstrated that similar or greater risks associated with other industrial or governmental facilities or natural features are commonly accepted by the public. For UPH and CAES, the safety concerns addressed included underground cavern collapse and surface subsidence, site security, upper reservoir failure and mechanical failure of plant equipment.

Precautions applying to operational procedures and design have been proposed which reduce the risk of accidents during plant operation to acceptable levels. Natural effects such as earthquakes, faulting, probable maximum flood and severe weather phenomena have been reviewed in relation to possible impact on the proposed energy storage facilites. All impacts can be mitigated by design provisions to acceptable levels.

CONCLUSIONS

The environmental study has provided useful information relevant to the preliminary design of both UPH and CAES plants. In general, the proposed facilities do not present any singular environmental impact that cannot be at least partially mitigated. No impacts were identified that were significantly more severe than industrial development of any land area of comparable size.

Section 6

LICENSING ISSUES

PRIMARY JURISDICTIONAL AGENCIES

Development of either a CAES or UPH plant at the Sunshine, Maryland site which was selected for this study would require numerous regulatory approvals by agencies of the Federal government, the State of Maryland and Montgomery County. As indicated on Figure 6-1, virtually all aspects of the project are subject to governmental review, including the overall need for the plant, its economic justification and those areas affecting the environment, safety, water use, land use, fuel use, building design and overall project feasibility. This analysis documents the conditions as of early 1980. Since the regulatory process is dynamic, it has already experienced moderate changes and will undoubtedly continue to do so.

The most critical of the approvals for both UPH and CAES is likely to be the Certificate of Public Convenience and Necessity, issued by the Maryland Public Service Commission (PSC). The process of issue of this certificate has been set up by Maryland law as the primary vehicle for power plant siting approval. It is a comprehensive procedure which includes input from the involved state agencies regarding electric power need, air quality, land use, socioeconomics and other considerations to determine the suitability of the plant and requires a two-year period from submittal of the application to certification. Most of the major licensing issues surrounding the project, including that of establishing need and those of siting considerations, would be addressed under this regulatory process.

Other permits required by the State of Maryland would include its National Pollution Discharge Elimination System (NPDES) permit, a waterways or dam construction permit, water quality and other minor operating permits.

At the Federal level, both UPH and CAES plants would be subject to the U.S. Army Corps of Engineers' dredge and fill permitting process. The CAES plant would require a fuel mixture exemption from prohibitions under the Fuel Use Act, which is administered by the DOE, and also air quality impact approval from the Environmental Protection Agency (EPA). The UPH plant is expected to be subject to the Federal Energy Regulatory Commission (FERC) hydropower licensing process, which would be the major Federal action governing the project. Since a substantial proportion of the facility, including the lower reservoir, is underground and development is not dependent on the alteration of any natural water course, it is anticipated that this process will incur fewer problems than arise with conventional hydroelectric pumped storage projects.

At the county level, both projects would be subject to sediment control plan approval, well/septic systems permitting and the building permit process. Montgomery County officials would be expected to participate in the PSC certification process since land use issues will be addressed in that forum.

MAJOR ISSUES

The major issues surrounding regulatory approval of the projects are expected to lie primarily within the state level of interest. The Federal level of regulation covers issues of a specific nature, none of which appears to be critical in that it would require excessive policy consideration or intervention by outside interests during permit processing. An exception is the FERC licensing requirement for UPH, which is a Federal authorization relating to water power development on navigable streams and interstate commerce. The Federal processing periods, including preparation of an environmental impact statement, are expected to be shorter than the two-year PSC certification process, assuming no adversary intervention which would delay the process.

Major issues which will be addressed at the state and local regulatory level are primarily related to siting concerns and the demonstration of need for both the capacity and type of generation. Based upon the enviromental assessment performed in this study, the qualitative impacts on current land use of either the CAES or UPH plants will be important considerations.

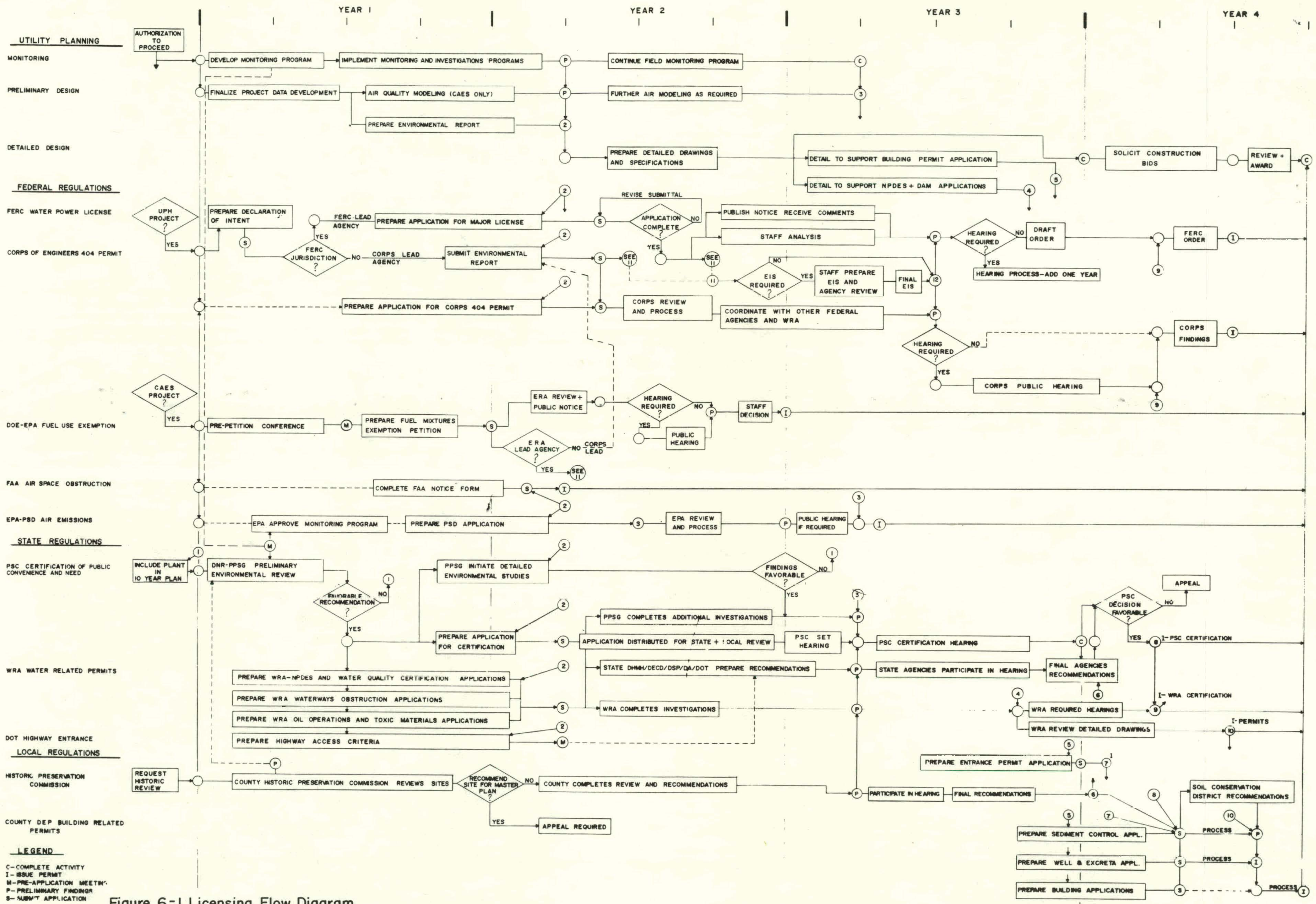

Figure 6-1 Licensing Flow Diagram

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The existing zoning ordinances, the state scenic river system, prime farmland, plant aesthetics and construction disturbance are possible elements of conflict which will have to be considered by the PSC in light of the mitigating measures proposed and of demonstrated plant benefits prior to issuance of the certification.

A specific issue is the existence of two potential historic sites within the project area. These sites are listed in a locational atlas of sites and would require a negative determination of historic significance by the County Historic Preservation Commission prior to site development. Should the structures be found in fact to have significance, the project could be delayed while the County Council takes action on alternative methods of preserving the historic values.

ASSESSMENT OF SIGNIFICANCE OF REGULATORY PROCESS ON SCHEDULE

Many of the regulatory processes involved are affected by changes in regulations or in organization within the administrative agencies. This study has concluded however that, based on the current requirements, the expected licensing period for either the UPH or CAES plants will be three years and nine months. This includes more than one year of pre-application preparation and submittal of application so that processing will occur in parallel as far as possible. This schedule could, however, be extended by intervention of outside parties with interest in the project. However, although there are issues of concern at this time, no insurmountable obstacles to ultimate regulatory approval are anticipated; in comparison to other generating plant alternatives to meet peaking need, both UPH and CAES have a lower environmental impact and should be viewed favorably by regulatory authorities.

Section 7

CAES PLANT DESIGN

GENERAL

The CAES plant design developed during the study presents a detailed response to the specific requirements imposed by PEPCO system needs and the features of the selected site, including such items as:

- A generating capacity of approximately 1000 MW;
- A level of energy storage which would permit generation at full output for a period of 10 hours;
- A 1:1 ratio between compressing and generating air flow;
- A "dry" type compressor intercooler/aftercooler system;
- A hard-rock mined, water-compensated storage cavern system;
- A 500 kV switchyard; and
- Fuel delivery by pipeline.

The plant design is based upon a Brown Boveri (BBC) turbine system and Sulzer compressors which, for near-term applications, appear to present the most attractive approach. BBC provided advice, under subcontract, on the design of CAES plant and equipment.

This section presents the major aspects of the CAES plant design established during the study including:

- Energy storage/power generation systems;
- Surface plant layout;
- Air storage system;
- Site development plan; and
- Capital cost estimate.

The philosophy used in developing this design reflects conservatism in areas where any technical uncertainties exist and utilizes standard utility practices based on similar types of systems and structures wherever possible.

ENERGY STORAGE/POWER GENERATION SYSTEMS

General

The air compression and power generation functions of the CAES plant will be performed through a modification of the conventional Brayton or "gas turbine" cycle. The air compression (energy storage) portion of the cycle will occur during utility system off-peak periods, with the combustion and expansion (power generation) portion of the cycle taking place at the time of peak demand.

Conventional gas turbine hardware and technology form the basis for the development of CAES energy storage and power generation systems. However, analysis indicates that CAES systems operating at conventional gas turbine pressures of 150 to 200 psig are significantly less economical than CAES systems operating at greater pressures of 600 to 1000 psig. Modifications to conventional gas turbine systems or completely new turbomachinery designs will therefore be required to produce an economically attractive CAES system.

The air compression/power generation system developed by BBC for PEPCO combines a compressor system design provided by Sulzer with BBC turbine and motor-generator system design. Air mass flow rate through the compressor and turbine systems is matched at a 1:1 ratio in accordance with the planned operating cycle established by PEPCO.

The energy storage and power generation systems are shown schematically on Figure 7-1, and a brief description of each of the major components within these systems follows.

Component Description

The design of the energy storage/power generation system for PEPCO employs the same "single train" concept as that currently operating in the CAES plant at Huntorf, West Germany. In this concept, all of the turbomachinery operates on one shaft (suitably connected with clutches) driving, or driven by, a single motor-generator.

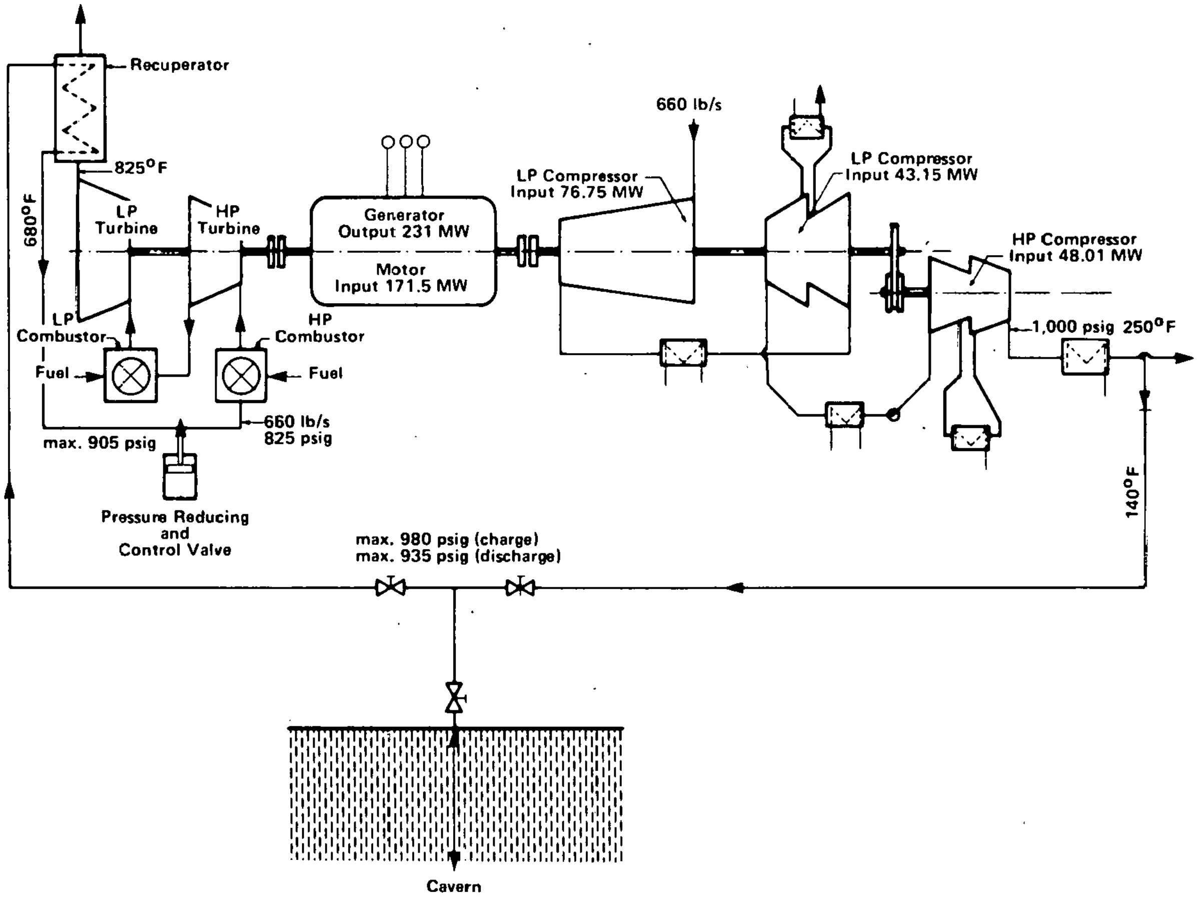


Figure 7-1 Basic CAES Cycle

The CAES turbine assembly will be composed of two separate turbines on a common shaft assembly (as shown in Figure 7-2) with combustion chambers provided ahead of each turbine section. The high-pressure turbine will follow standard steam turbine design practice with seven stages of blading. The low-pressure turbine will be a standard BBC GT-11 gas turbine which, together with the high-pressure turbine, will deliver 231 MW of power to the electrical generator at design air flow of 661.5 lb/s.

A double-ended, hydrogen-cooled synchronous generator rated at 270.6 MVA will be driven by the CAES turbine system. This generator will also operate in reverse as a motor during the air compression cycle, providing 171 MW of drive power to the compressors. Clutches at each end of the machine will allow the motor-generator to engage or disengage the compressor or turbine systems as necessary to perform the selected duty. In conjunction with a static inverter, the motor-generator will allow variable frequency starting of the compressor system without use of the turbine system, thereby increasing the life of the turbine "hot end" parts.

Air compression will be accomplished by a three unit, series-flow compression system. The axial low-pressure compressor is the Sulzer equivalent of the Brown Boveri GT-11 axial compressor with adjustable stator blades developed for industrial applications. The medium-pressure compressor (operating at 3600 rpm) and the high-pressure compressor (operating, through a step-up gearbox, at 6650 rpm) will be horizontal, split-casing centrifugal designs similar to several units designed for industrial applications. Intercoolers will be positioned at various stages of the compression process to improve compression efficiency and to protect the compressors from excessive temperatures.

The power generation system will also incorporate an exhaust gas recuperator downstream of the low-pressure turbine which will act as a combustion air preheater and thereby improve the overall efficiency of the CAES cycle by approximately 8 percent. Of even more importance, however, is the ability of the recuperator to reduce the fuel oil consumption during the CAES power generation cycle by approximately 20 percent.

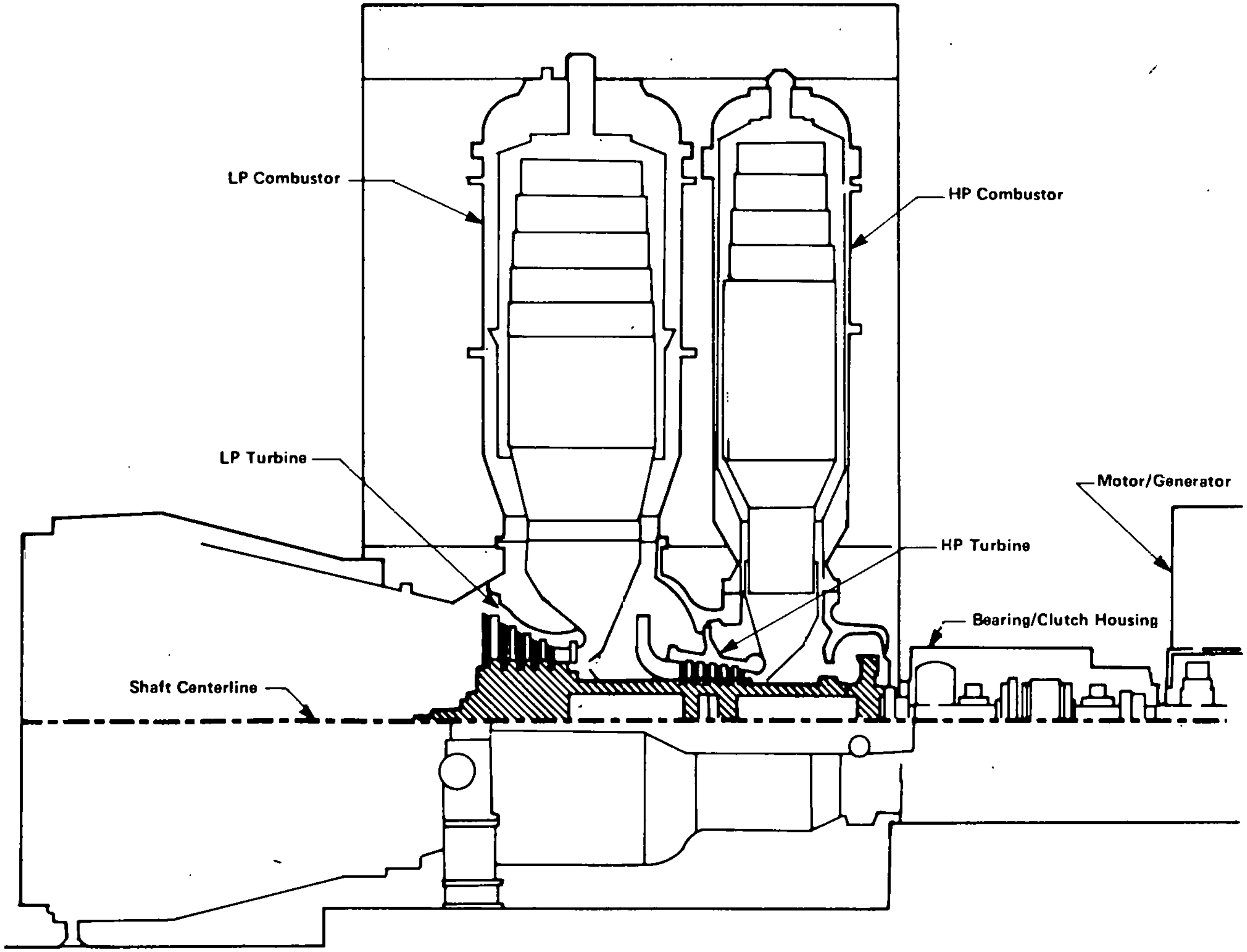


Figure 7-2 Turbine System

Performance

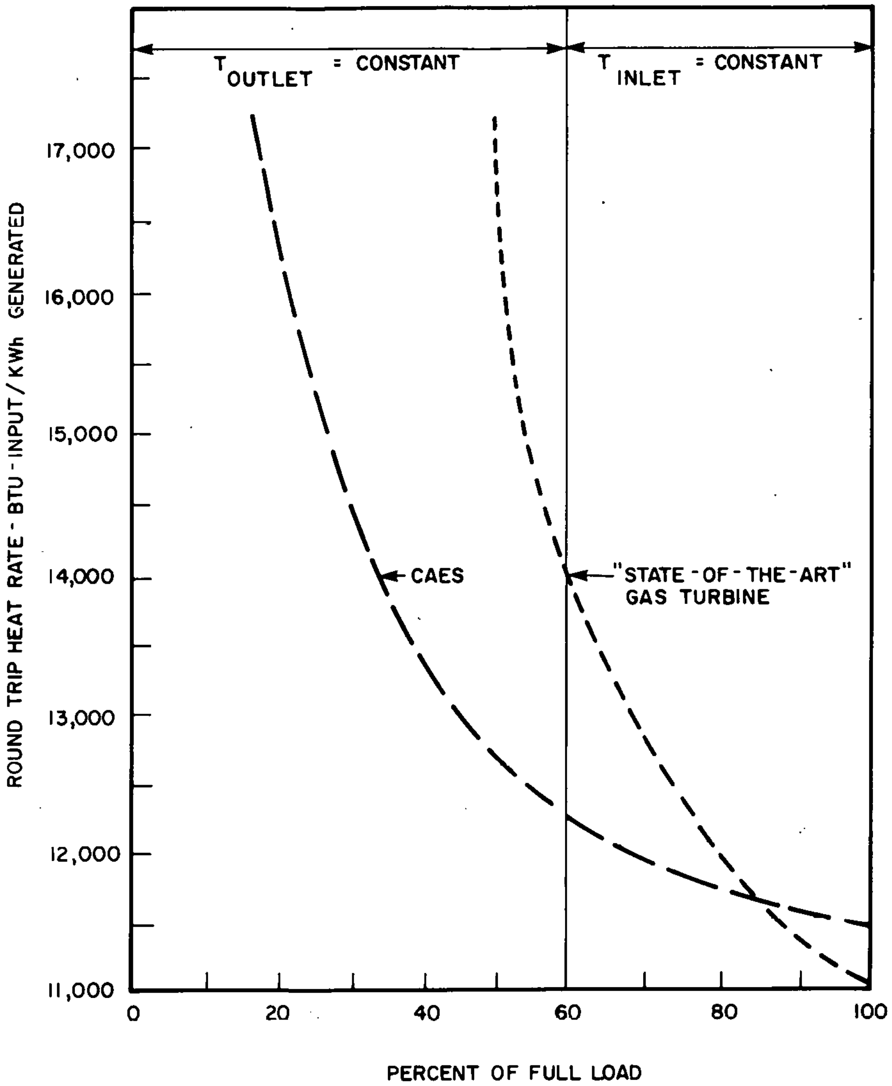
The performance of the CAES plant can best be expressed in terms of its "Round Trip Heat Rate" (Btu-input/kWh-generated) developed by summing the energy used during compression to provide enough air to generate one kWh together with the energy input in fuel during generation to produce that one kWh. A comparison of the CAES plant performance and a modern, simple-cycle gas turbine is shown in Figure 7-3. Because two-thirds of the energy making up the round trip heat rate of a CAES plant is derived from non-oil compression energy sources in the cycle, the CAES plant also becomes a much more efficient user of fuel oil than conventional gas turbines designed for comparable heat rates.

Operation

The CAES energy storage/power generation system must operate according to a daily cycle which includes both the compression and power generation operating modes. The present operating schedule envisioned for PEPCO includes a 10-hour period of compression and a 10-hour period of electric power generation, with 2 hours allowed for each changeover from one operating mode to the other. Figure 7-4 illustrates the actual time required for a typical changeover sequence of the CAES plant system. In emergency situations, this changeover sequence can be performed more rapidly.

Both the compression and power generation systems will be designed to operate at part-load conditions. The compression system can operate down to 75 percent of full load with only about a 5 percent loss in compression efficiency. In the power generation mode, the turbine can operate over a range of 10 percent to 100 percent of full rated load.

The power generation system developed for PEPCO will use ASTM No. 2 fuel oil as the heat energy source. With this fuel, all current Federal and state regulations for NO_x, SO_2, and particulates, as applied to the CAES configuration, can be met. The CAES power generation system could also burn natural gas with a minimum impact on equipment design and still remain well within environmental constraints. Other fuels, including coal-derived liquids and synthetic gases, would exhibit combustion characteristics in a CAES plant similar to those they exhibit in a conventional gas turbine system.



*BASED ON COMPRESSING AT 100% LOAD
AND A NET SYSTEM HEAT RATE OF 10,000 BTU/KWH

Figure 7-3 CAES Round Trip Heat Rate

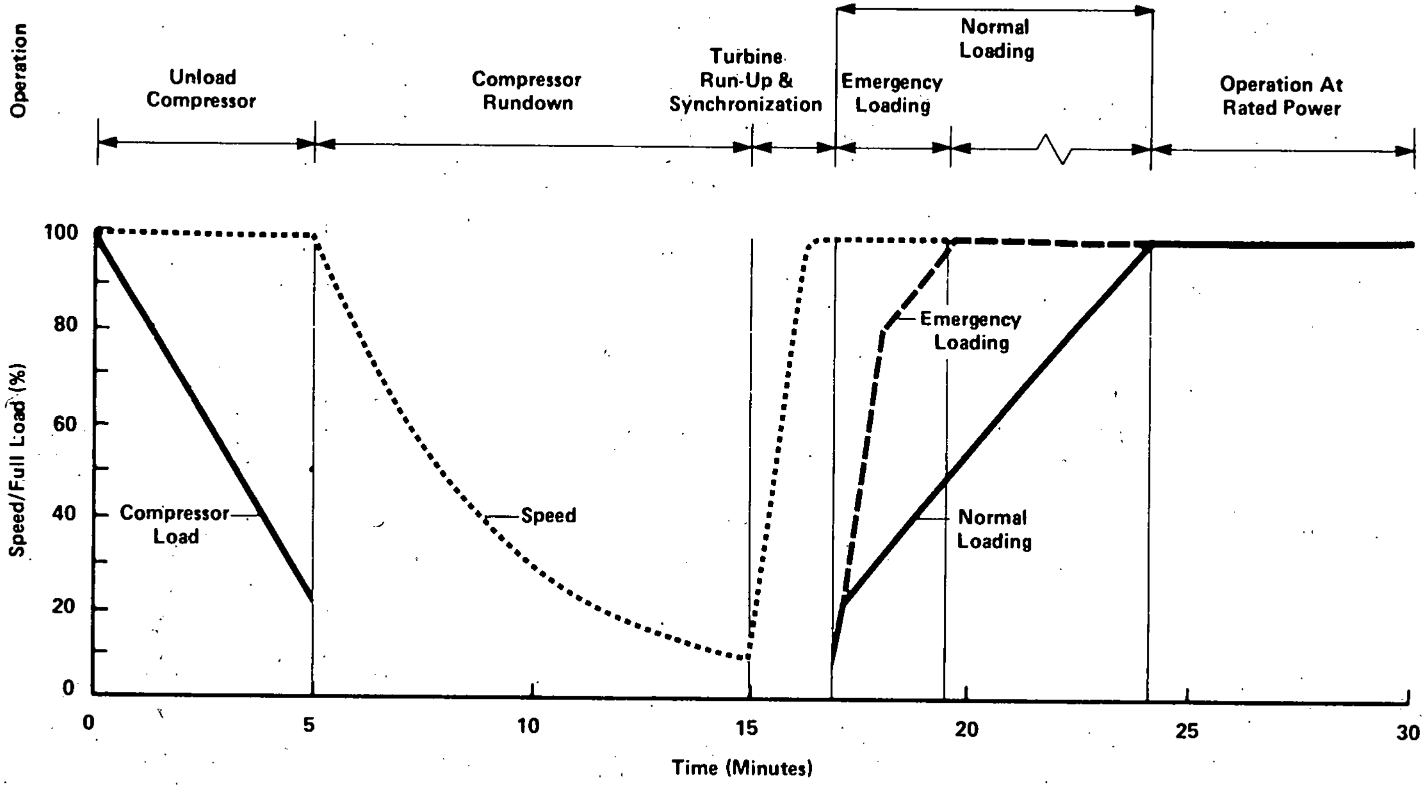
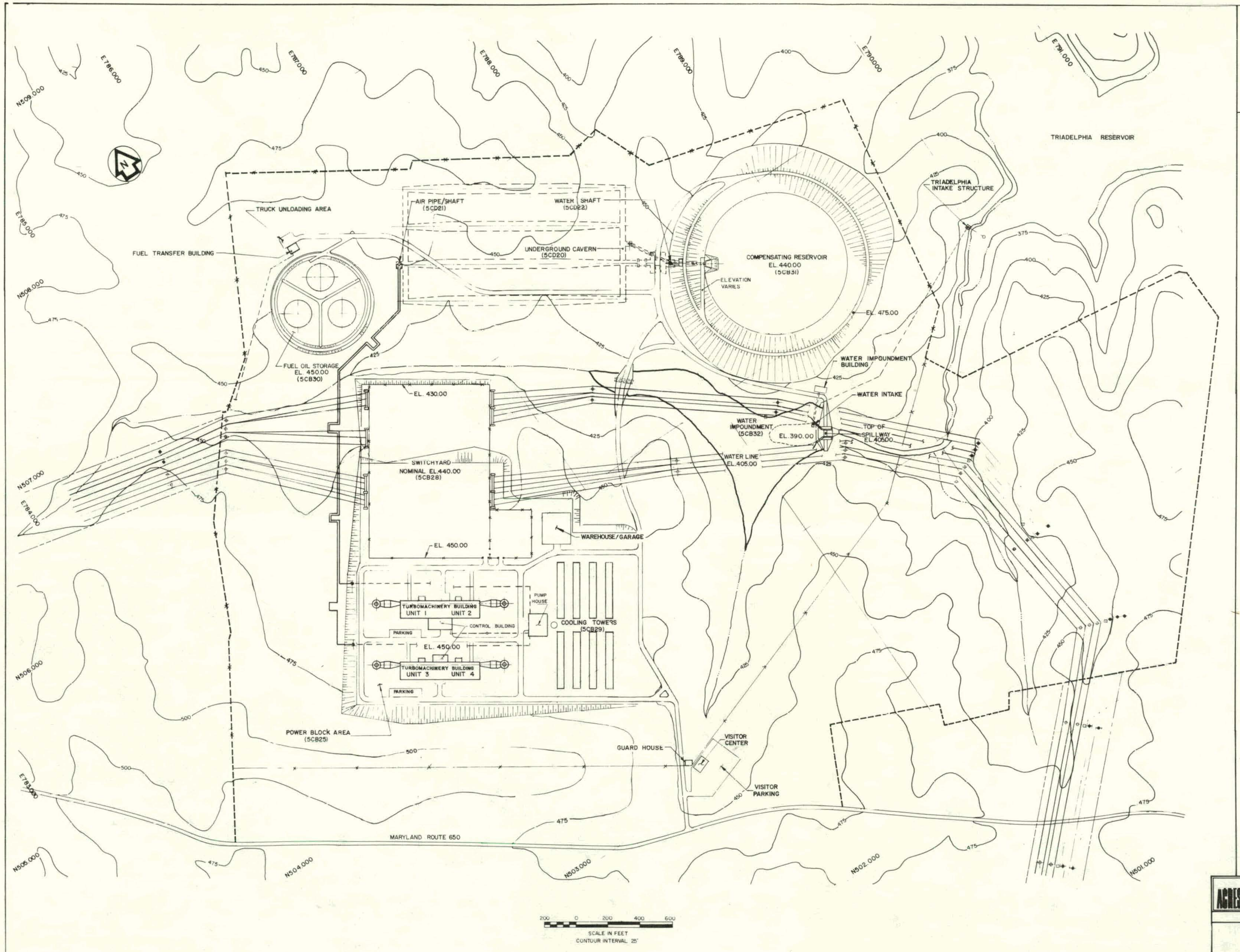


Figure 7-4 Normal Changeover - Compression To Generation



KEY PLAN

LEGEND

✦ EXISTING TRANSMISSION TOWER (1980)
⌖ PLANNED TRANSMISSION TOWER
—··— STREAM BED
— — — PROPERTY LINE
- - - - BURIED PIPE LINES
—×— FENCE
—·— EXISTING TRANSMISSION LINES (1980)

REFERENCE DWGS:

5CB20	SITE PLOT PLAN
5CB22	SITE DEVELOPMENT PLAN, SHEETS 1,2 & 3
5CB23	ARCHITECTURAL RENDERING
5CB25	POWER BLOCK GENERAL ARRANGEMENT
5CB26	TURBOMACHINERY BUILDING EQUIPMENT LOCATIONS, SHEETS 1 AND 2
5CB27	TURBOMACHINERY BUILDING AND FOUNDATIONS, SHT. 1&2
5CB28	SWITCHYARD-GENERAL ARRANGEMENT AND DETAILS
5CB29	COOLING TOWER-GENERAL ARRANGEMENT & DETAILS
5CB30	FUEL OIL STORAGE-GENERAL ARRANGEMENT & DETAILS
5CB31	COMPENSATING RESERVOIR & INTAKE STRUCTURE-GENERAL ARRANGEMENT & DETAILS
5CB32	WATER IMPOUNDMENT-GENERAL ARRANGEMENT & DETAILS
5CD20	UNDERGROUND CAVERN
5CD21	AIR PIPE/SHAFT
5CD22	WATER SHAFT

FIGURE 7-5

ACRES

DEPARTMENT OF ENERGY
AND
ELECTRIC POWER RESEARCH INSTITUTE
POTOMAC ELECTRIC POWER COMPANY
ENERGY STORAGE STUDY-CAES

SITE ARRANGEMENT PLAN

M J Hobson
ACRES AMERICAN INCORPORATED
DATE OCTOBER 11, 1979
DEPARTMENT
PROJECT P4800
SCALE: 1" = 200'
DWG. NO. 5CB21
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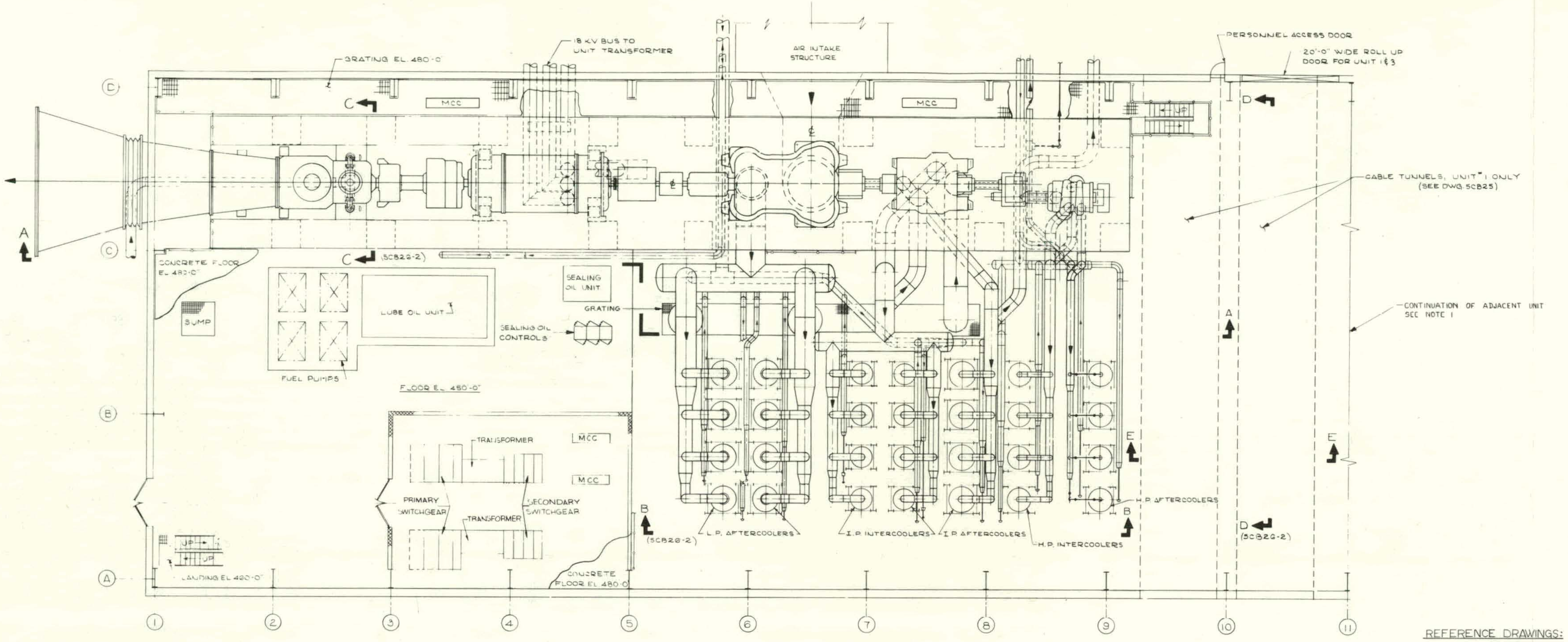
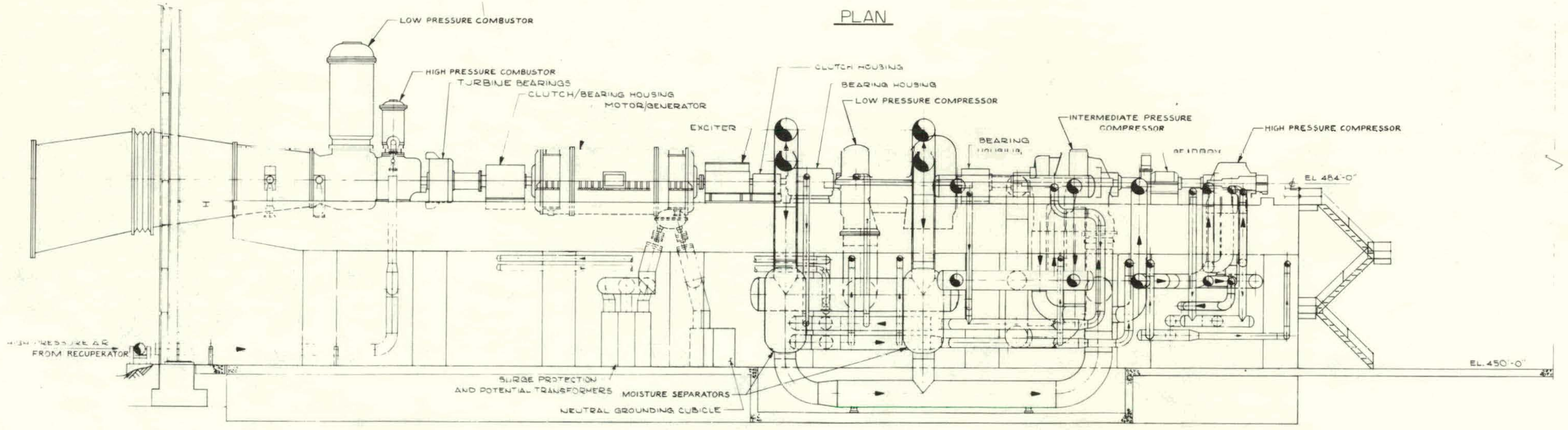


PLAN



SECTION A-A

REFERENCE DRAWINGS:

DWG. NO	DWG. TITLE
5CB21	SITE ARRANGEMENT PLAN
5CB25	POWER BLOCK GENERAL ARRANGEMENT
5CB27-1,2	TURBOMACHINERY BUILDING & FOUNDATION
5CC20	FUEL OIL SYSTEM SCHEMATIC
5CC21	WATER SUPPLY & TREATMENT SYSTEM SCHEMATIC
5CC23	COOLING WATER SYSTEM SCHEMATIC
5CC28	MAIN AIR SYSTEM SCHEMATIC

NOTES:

1. UNIT "1 SHOWN, OTHER UNITS SIMILIAR UNLESS OTHERWISE NOTED
2. PORTIONS OF MAIN AIR SYSTEMS & COOLING WATER SYSTEMS ARE REMOVED FOR CLARITY.

0 8 16
SCALE IN FEET

FIGURE 7-6

ACRES
DEPARTMENT OF ENERGY
AND
ELECTRIC POWER RESEARCH INSTITUTE
POTOMAC ELECTRIC POWER COMPANY
ENERGY STORAGE STUDY-CAES

TURBOMACHINERY BUILDING
EQUIPMENT LOCATIONS

M J Hobson
ACRES AMERICAN INCORPORATED
DATE DECEMBER 1979
DEPARTMENT
PROJECT P4800
SCALE 1/8" = 1'-0"
DWG NO 5CB26
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SURFACE PLANT LAYOUT

General

Development of the surface plant layout was a compromise between the numerous operational, design and construction requirements and the various environmental and aesthetic concerns. The final site arrangement developed in the study adopted what is considered to be an operationally sound and environmentally acceptable design presenting the following benefits:

- Minimal visual impact;
- Convenient tie-in to the existing 500 kV transmission lines;
- Compact grouping of the turbomachinery buildings, switchyard and ancillary systems to minimize the length of piping runs and electrical connections; and
- Separation of the underground and surface construction activities.

The major surface features shown in Figure 7-5 include:

- Two turbomachinery buildings;
- A 500 kV switchyard and transmission lines;
- An oil storage facility;
- The water supply system and dry cooling towers; and
- The compensating reservoir.

These are briefly discussed in the following section.

Turbomachinery Buildings

Each turbomachinery building will house two CAES units and their associated mechanical and electrical auxiliaries. The buildings will be constructed with a conventional rigid steel frame with insulated metal siding. Details of the interior of these buildings and the layout of the turbomachinery are shown in Figure 7-6.

Switchyard

The tie-in to the 500 kV transmission line will be made through overhead connections to the switchyard, which has a breaker-and-a-half configuration. The air-insulated switchyard will utilize SF_6 gas-insulated switchgear and will be basically similar in design to PEPCO's 500 kV switchyard at the Chalk Point Generating Plant. Provisions will be included in the yard for:

- Four transmission lines to Mount Airy;
- Four transmission lines to Brighton;
- Four motor-generator circuits; and
- Two station service connections.

Oil Storage

An oil-storage system consisting of three 110,000 barrel tanks of No. 2 fuel oil will be provided in the northern corner of the site. Provisions for both pipeline and truck deliveries of oil will also be included.

Water Supply and Cooling Towers

A water impoundment area has been incorporated into the plant design to allow the on-site stream to provide consumptive water. Additionally, provisions will be provided on the Triadelphia Reservoir for a backup water supply in the event that area run-off proves to be insufficient during certain periods to meet the plant's water requirements.

The secondary heat exchange for the compressor intercooler/aftercooler system will be provided by the dry cooling towers located adjacent to the southeast corner of the turbomachinery buildings. These towers will also provide cooling water for the other mechanical systems.

Surface Reservoir

The compensating water for the air storage system will be contained by the circular rockfill dike at the eastern corner of the site. This asphalt-lined reservoir will provide a live water storage volume of 756,000 yd^3 with a level variation of 25 ft during operation.

AIR STORAGE SYSTEM

General

Development of a reliable and economic storage system for high pressure air (at 500 psig - 2000 psig) is essential to the implementation of CAES. Three concepts for air storage, each based on a different type of geological formation, have been proposed. These are:

- A cavity formed by solution mining a salt dome;
- Porous media suitably confined by a caprock; and
- A mined cavern in a hard rock formation.

The air storage system developed during this study will use a hard rock mined cavern for containment of the air. To reduce the required cavern volume, a hydraulic compensation system will be used to maintain an essentially constant air storage pressure. This type of storage system will consist of three major items: the underground storage cavern, the water shaft and the air shaft.

For the CAES plant design developed during this study a total cavern volume of 811,000 yd^3 at a depth of approximately 2300 ft, using an approximate storage pressure of 1000 psig, was selected.

Storage Cavern

The preliminary design of the underground storage cavern system as shown in Figure 7-7 will consist of four parallel caverns interconnected at one end by smaller tunnels, one for water collection and the other for air collection. The main caverns will have transition sections to smaller tunnels to allow a reduction in the dimensions of intersections to render these more stable. The large caverns will be aligned in a direction which will utilize the geotechnical characteristics of the rock mass to gain maximum structural integrity for the cavern. The northwest-southeast direction appears to be most suitable based on the limited information gathered to date from preliminary field investigations.

Various methods of cavern excavation were considered, including heading and benching with conventional drilling and blasting techniques, mechanical excavation, and mining methods. After the preliminary selection of the method of heading and benching, a cost comparison of several cavern cross sections showed a 50 ft wide by 106 ft high cavern to be the least costly due to the high percentage of bench excavation. However, an analysis based upon:

- A review of existing caverns;
- An empirical assessment of the rock mass; and
- A stress analysis which related the developed stresses around a single cavern to the strength of the intact rock

indicated that a smaller 60 by 85 ft cavern was preferable to the higher cavern as it allowed a reduction in the tensile stress zone in the lower side walls. The 60 by 85 ft cross section was therefore selected as the basis for the study design.

Air and Water Shafts

A shaft arrangement involving a 4 ft internal diameter air pipe and a 13 ft internal diameter water shaft has been selected as the preliminary design arrangement. During construction, the air shaft can be used for a portion of the ventilation requirements as well as for emergency access. The remainder of the construction activities will be provided through the water shaft. In the operating mode, a 4 ft diameter air pipe will give a maximum air flow velocity of approximately 45 ft/s with a pressure loss of about 5 psi. The maximum water velocity will be 4 ft/s in the water shaft and 11 ft/s through the U-tube.* During construction, the water shaft will be used for rock removal, personnel access, ventilation and construction service. During operation, the water shaft can be used as access for inspection and maintenance of the caverns when the caverns are depressurized.

Tentatively, stainless steel has been selected for the construction of the 4 ft internal diameter air pipe. It is designed to be encased in concrete in the manner adopted for hydroelectric penstocks. The 8 ft excavated diameter provided will allow sufficient space for installation of the air pipe and concrete liner. The pipe wall thickness varies as a function of depth and ranges from 7/16 inch to 1 inch.

The water shaft will require a 12-inch concrete lining. Provision has been made for drain holes through the shaft lining so that in the dewatered condition the lining will not have to accommodate the external hydrostatic loads.

SITE DEVELOPMENT

The first stage of the four-unit CAES plant will include construction of a two-unit plant together with facilities such as the underground cavern, air and water shafts, compensating reservoir, as well as part of the switchyard, fuel oil storage and water impoundment. The second stage will then include construction of a second two-unit plant and completion of the other facilities.

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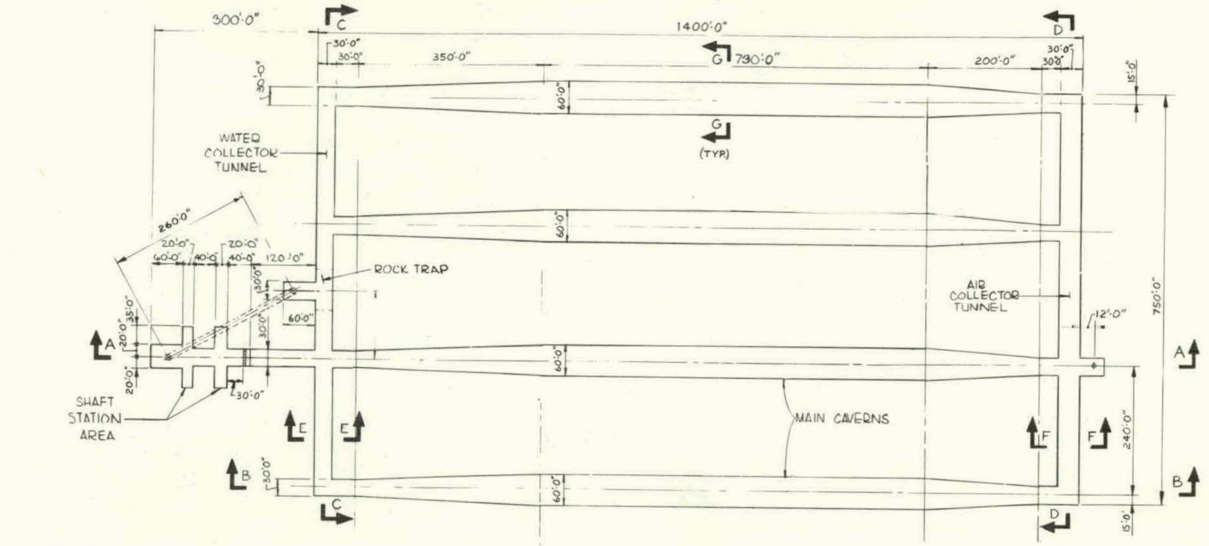
*The U-tube will provide a mechanism for maintaining a seal in the water to avoid accidental release of the air from the cavern in the event of a phenomenon related to air dissolution called the "Champagne Effect".



PLAN
UNDERGROUND CAVERN
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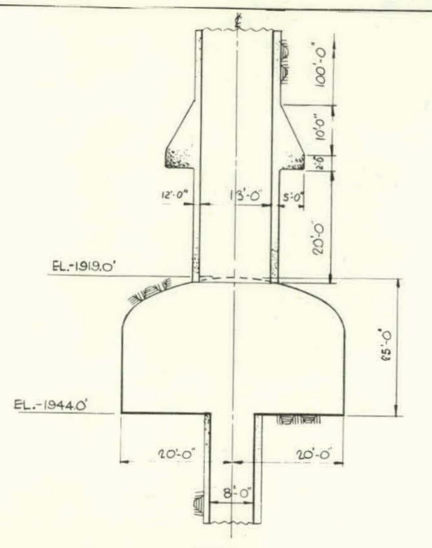
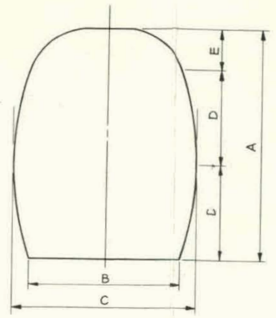
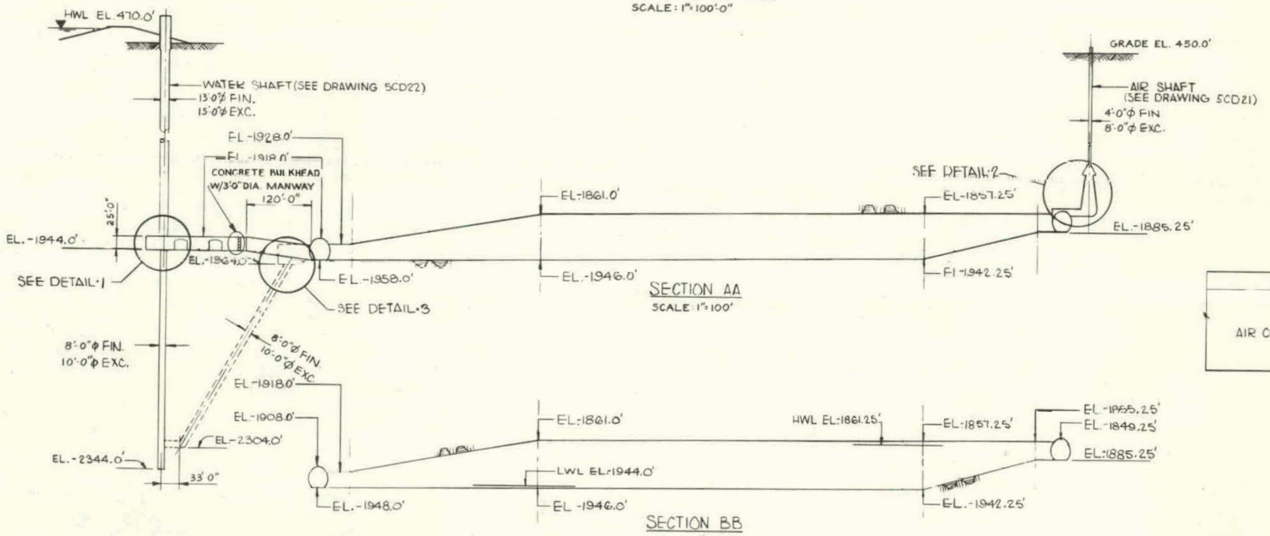


DETAIL - 1
WATER SHAFT
SCALE: 1"=10'



LOCATION	A	B	C	D	E	R
MAIN CAVERN	85	54	66	35	15	105
WATER COLLECTOR	40	26	34	17.5	5	40
AIR COLLECTOR	36	26	34	15	6	30
MAIN COLLECTOR CONNECTION	30	27	33	12.5	5	27.5

NOTE: ALL DIMENSIONS IN FEET



SECTION AA
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SECTION BB
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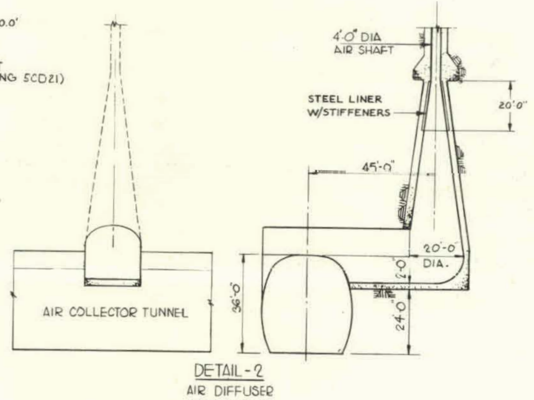
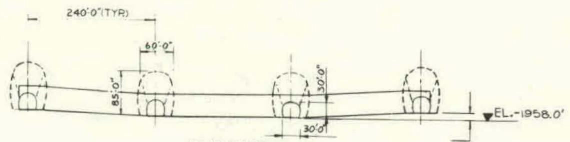


DETAIL - 2
AIR DIFFUSER
SCALE: 1"=20'

REFERENCE DRAWINGS
5CB21 - SITE ARRANGEMENT PLAN
5CD21 - AIR PIPE SHAFT
5CD22 - WATER SHAFT



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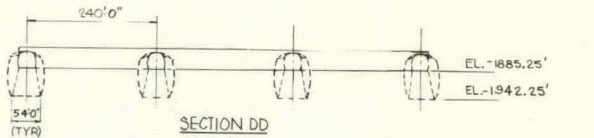

SECTION DD
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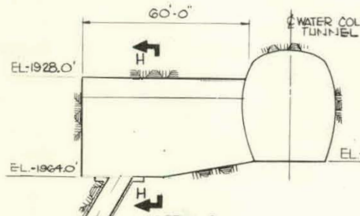

DETAIL-3
U-TUBE CONNECTION
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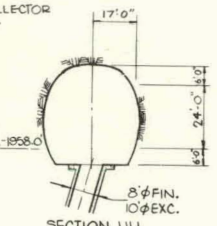

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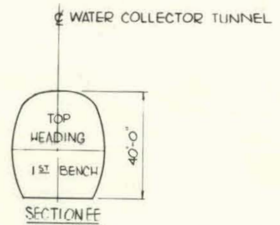

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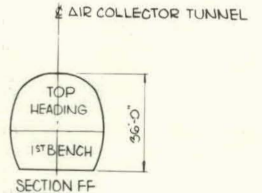

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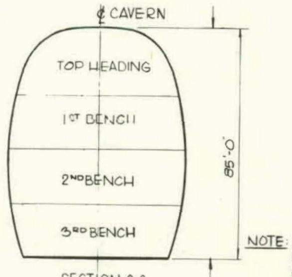

SECTION GG
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NOTE: HEIGHTS OF HEADINGS AND BENCHES MAY VARY

FIGURE 7-7

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ENERGY STORAGE STUDY-CAES

UNDERGROUND CAVERN

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Based on these requirements, the following phases for site development were established:

- PHASE I (0-24 months) - This phase will include site preparation, mobilization, establishment of construction facilities, excavation and construction of major foundations, construction of air and water shaft, and excavation of the compensating reservoir;
- PHASE II (24 - 32 months) - This will include excavation and completion of underground cavern and construction of major structures and facilities;
- PHASE III (32 - 60 months) - This will include installation of mechanical and electrical equipment, pre-operation testing and startup, and commercial operation of Units 1 and 2; and
- PHASE IV (84 - 144 months) - This will include construction of Units 3 and 4 for commercial operation.

The site development plan was formulated from the detailed activities involved in each construction phase to assure compliance with the project milestone and overall schedules. An in-depth review was made to determine the compatibility of rock production from cavern excavation with its utilization for construction of other facilities. This was important in assuring the uninterrupted construction of the dikes for the compensating reservoir. Other construction activities which utilize excavated rock were scheduled to provide a balance between rock production and utilization to minimize rock inventory.

CAPITAL COST ESTIMATE

The cost estimate for the four-unit plant (each unit rated at 231 MW) developed in this study is site specific and based upon a location near Sunshine, Maryland. The cost estimate is in mid-1979 dollars and includes all costs associated with labor, equipment, material, fabrication, delivery and site preparation work.

A summary of the capital cost estimate for the CAES plant is given in Table 7-1. The total direct costs are $347.0 million, or $375.5 per kW. Of these totals, the generator/compressor system makes up approximately 50 percent and the storage system 16 percent of the cost. The indirect costs consisting of owner costs, engineering and construction management costs with contingencies are $156.3 million, bringing the total capital costs to $503.3 million or $544.7 per kW.

Table 7-1

SUMMARY OF CAPITAL COST ESTIMATE
CAES

Installed Capacity .... 924 MW
Storage Capacity .... 9,240 MWh
Estimate Based on Mid-1979 Costs

Item	Amount, \$ x 10^6
Land, Site Access and Mobilization	8.7
Surface Facilities	23.5
Storage System	55.9
Generator/Compressor System	172.2
Balance of Mechanical Plant	31.8
Switchyard	32.5
Electrical Plant	22.4
Total Direct Costs	347.0 (\$375.5/kW)
PEPCO Costs (15% of Direct Costs)	52.1
Engineering Costs (5% of Direct Costs)	17.4
Construction Management Costs (10% of Direct Costs)	34.7
Contingencies (15% of Direct Costs)	52.1
TOTAL	503.3 (\$544.7/kW)

NOTES:

(1)No provisions have been made in this capital cost estimate for escalation or interest during construction.

(2)The estimates were prepared using vendor-supplied equipment cost quotations where possible or estimates based on the plant design developed during the study. In those areas where information was not sufficient to produce a quantity take off, lump sum allowances were made based on similar systems found in conventional thermal generating plants in the 900 to 1000 MW size.

Section 8

UPH PLANT DESIGN

GENERAL

Underground pumped hydroelectric (UPH) energy 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 UPH, the lower reservoir consists of excavated caverns deep below the surface and, 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 UPH can be chosen from a wide range. The UPH concept offers an approach to the design of pumped storage facilities which can optimize the nominal operating head in relation to the pumping/generating equipment and to the size of the underground caverns.

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

The basic requirements stipulated by PEPCO for an UPH energy storage plant were:

- A generating capacity of 2000 MW;
- A level of energy storage which would permit generation at full output for a period of 10 hours; and
- A plant capable 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 2500 ft. This enabled an overall nominal operating head of 5000 ft to be adopted. Detailed plant design and capital cost estimates were then developed for the arrangement shown in Figure 8-1. The facility is 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.

This section presents the major aspects of the UPH plant design established during the study including:

- Selection of pump-turbine arrangement;
- Major components of the UPH facility including:

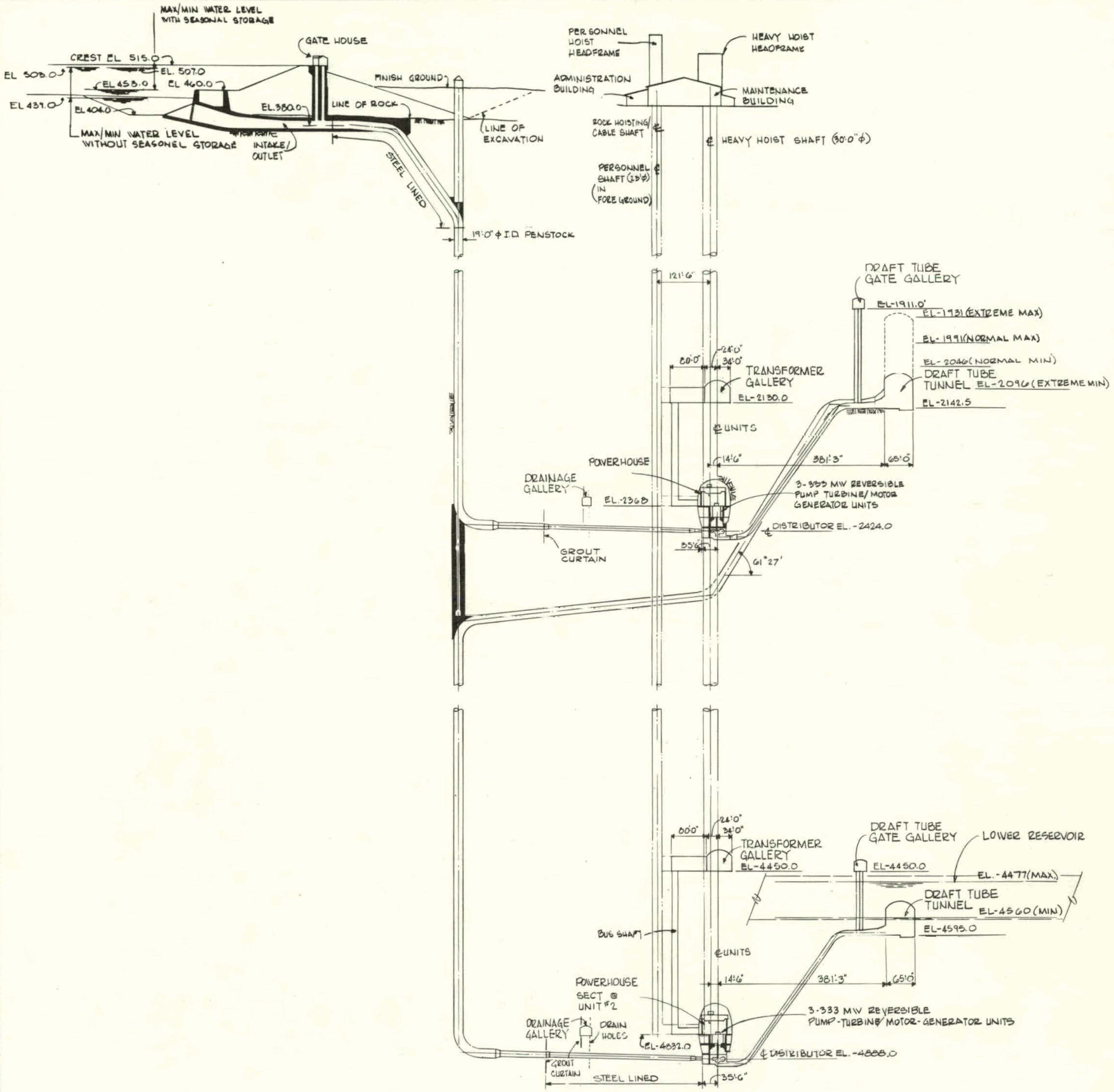
  -- Surface facilities and upper reservoir
  -- Intake
  -- Penstocks and shafts
  -- Intermediate reservoir
  -- Power generating/pumping facilities
  -- Lower reservoir
  -- Transformation and power circuits
  -- Switchyard

- Site development; and
- Capital cost estimate.

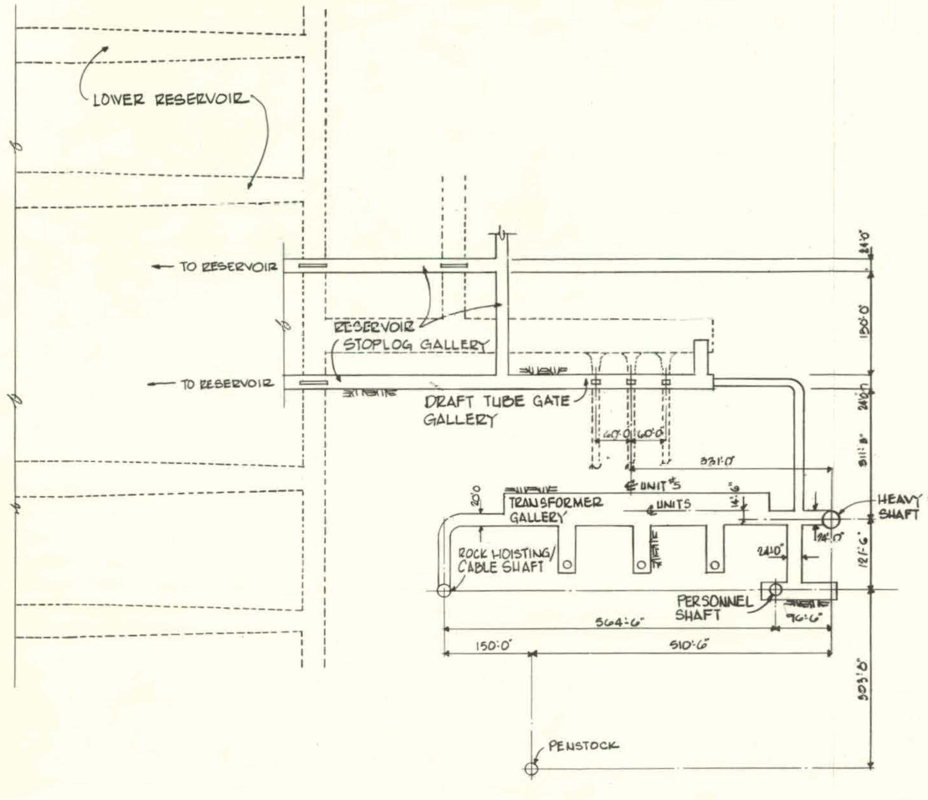
SELECTION OF PUMP-TURBINE ARRANGEMENT

Comparison of Pump-Turbine Alternatives

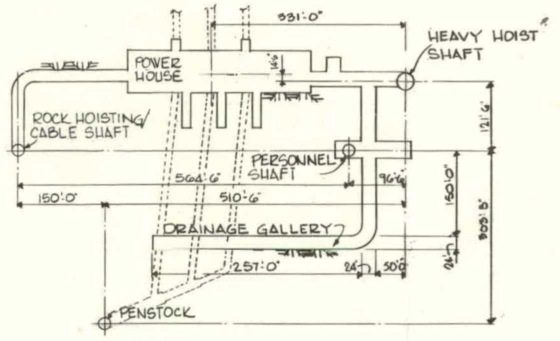
At the outset of the study, practice overseas had accepted heads of 2000 ft for single-stage reversible pump-turbines with normal provision for turbine load regulation by means of wicket gates. Consideration was being given to pump-turbines having more than one stage, with regulation provided on one or more stages. The practice of assigning pumped storage duty to non-regulating multi-stage pump-turbines designed in accordance with very high head pump practice and accommodating heads of over 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 upwards.



SECTION THROUGH POWER INSTALLATION



PLAN AT EL.-4450.0



PLAN AT EL.-4832.0

NOTES:
PLANS SHOW LOWER LEVEL POWER FACILITY ONLY
INTERMEDIATE POWER FACILITY IS ESSENTIALLY
THE SAME.

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SCALE IN FEET

Figure 8-1

ACRES
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ENERGY STORAGE STUDY - UPH

GENERAL
ARRANGEMENT

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For initial selection purposes, cost comparisons of 2000 MW plants using single-stage reversible pump-turbines in one step (SSRPT-1), single-stage reversible pump-turbines in two steps (SSRPT-2), multi-stage reversible pump-turbines in one step (MSRPT), uni-rotational separate pump-turbines with multi-stage 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 4600 ft (two steps of 2300 ft), MSRPT at nominal head of 4600 ft and TSRPT at nominal head of 3400 ft were the most economic. The costs for SSRPT-1 at nominal head of 2300 ft were higher because of the higher volume of lower reservoir excavation involved. Plant designs based on uni-rotational separate pump-turbines with Francis turbines and single-stage pumps and on completely separate multi-stage pumps and motors and impulse turbines with generators were also considered but were discarded because of cost.

At the time of this study, no TSRPT units had been built and therefore, because of lack of design and operating experience with these units, they were not considered further. Detailed investigation, including marginal cost-depth studies, of the SSRPT-2 and MSRPT arrangements showed that the estimated costs for both arrangements were essentially the same. The studies confirmed the optimum nominal head for MSRPT as 4600 ft but indicated that the corresponding head for SSRPT-2 is 5000 ft (two steps of 2500 ft). The SSRPT-2 arrangement was preferred to MSRPT in this study because of its load following ability and because of its greater flexibility. Although designs involve some extrapolations from previous operating practice, it is 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 the adoption of 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 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 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 economic development of the UPH concept with plant capable of operating in a single-step with heads of the order of 4000 to 5000 ft.

Operational Considerations

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 minutes; alternatively, one unit could operate alone for about 45 minutes. In the majority of situations, the UPH 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 unbalanced number of units for short periods of up to 3/4 hour) with actual power determined by the operating head at any particular stage of upper reservoir filling.

Units will be started in the pumping cycle with the main motor-generator supplied with power through a static converter system. Full station pumping load can be applied in approximately thirty minutes.

Spherical-type penstock valves located on the high pressure side of each pump-turbine will 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 will be installed in the underground facilities and power will be transmitted to and from the transformer banks, motor-generator units and the surface by SF_6 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.

Operation is planned to meet the high quality of performance and level of availability called for by PEPCO. Following an initial start-up and proving period, the SSRPT-2 facilities will perform at a high standard of overall cycle efficiency of about 76 percent and provide about 94 percent 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 percent.

PUMPED STORAGE PLANT LAYOUT

General

In UPH facilities, energy storage is achieved through transfer of water by pumping from the lower underground reservoir to a natural or man-made impoundment on the surface. For the PEPCO study, 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 make-up from an existing nearby reservoir. A single penstock will connect from 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. SF_6 gas-insulated bus will provide the power circuit connection to the surface.

Equipment must be designed and installed in such a way that all services can be supplied through vertical shafts from the surface. Economies will be achieved by the adoption of high unit speeds and compact designs.

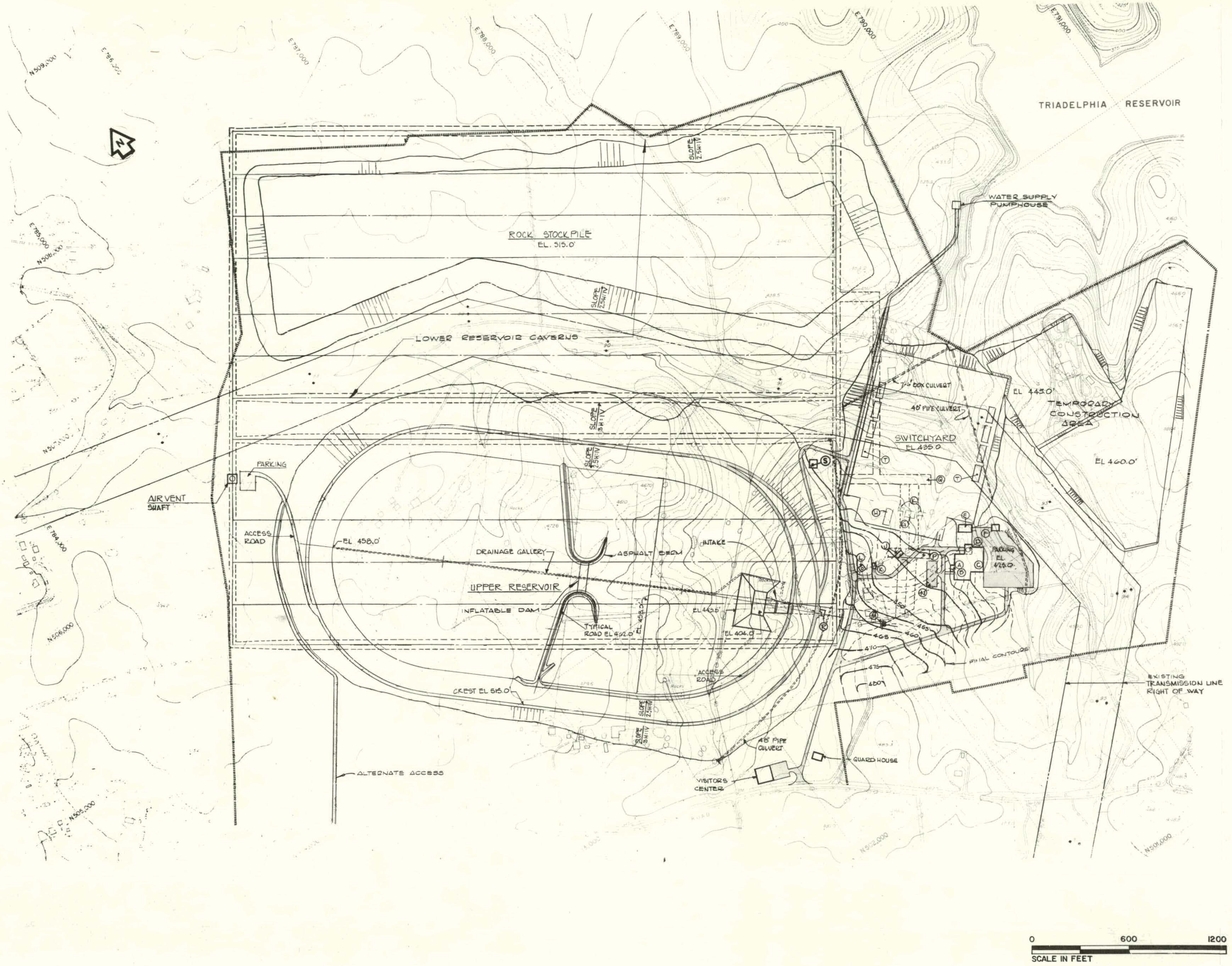
The UPH facilities will rely substantially on subsurface construction, and the various excavated powerhouses, reservoir and galleries will be accessible only by vertical shafts from the surface. This fact has a substantial influence on the design considerations for UPH as reflected in the following paragraphs. The general arrangement of the facility is shown on Figure 8-1 and the site layout on Figure 8-2.

Surface Facilities and Upper Reservoir

The arrangement of surface facilities and upper reservoir is shown in Figure 8-2. Buildings and structures provided for operational purposes include the administration and control building, heavy hoist headframe, heavy hoist machinery room, personnel hoist headframe, standby generator building, station service switchgear building, relay building, safety building, penstock and air vent access buildings, the visitors center and security building. The major feature of the surface works for an UPH plant will be the asphalt-lined earth and rockfill embankment rising approximately 15 to 115 ft above the original ground surface with outside slopes of 3:1 and a 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 4.5 ft x 7.5 ft gallery running along the center line from the northwest end to the intake structure. Initially the reservoir will be filled with water by pumping from the Triadelphia Reservoir and this supply will continue to be used in operation for makeup water requirements.

Intake

The intake structure carrying water to the penstock system will be conventionally formed and designed to deliver water to and draw water from the reservoir with uniform velocities and minimum head losses. Intake gates and bulkhead gates which are provided to allow inspection and maintenance of the intake have a vital function to perform in providing a high degree of security in control of water flows to the underground facilities.



NOTES –

1. ROCK STOCKPILES & TEMPORARY CONSTRUCTION AREA TO BE FORMED & LANDSCAPED TO MINIMIZE VISUAL IMPACT.
2. UPPER RESERVOIR EMBANKMENT TO BE FORMED & LANDSCAPED TO MINIMIZE VISUAL IMPACT. PLANTING ON THE EMBANKMENT WILL BE UNDERTAKEN WITH DUE REGARD TO THE WATER SEEKING PROPERTIES OF, THE SELECTED SHRUBS.
3. SITE TO BE FULLY FENCED.

LEGEND

▪▪▪▪ PROPERTY LINE
═ ASPHALT PAVING (ROADS & PARKING)

KEY

Ⓐ PERSONNEL SHAFT
Ⓑ ADMIN. & CONTROL BLDG
Ⓒ MAINTENANCE BLDG
Ⓓ HEAVY HOIST SHAFT
Ⓔ HEAVY HOIST MACHINERY ROOM
Ⓕ STANDBY POWER
Ⓖ 13.8KV SWITCHGEAR BLDG
Ⓗ RELAY BLDG
Ⓙ SAFETY BLDG
Ⓚ STATION SERVICE TRANSFORMERS
Ⓛ ROCK HOISTING/CABLE SHAFT
Ⓜ PENSTOCK
Ⓝ PARKING
Ⓟ UNDERGROUND POWERHOUSE
Ⓠ UNDERGROUND DRAFT TUBE COLLECTION TUNNEL
Ⓡ GATE HOUSE
Ⓢ WATER TREATMENT FACILITIES
Ⓣ LINE DEAD-END STRUCTURE

Figure 8-2

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ENERGY STORAGE STUDY-UPH

SITE PLAN

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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 5000 to 5500 ft. Three of these shafts will contain hoisting conveyances, SF_6 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 only access to the operating facilities below ground will be by vertical shaft. The need to maintain a high degree of integrity in shaft service, therefore, has been reflected in the design of the shafts themselves and the equipment with which they are furnished.

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 200 tons capacity with variable speeds up to 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 20 tons of material at speeds up to 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 SF_6 bus, as well as emergency access for personnel.

Shafts will be required to provide functions which may differ from construction to operational phases. The major portion of rock removal will take place through the shaft ultimately to be used for SF_6 bus and cables. The heavy hoist shaft will provide ventilation air.

The vertical penstocks will have a diameter of 19 ft and be designed for a maximum flow of 5400 ft^3/s. Construction of these and other shafts required for the facilities will be accomplished by sinking from the surface using conventional drilling and blasting methods. The penstock walls will have rock bolt support and have 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 11 ft diameter penstocks at each level. A 290 ft length of the penstocks upstream from the powerhouses will be lined with 2-3/4 inch thick high strength steel lines which have flanged connection penstock valves upstream of the pump-turbine spiral cases.

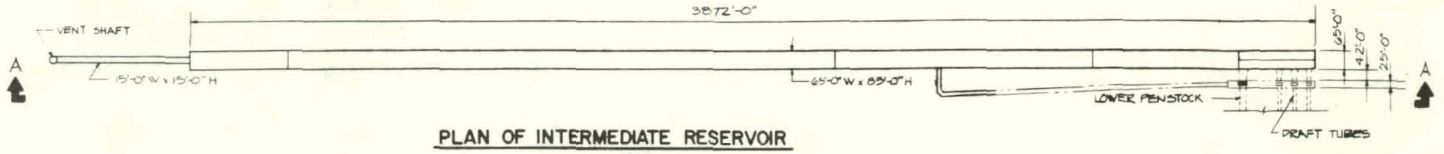
Intermediate Reservoir

With the two-step arrangement, the nominal head on each of the two powerhouses will be limited to 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. Details of the intermediate reservoir are shown on Figures 8-3 and 8-4. 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 minutes.

Power Generating/Pumping Facilities

The underground powerhouses located respectively at 2939 ft and 5403 ft below the crest level of the surface reservoir (measured to the center line 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 64.6 inch 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 bulkhead gate isolation of the 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 underground.

Figure 8-5 shows an isometric of the lower power plant facility and its associated shafts, tunnels and galleries. Figure 8-6 shows typical powerhouse cross-sections and Figure 8-7 shows sections through the pump-turbine and motor-generator. Generally speaking, a highly compact arrangement has been achieved, economizing on underground excavation.



PLAN OF INTERMEDIATE RESERVOIR

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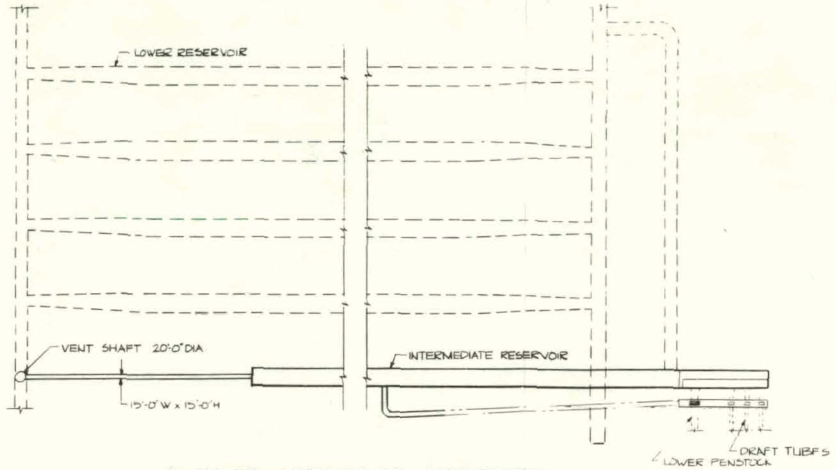

PLAN OF UNDERGROUND RESERVOIRS

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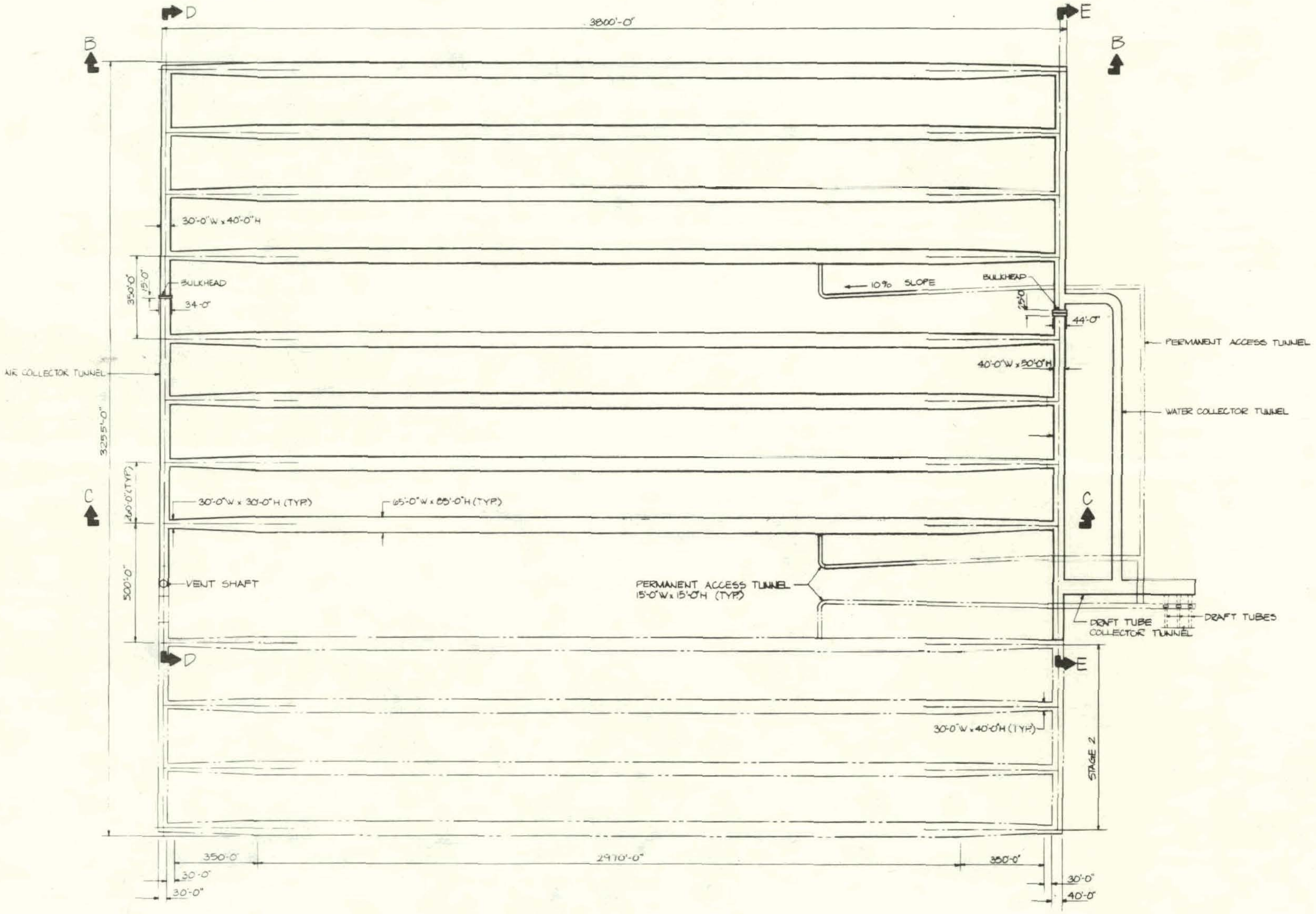

PLAN OF LOWER RESERVOIR

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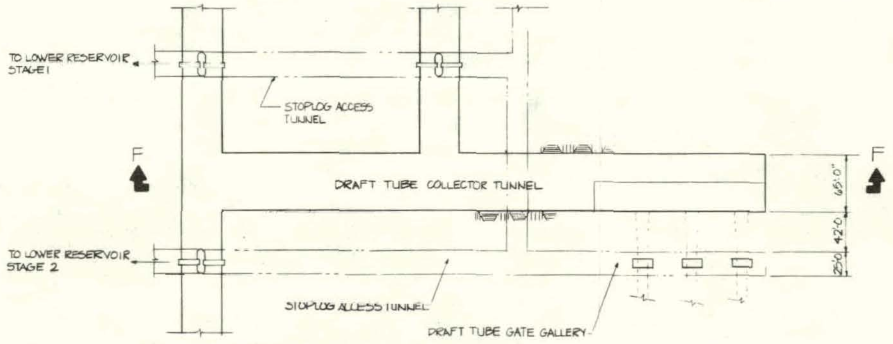

PLAN OF COLLECTOR TUNNELS

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1. SEE DWG SK-4800-D-631 FOR SECTIONS OF LOWER AND INTERMEDIATE RESERVOIRS.

① 0 600 1200

② 0 180 360

SCALES IN FEET

Figure 8-3

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LOWER & INTERMEDIATE RESERVOIR PLANS

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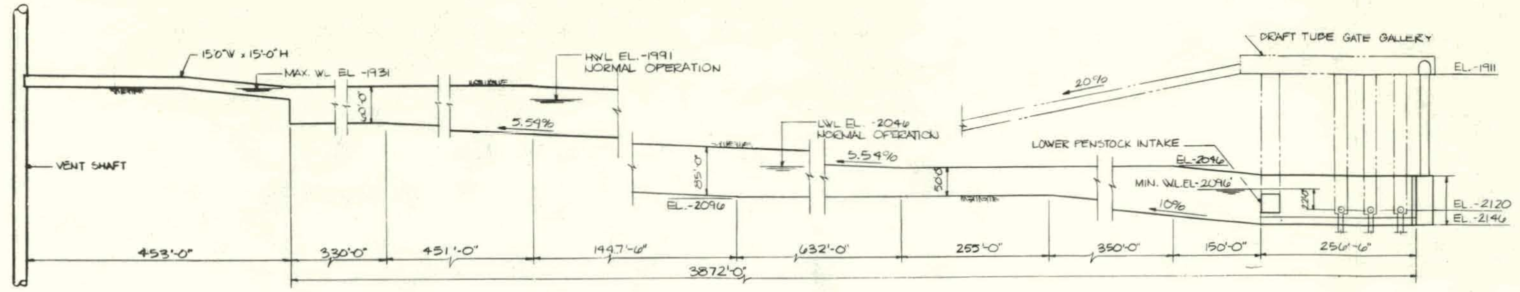

SECTION A-A

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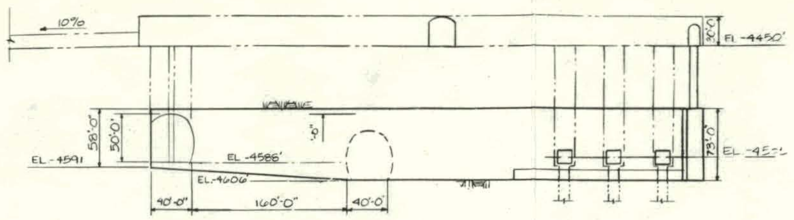

SECTION F-F

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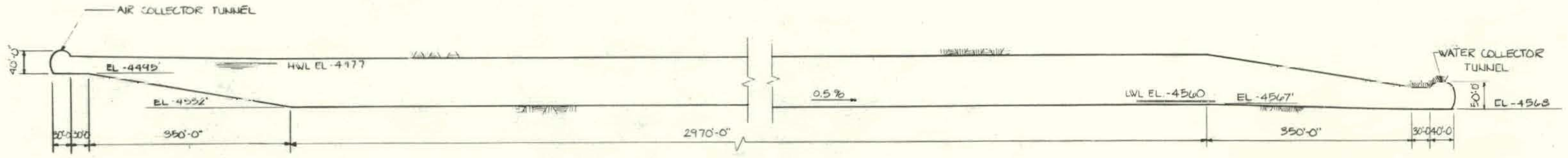

SECTION B-B

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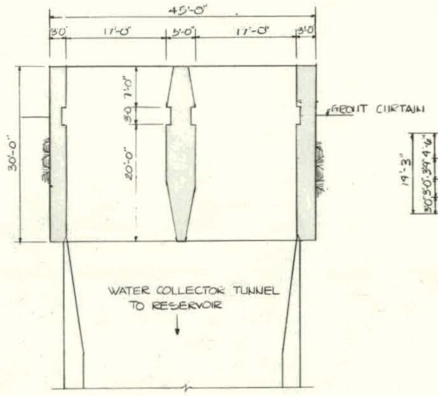

TYP. SECTION OF STOPLOP
CHECK AT WATER PASSAGE

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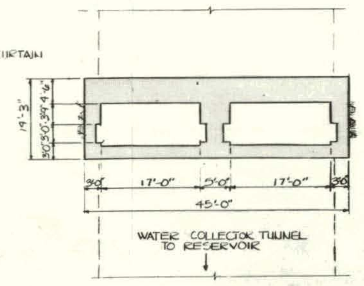

TYP. SECTION OF STOPLOG
CHECK ABOVE WATER PASSAGE

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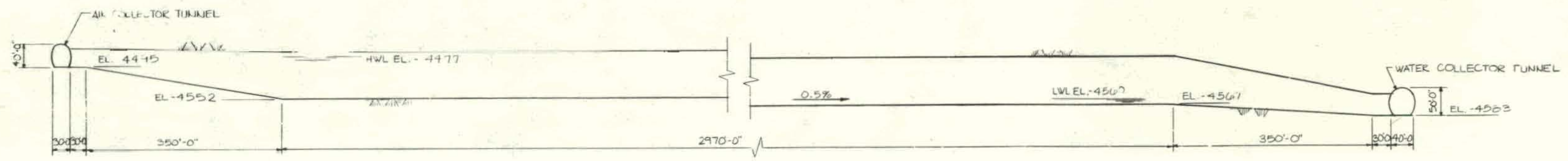

SECTION C-C

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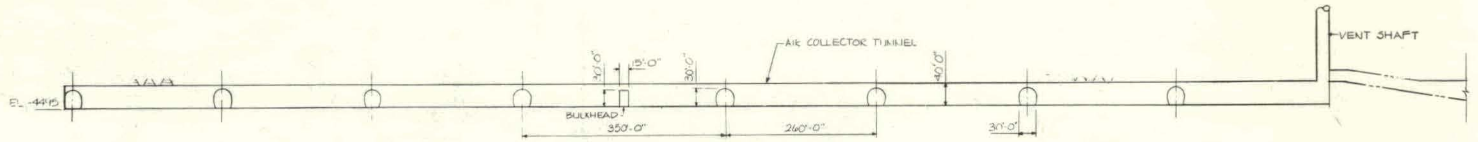

SECTION D-D

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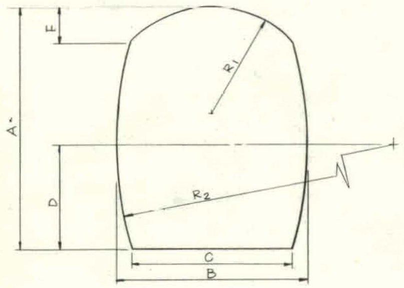
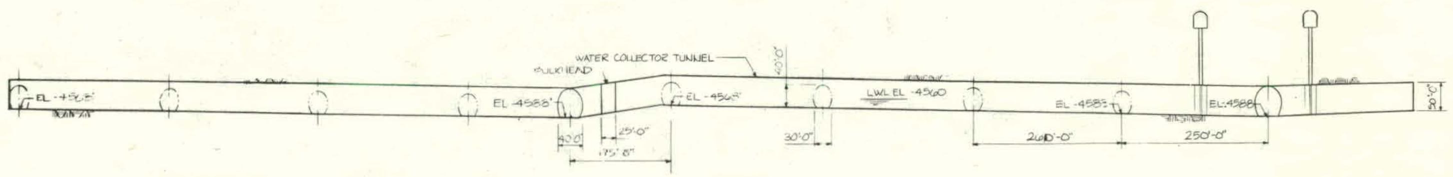


TYPICAL SECTION

		A	B	C	D	E	R_1	R_2
1	MAIN CAVERN	85'	65'	55'	36.25	12.5'	37.5'	135'
2	WATER COLLECTOR TUNNEL	50'	40'	34'	21.2'	7.5'	23'	76.3'
3	AIR COLLECTOR TUNNEL	40'	30'	25.5'	17'	6'	16.6'	65.4'
4	MAIN CAVERN ENTRANCE TO WATER COLLECTOR TUNNEL	40'	30'	25.5'	17'	6'	16.6'	65.4'
5	MAIN CAVERN ENTRANCE TO AIR COLLECTOR TUNNEL	30'	30'	26.5'	12'	6'	17.6'	42'



SECTION E-E

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NOTES
1. SEE PLATE 29 FOR PLAN OF LOWER AND INTERMEDIATE RESERVOIRS

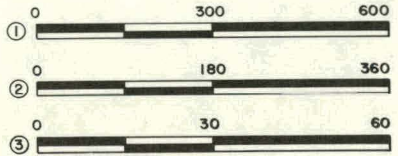

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Figure 8-4

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LOWER & INTERMEDIATE RESERVOIR
SECTIONS & DETAILS

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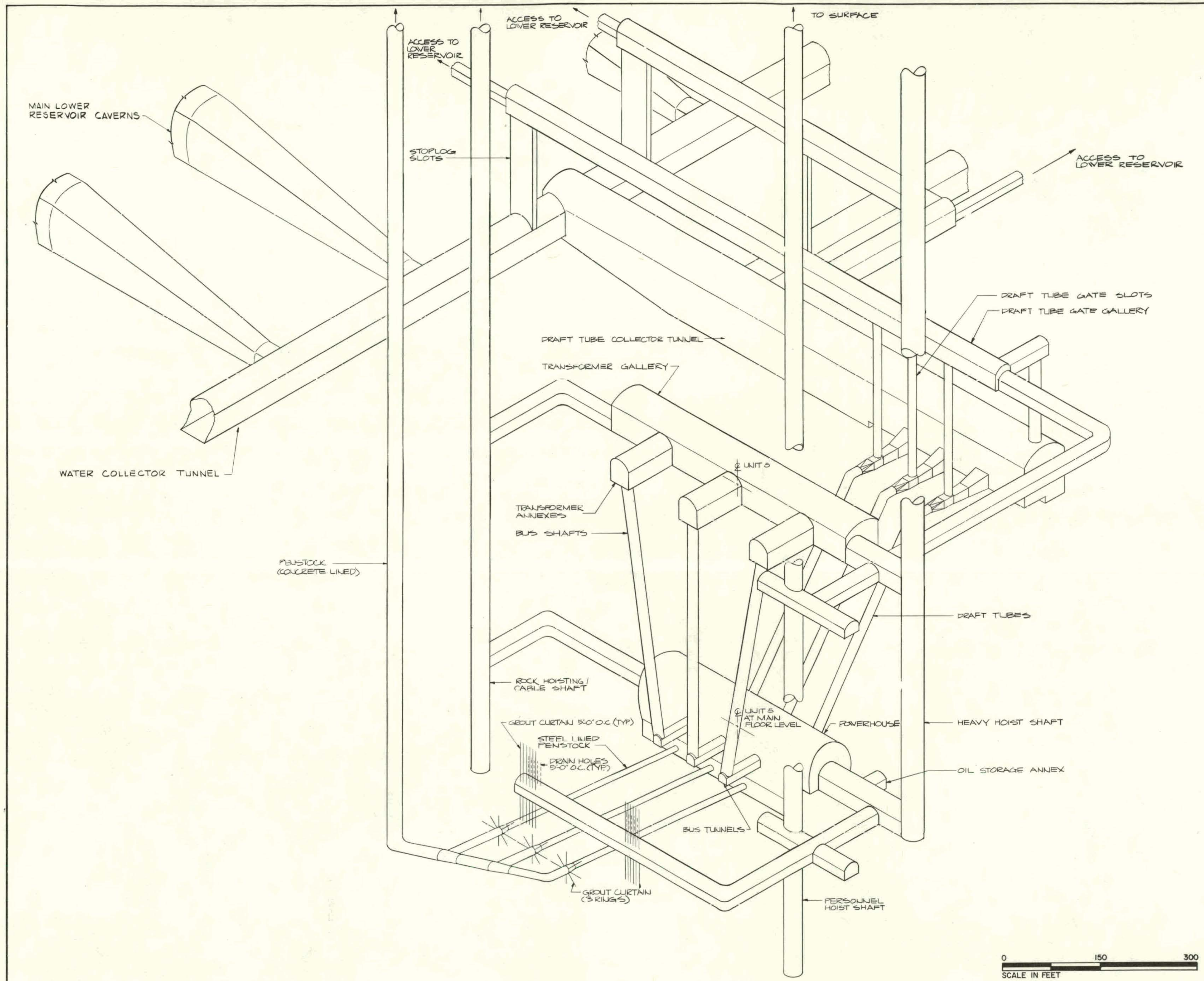

Figure 8-5

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ISOMETRIC OF
LOWER POWER FACILITY

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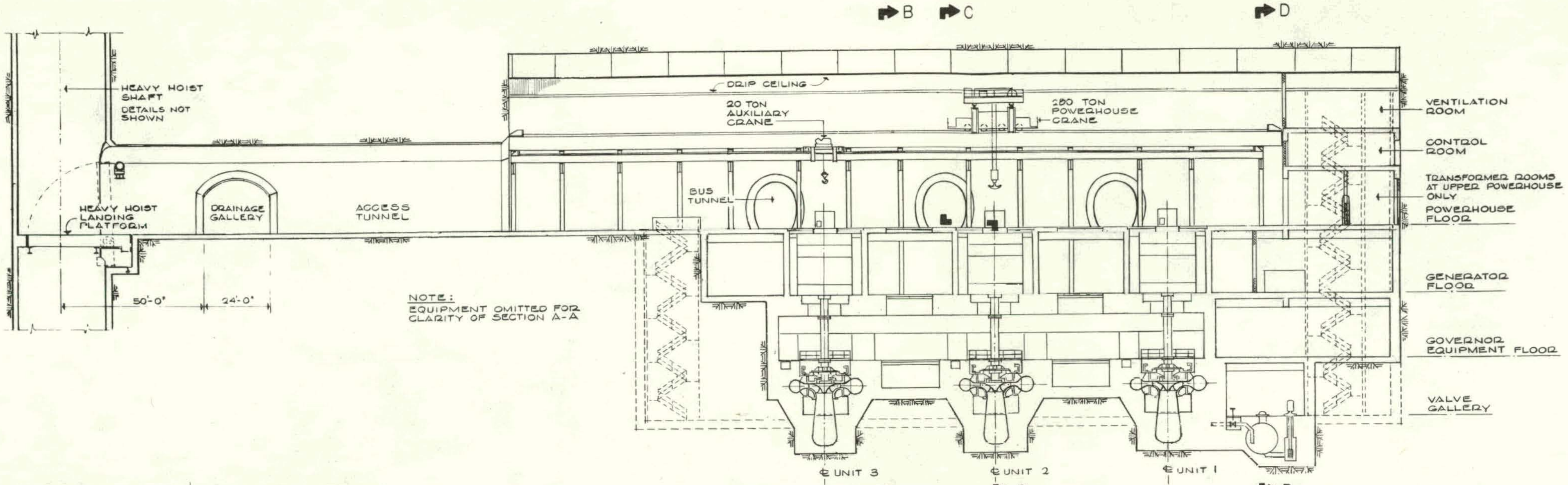
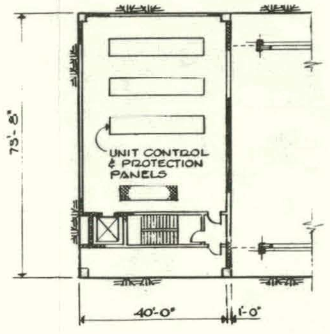
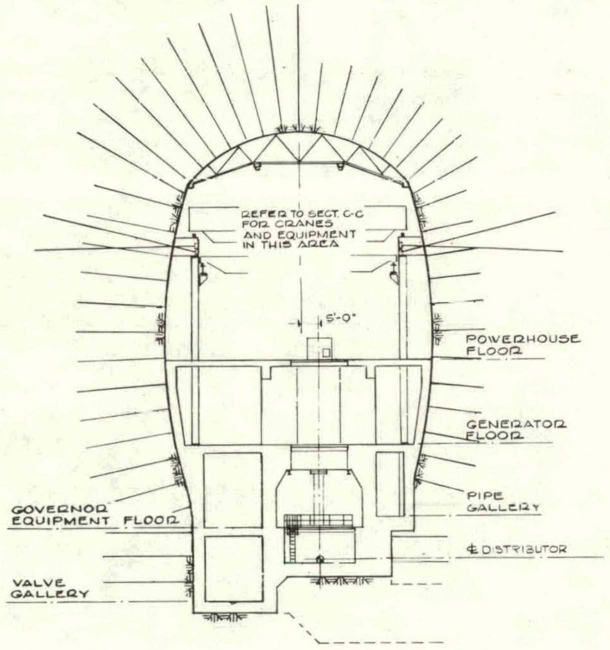


LONGITUDINAL SECTION A-A THROUGH POWERHOUSE



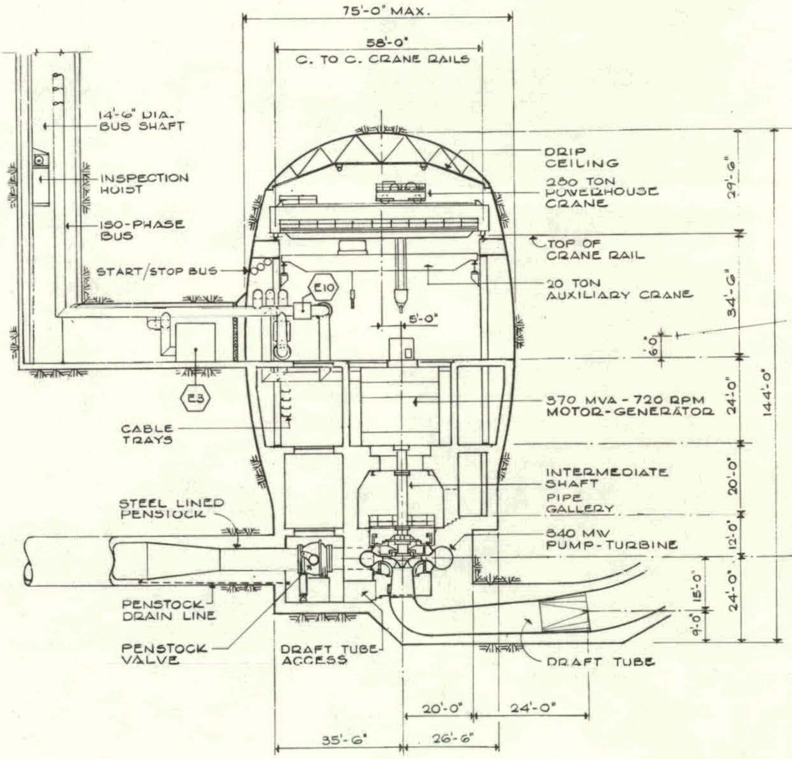
CONTROL ROOM PLAN

	LOWER POWERHOUSE	INTERMEDIATE POWERHOUSE
CROWN:	35 FOOT-75 KIP ROCKBOLTS 5'x5' GRID 4" SHOTCRETE W/ MESH	20 FOOT-75 KIP ROCKBOLTS 5'x5' GRID 4' SHOTCRETE W/ MESH
WALLS:	25 FOOT-75 KIP ROCKBOLTS 7'x7' GRID 4' SHOTCRETE W/MESH	15 FOOT-75 KIP ROCKBOLTS 7'x7' GRID 4"SHOTCRETE W/ MESH

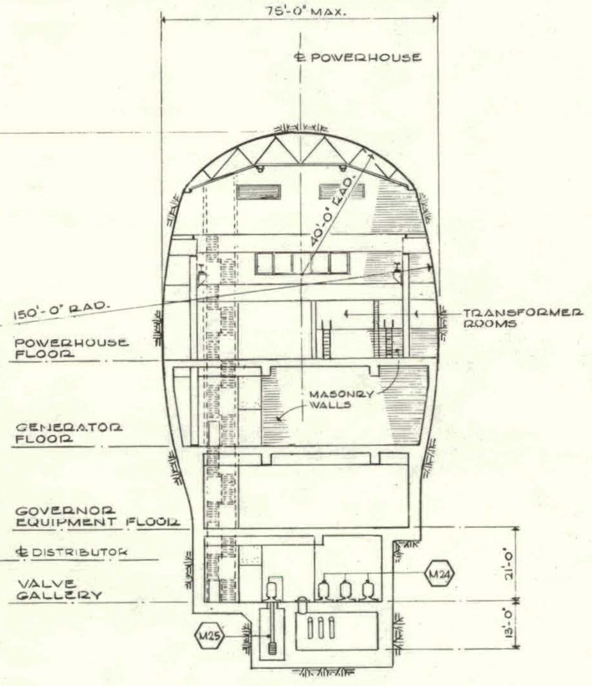


NOTE:
ROCKBOLT SPACINGS ARE APPROXIMATE AND ARE FOR ESTIMATING PURPOSES ONLY.

SECTION B-B



SECTION C-C



SECTION D-D

NOTE:
REFER TO PLATE 16 FOR EQUIPMENT SCHEDULES.

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Figure 8-6

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POWERHOUSE
SECTIONS

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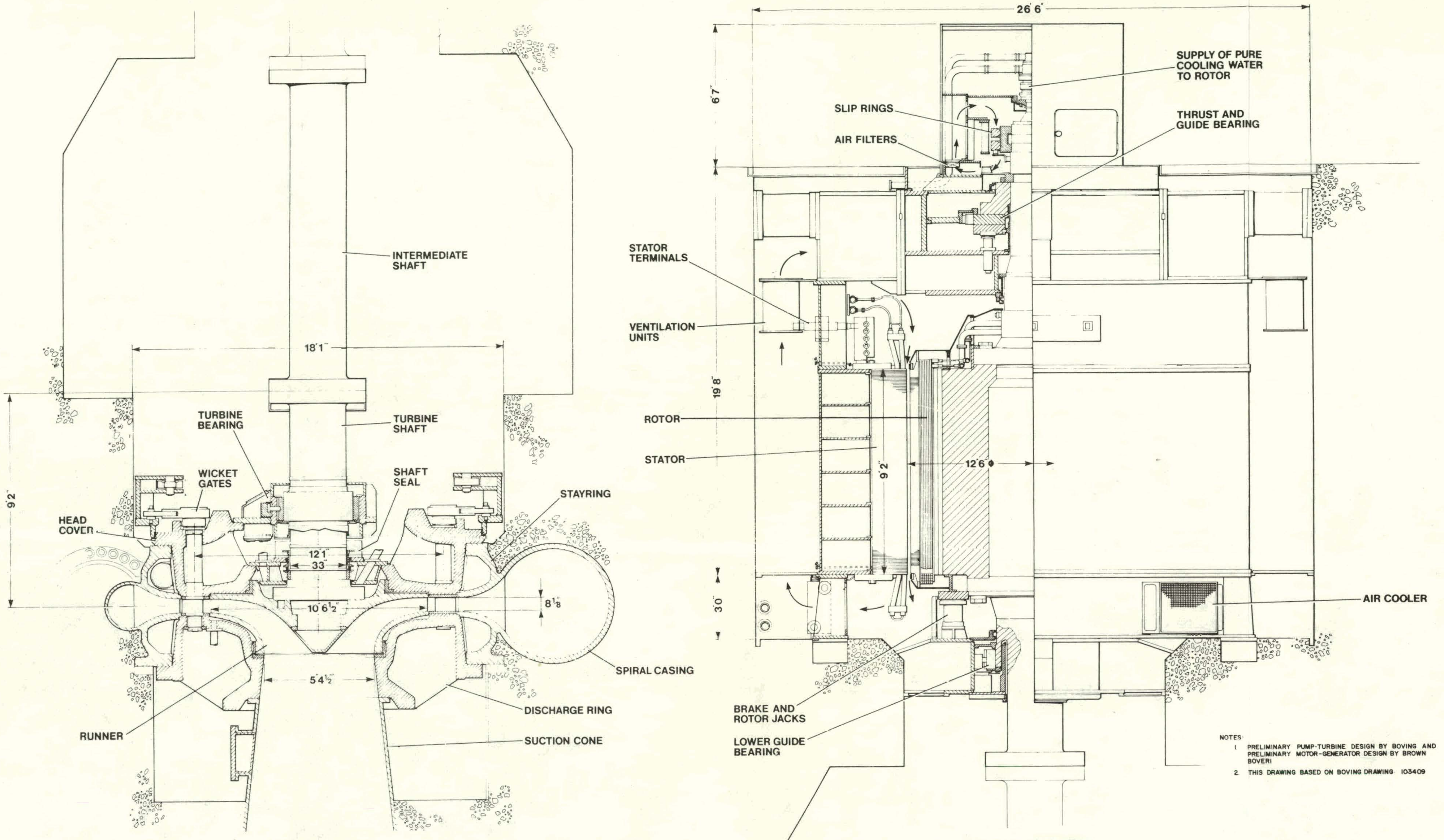

NOTES:
1. PRELIMINARY PUMP-TURBINE DESIGN BY BOVING AND PRELIMINARY MOTOR-GENERATOR DESIGN BY BROWN BOVERI
2. THIS DRAWING BASED ON BOVING DRAWING 103409

PUMP-TURBINE

HEAD	2500 FT.
OUTPUT	340 MW
SPEED	720 RPM

MOTOR-GENERATOR

OUTPUT	370 MVA
POWER FACTOR	1.0 (MOTOR)
	0.9 (GENERATOR)
SPEED	720 RPM

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Figure 8-7

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ENERGY STORAGE STUDY – UPH

PUMP-TURBINE
AND
MOTOR-GENERATOR

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Switchyard

The tie-in to the 500 kV transmission line will follow the arrangements adopted for the CAES plant and will be made through overhead connections to the switchyard arranged in the breaker-and-a-half configuration. The air-insulated switchyard will use SF_6 gas-insulated switchgear and will be basically similar to PEPCO's 500 kV facilities at the Chalk Point generating plant. Provisions are made in the switchyard for:

- Four transmission lines to Mount Airy;
- Four transmission lines to Brighton;
- Three motor-generator circuits (500 kV bus); and
- Two station service connections.

Lower Reservoir

General. The final component of the UPH facility is the lower reservoir, the feature which introduces the "unconventional" nature of this concept of hydroelectric pumped storage. Excavations of the equivalent volume of rock removed for the proposed UPH lower reservoir have been made previously in a variety of host rocks and integrity with time has been clearly established. With the excavation of seven to eight million cubic yards of rock specifically from the lower reservoir in an UPH system, certain new requirements mainly influenced by schedule will be introduced. It is clear, furthermore, that the economic viability of the UPH concept will depend substantially on the ability to excavate large volumes of rock from substantial depth on a rapid schedule. The necessary level of performance appears to be well within reach of modern construction practice.

Lower Reservoir Caverns. For the UPH 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 a further storage cycle. The lower reservoir will operate at all times at near atmospheric pressure with a free water surface. Details of the lower reservoir are shown on Figures 8-3 and 8-4.

The required excavation will be in the form of 12 tunnels of substantial cross section (85 ft by 65 ft) interconnected by smaller air and water collector tunnels at the extreme ends of the reservoir system. The excavation volume will be 7,860,000 yd^3, which will allow 2.3 percent for "safety" storage to prevent overfilling of the lower reservoir, and a further 0.3 percent 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 smaller cross section and can be safely constructed with the less desirable rock conditions in line with the strike of the rock folation. 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 which 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.

SITE DEVELOPMENT

The first phase of development for the two-step (SSRPT-2) UPH facility will be planned to include construction of those works necessary to accommodate and provide storage for four pumping/generating units (two in an upper power plant and two in a lower one) each of 333 MW capacity (thus providing a total first phase installation of 1333 MW). All shafts, penstocks and excavations for operating plant facilities underground will be provided in the first phase. However, the lower reservoir will only be excavated to two-thirds of its final designed volume. The second phase of development will include the construction of those works necessary to bring the total installed capacity up to 2000 MW.

Based on this requirement, the following stages for site development were established:

- STAGE I (0-45 months) - This will include site preparation, mobilization, establishment of construction facilities, construction of vertical penstock, air-vent shaft, heavy hoist shaft, cable shaft and personnel shaft;
- STAGE II (45-75 months) - This will include construction of the underground powerhouses, the upper reservoir and intake structure and the intermediate reservoir. Excavation for the lower reservoir will commence;
- STAGE III (75-96 months) - This will include the completion of the lower reservoir excavation and the installation of mechanical and electrical equipment and commissioning of the first four units; and
- STAGE IV (108-180 months) - This phase will include completion of the lower reservoir to its final designed volume and the construction of the remaining two units.

The site development for the UPH facility was formulated from the detailed activities involved in each construction phase to assure compliance with the project milestone and overall schedules. An in-depth review was made to ensure the compatibility of rock production from underground works with its potential utilization on surface works. This is particularly important in consideration of assuring uninterrupted construction of the main surface reservoir. It is envisioned that a stockpile of rock will accumulate during construction and remain on site after completion.

CAPITAL COST ESTIMATE

The cost estimate for the six-unit plant (each unit rated at 333 MW) developed in this study is site specific and based upon a location near Sunshine, Maryland. The cost estimate is based on price levels ruling for labor, material, equipment and services in mid-1979.

A summary of the cost estimate is given in Table 8-1. The total direct costs are $831.5 million or $415.7 per kW. It will be noted that the estimate for the lower reservoir amounts to approximately 20 percent of the total direct costs and that the estimate for all the shafts required amounts to approximately 16 percent of the total direct costs. The indirect costs, consisting of owner costs, engineering, and construction management costs with contingencies, are $375.1 million, bringing the total capital cost to $1205.6 million or $602.8 per kW.

Table 8-1

SUMMARY OF CAPITAL COST ESTIMATE
UPH - SSRPT-2

Installed Capacity:	2000 MW
Storage Capacity:	20,000 MWh
Nominal Operating Head:	5000 ft

Estimate based on mid-1979 costs

Item	Amount, $ x 10^6	
Land and Site Access	6.2	
Surface Structures	7.1	
Upper Reservoir & Intake	31.2	
Intermediate Reservoir	27.4	
Lower Reservoir	243.7	
Shafts	134.5	
Miscellaneous Tunnels & Galleries	63.6	
Powerhouse Civil Works	46.4	
Pump-Turbines & Valves	56.8	
Motor-Generators	80.9	
Transformers & Electrical Equipment	62.3	
Auxiliary Mechanical Equipment & Hoists	42.3	
Switchyard & Transmission	29.1	
Total Direct Costs	831.5	($415.7/kW)
PEPCO Costs (15% of Direct Costs)	124.7	
Engineering Costs (5% of Direct Costs)	41.6	
Construction Management Costs (10% of Direct Costs)	83.1	
Contingencies (15% of Direct Costs)	124.7	
TOTAL	1205.6	($602.8/kW)

NOTE: No provisions have been made in this capital cost estimate for escalation or interest during construction.

Section 9

COMPARISON OF CAES AND UPH

Choosing a preferred concept (UPH or CAES) to meet the energy storage needs of a power utility depends on several factors, including the existing generation mix, the desired level of energy storage, the rate of load growth, the extent of interconnection, and several other factors specific to the utility or planning group. This study has shown that there is no clear advantage of the UPH concept over the CAES concept on the PEPCO system, or vice versa, and that the selection of one or the other can only be made after a careful evaluation of all alternatives within the context of constraints and opportunities particular to the utility system.

On the more positive side, this study has demonstrated that both UPH and CAES are viable forms of central energy storage which, given the appropriate conditions, can compete economically with other forms of peaking power such as combustion turbines, cycling thermal plants, hydroelectric generation and conventional hydroelectric pumped storage. Both UPH and CAES have been shown to be technically feasible and to have appreciably lower environmental impact than conventional hydroelectric pumped storage relying on surface elevations for reservoir location.

The principal common feature in the UPH and CAES concepts examined in this study is the use of large underground caverns excavated in rock. Whether either of these concepts could be considered for a given service area or planning region therefore depends on the presence of reasonably high quality rock at the appropriate depth. Fortunately, large areas of the U.S. are underlain by bodies of suitable rock, the primary exceptions being in the southeastern (Florida) and central-southern (Louisiana, Mississippi) regions. The economic attractiveness of both UPH and CAES is likely to be eroded very rapidly if the rock is not of high quality.

UPH and CAES have several features in common, including the need for a relatively small site area, the potential for locating the site near the load center (given adequate geotechnical conditions), and the need for relatively small quantities of initial fill and make-up water.

Some other characteristics of the CAES and UPH plants are appreciably different and the more quantifiable of these are listed in Table 9-1. One of the most significant differences is that, to obtain a competitive level of economy, the minimum installed capacity for an UPH facility is in the order of 1200 to 1500 MW with 10 hours of energy storage. The comparable economy level for a CAES facility is probably no more than 400 to 500 MW with 10 hours of storage. This means that other factors being equal, an UPH plant will be less attractive to any small system that is unable to share with others the cost of construction, the operation of a large facility, and the benefits.

However, if the system or interconnected pool is able to accept the larger UPH capacities and plant output, then it can be seen that the system economy improvements per unit of installed capacity projected for both UPH and CAES are essentially the same with respect both to revenue requirements and to oil consumption savings.

The CAES system (in contrast to UPH) consumes No. 2 fuel oil during the power generation cycle and the implications of an oil-burning facility must be considered, especially with regard to the sensitivity of overall plant economy to fuel cost. Both UPH and CAES accounted for about the same total fuel oil (No. 6 and No. 2) savings in the PEPCO system studies, which tended to mitigate this concern. Nevertheless, CAES economics are very sensitive to No. 2 oil relative costs and must be evaluated on a utility specific basis to obtain full appreciation of the phenomenon.

The smaller size and shallower depth of the CAES facilities lead to a reduction of some three years in the construction period required to bring the first units on line compared with UPH. The pre-construction licensing and permitting processes are projected to require the same period of time for both types of facilities. From the standpoint of the preliminary exploratory program, the greater depth required for the UPH caverns may lead to additional problems and additional costs. However, the rock in which the UPH caverns will be

Table 9-1

COMPARISON OF COST, ECONOMY AND SCHEDULE FOR CAES AND UPH

NOTE:

CAES installed generating capacity = 924 MW (675 MW required on PEPCO system)
UPH installed generating capacity = 2000 MW (667 MW required on PEPCO system)

	CAES	UPH
1. COST		
Direct Cost	$\$347.0 \times 10^6$	$\$831.5 \times 10^6$
Direct Cost/kW	$376	$416
2. ECONOMY		
Revenue Improvement 1990-2007	$\$1358 \times 10^6$	$\$1246 \times 10^6$
Oil Savings 1990-2007	19×10^6 bbl	16×10^6 bbl
Annual Oil Saving After 2007	2×10^6 bbl	2×10^6 bbl
3. SCHEDULE		
Licensing	3.75 years	3.75 years
Construction (Phase I only)	5 years	8 years

constructed will be subject to less severe operating requirements than would be the case for the pressurized CAES caverns. The potential for accelerated deterioration of CAES rock caverns operating under repeated cycles of pressure and temperature has caused concern. No significant problems are anticipated with the ranges proposed in this study but should these ranges for one reason or another be substantially elevated or prolonged, long-term cavity stability might be affected.

The proposed operating cycle and machinery train selected for the CAES plant provides considerable flexibility in plant operation, allowing unit output over the full range from 10 to 110 percent of rated output and compression (equivalent to pumping on UPH) input over a 75 to 105 percent range of motor power. The UPH facility is somewhat limited by the characteristics of the reversible pump-turbines which function best between about 50 to 105 percent of rated output when generating, and can pump only at a fixed duty point depending on head and requiring full motor output. The multi-unit station is able to follow demand for steadily increasing generation by adjusting load on the several units operating; when pumping, system power has to be picked up in blocks of unit motor capacity. The reduced load following capability of the UPH plant, however, is offset by its ability to provide more rapid starting, stopping and mode changing as shown in Table 9-2.

The smaller and shallower cavern excavations and the shorter construction schedule of the CAES facility provides possibly a firmer basis for the projection of construction costs than do the very large and deep caverns required for the UPH facility. Other considerations, however, impact greater confidence to UPH facilities. For instance, the more extensive experience already gained in the design and operation of high-head pump-turbines of the type required is significant. There are, furthermore, still some uncertainties associated with the design and operation of the compressed air storage caverns for CAES.

In summary, although CAES and UPH plants have distinct and different characteristics, design features, construction requirements and operation modes, both concepts are now viable and feasible for power utility use. The choice of which alternative to select must be made on the basis of a careful evaluation of the characteristics of each in relation to the required energy storage duty of a particular system.

Table 9-2

COMPARISON OF OPERATING CHARACTERISTICS OF CAES AND UPH
(On a unit basis)

	CAES	UPH
Operating Range:		
- generating (% rated load)	10 - 110%	50 - 105%
- pumping (% motor input)	105 - 75%	100%
"Cold Start" Time:		
- generating	10.0 min 5.5 min*	1.7 min
- pumping	5.0 min	9.7 min
Full Generating from Spinning Reserve	6.0 min	0.7 min**
Full Pumping to Full Generating	24.0 min 14.5 min*	7.7 min 2.0 min*
Rate of Change of Output	5% per min	0 - 100%/10 s

*Emergency Loading Characteristics
**Pump-Turbine Unwatered

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