ECONOMIC EVALUATION OF TWO ENERGY STORAGE SYSTEMS

John B. Jutasi

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ABSTRACT

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John Bela Jutasi

As demands for electric power continue to increase at a rapid rate, the generation of peaking power becomes a major concern for the utility industry.

The concept of storing excess base-load energy for later release as peaking power is very attractive, particularly for utilities with system demands sensitive to atmospheric temperature and with wide day-to-day load fluctuations. In North America, during the past 20 years, conventional pumped storage found fairly wide application, and has advanced to its present significant role in the production of peaking power.

However, conventional pumped storage is now by no means the only available choice. During the past decade attention has been focused on the development of new means of bulk energy storage. These alternatives include Underground Storage Pumped Hydro (UPH) and Compressed Air Energy storage (CAES).

The objective of this thesis is to describe these two near-term energy storage systems and to generate preliminary capital and fixed annual costs for each in order to develop information for decision makers as an aid in the selection of one of the alternatives for the purpose of constructing a 1000MW plant to be designed to provide peaking power for a period of 2 hours daily in Montreal.

Based on the available information it was found that the UPH system would be a more economical choice, in spite of higher capital cost requirements, because of the greater reliability, its longer service life, and its independence from potential inflation affecting fossil fuels. The UPH system also has a comparatively smaller negative ecological impact.

ACKNOWLEDGEMENTS

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INTRODUCTION

A significant element of the present energy crisis is the growing inability of existing generating facilities to meet the ever increasing peak loads demanded by commercial, industrial and domestic consumers. Before 1960 these peak loads were supplied by conventional hydro plants and gas turbines. Technically it would be possible to incorporate at the existing hydroelectric plants sufficient capacity to meet the peak load demands. This would, however, require additional turbine-generator units - which would be severely under-utilized during periods of low load demand - and the construction of additional transmission lines to carry the extra load. Considering the great distances between the major hydroelectric generating sites in Quebec (over 500 miles in some cases) the cost of electricity generated in this manner would be prohibitive.

The objective of this report is to examine the economic feasibility of two possible alternative schemes. They are: Underground Pumped Hydroelectric Energy Storage (UPH) and Compressed Air Energy Storage(CAES).

In this report the UPH and the constant pressure CAES systems will be compared.

Although the exact requirements are not known, for the purpose of this report it will be assumed that there exists, at the present time, a need for approximately 1000 MW peak-power generation in Montreal for a period of two hours per day.

The economic evaluation will be based on:

a) the dollars per kilowatt capital cost, and
b) fixed annual costs.

CHAPTER I

ENERGY STORAGE

1.1 General

During the last twenty years, peaking capacity in North America has been provided by an increasing number of hydroelectric pumped storage plants. These plants employ water as the working fluid, storing energy by increasing the potential of the water by pumping it to a higher-level pond utilizing off-peak power generation and releasing it through the kinetic energy of the stored water passing through a hydroelectric generating facility during the peak power demand period.

The total installed capacity of conventional pumped storage in North America is currently about 6,000 MW[1] with only one installation of 198 MW in Canada, the Sir Adam Beck plant in Ontario. All this capacity is in the form of reversible pump-turbine, motor-generator units operating under heads of between 80 and 1500 feet. It is forecast that in the next 20 years the total installed capacity of energy storage systems in North America could grow well over 50,000 MW.[3]

Conventional pumped storage suffers from a number of disadvantages, not the least being that suitable sites are generally remote from load centers and are often the subject of considerable opposition from environmentalists. This is why a growing number of utilities look to underground siting of at least a portion of their energy storage plants.

Underground pumped hydroelectric energy storage (UPH) is defined as a system where the lower reservoir and one or more power stations are located in deep chambers or caverns and the upper reservoir is located at ground level. Compared with conventional hydroelectric pumped storage plant, the site selection is greatly simplified by eliminating the topographic relief requirements and the need of ground space suitable for the power station and lower reservoir.

Figure 1 shows, in very general terms, the current light in which pumped energy storage absorption and generating capacity might be viewed in a planning sense. On the load generating side, pumped energy storage plants have five major advantages:

1. Standby capacity available at very short notice;
2. Spinning reserve capability;
3. Frequency regulation ability;
4. Load carrying capability in midload factor band;
5. Stored energy to meet system demand variations.

During the last ten years an alternative method, the Compressed Air Energy Storage (CAES) has become accepted as a potentially feasible system. A modified gas turbine uses off-peak electric power to compress air which is stored in an underground cavern. When electric generation is required the compressed air is supplied to the turbine along with fuel to drive the generator.

One type of compressed air storage system includes a pressure compensating water reservoir situated at ground level which is alternately filled and emptied. Site requirements for this system are similar to those of the underground pumped hydroelectric energy storage plant.

1.2 Characteristics of Electric Loads

It is, perhaps, rather remarkable that a large electric power system, like Hydro-Quebec, can operate well with no capacity for storing electricity. That it does so is largely due to the diversity of consumer demand which traditionally ensured that the total load on the system normally changed rather gradually, and in a fairly predictable way. However, the demand in the small hours of the morning may be only 1/3 of that during the peak hours of the working day.

System loads normally are highest during the weekdays and drop off on weekends as shown in Figure 2.

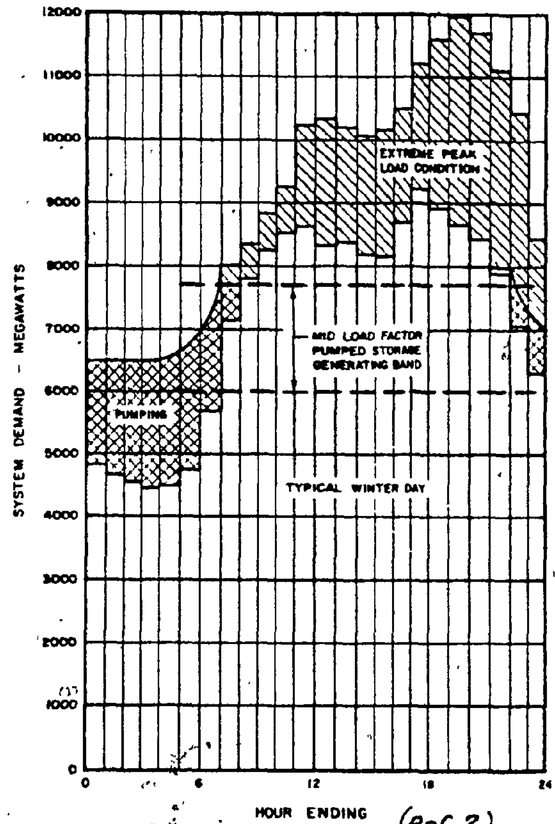


Fig. 1: Typical daily load curve for U S. Power System.

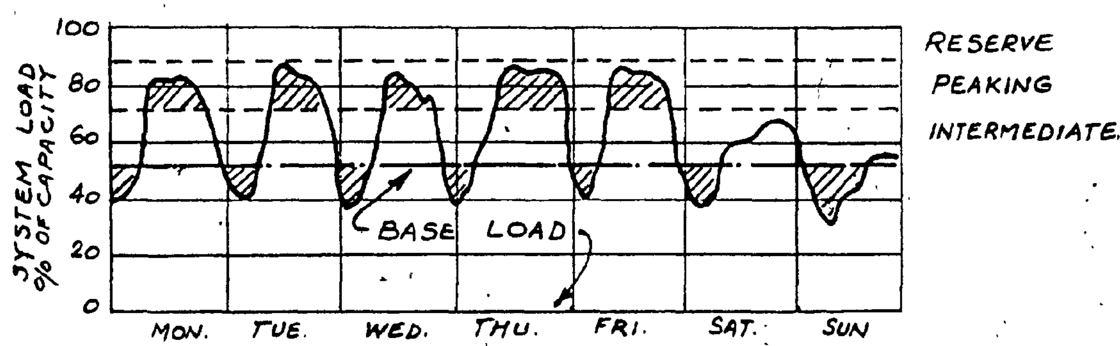


Figure 2 : Typical weekly load curve (Power Engineering, December 1977)

In recent years, many utilities have experienced a change in the character of their daily loads, due primarily to electric air conditioning during the summer and electric space heating in winter. These changes have increased the peaks and extended the duration of daily and seasonal near-peak demand levels. Examining Figure 2 it can be seen that about 50% of the system capacity of this particular utility is continuous. This is called the system's "base load". The "intermediate system load" amounts to approximately 30% of maximum demand and is continuous for periods of 12 or more hours on weekdays. The "peak" portion of the load, amounting to about 20% of the maximum demand can occur over a period of less than one hour to about 12 hours.

The immediate consequence of this load curve is an economic penalty. Generating plants must be available to meet the peak demand for only a few hours daily. As far as it can be seen the total demand will continue to vary markedly as a function of the time of day and this must be met either by direct generation from plants which take up and shed load in response to the variations, or through storage systems which would permit existing plants to operate at higher capacity factors to inject power into storage during low load periods for return to the system later.

1.3 Determination of Need for Peaking Power

The starting point in the evaluation of peaking power requirement for a utility is a system load forecast study. The forecast of peak loads and surplus off-peak capacity gives an indication of the size of the peaking power plant which the utility requires.

A detailed system load forecast study is outside the scope of this report, it is also a very specialized aspect of system management which requires an intimate knowledge of all aspects of a utility. However, there are other methods of establishing if there is a potential need for peaking power. One of these methods is the review of the system's capacity and the corresponding peak demands. Table 1 shows these figures for the Hydro Quebec system from 1965 to 1979 and also indicates the preliminary forecasts to the year 1990.

TABLE 1

HYDRO-QUEBEC - PROVINCIAL NETWORK
CAPACITY AND PEAK DEMANDS
FOR THE PERIOD 1965 - 1990

Year	Total Capacity (MW)	Peak Demand (MW)	Additional Generation Installed or Planned (MW)	
1965	6,496	5,804	Carillon: 187	Tracy: 150
1966	7,280	6,318	Manic 2: 634	Tracy: 150
1967	7,694	6,885	Manic 2: 254	Manic 1: 123
1968	8,106	7,595	Manic 2: 127	Tracy: 150
1969	8,292	7,856	Various: 141	Tracy: 150
1970	9,753	8,607	Various: 1388	
1971	10,568	9,041	Manic 5: 808	
1972	12,011	9,266	Churchill Falls: 950	Manic 5: 485
1973	12,965	10,122	Churchill Falls: 950	
1974	14,912	11,271	Churchill Falls: 1900	Others: 37
1975	16,349	11,794	Churchill Falls: 1425	Others: 12
1976	16,586	13,182	Manic 3: 197	Others: 31
1977	17,627	14,879	Manic 3: 986	Others: 54
1978	17,748	15,744	Various: 122	
1979	18,202	16,800	Outardes 2: 454	
1980	19,658	18,325	LG-2: 1307	LaCitiere: 284*
1981	21,007	19,725	LG-2: 1307	Carillon: 42
1982	23,603	21,200	LG-2: 1959	Gentilly 2: 685**
1983	24,832	22,375	LG-2: 653	LG-3: 576
1984	26,368	24,000	LG-3: 1536	
1985	28,590	25,775	LG-3: 192	LG-4: 2030
1986	30,470	27,650	LG-4: 580	Others: 2300
1987	32,522	29,500	LG-1: 352	Others: 1700
1988	35,000	31,775	LG-1: 528	Others: 1950
1989	37,704	34,200	LA-1: 660	Others: 972
1990	40,697	36,825	LA-1: 410	Others: 2783

Source: Hydro Quebec - March 1979

* Gas turbine peaking plant
** Nuclear power plant

Hydro Quebec's current generation expansion is designed to meet an average utility growth of 7.7% per annum in peak demand over the next decade(13).

Figure 3 shows the total capacity and peak demands of the Hydro Quebec system for the period 1965 - 1990.

The installation program is expected to have three stages during 1979 - 1990:

1979 - 1980

- Complete the Outardes hydroelectric base load plant of 454 MW capacity.
- Install the La Citière gas turbine peaking power plant of 284 MW capacity.
- Continue the purchase of peaking power, as required by seasonal demands, to meet the capacity deficit which would otherwise exist in this period.
- Start bringing into service, in stages, the La Grande complex now under construction in the James Bay region.

  The La Grande complex has an ultimate capacity of approximately 10,270 MW.

1981 - 1985

- Continue adding the La Grande complex to the system.

1986 - 1990

- Complete the La Grande complex.
- Add about 3,600 MW of nuclear base load capacity.
- Add about 4,600 MW of peaking capacity.

The following brief announcement appeared in the mid-January 1979 HYDRO-PRESSE publication (translated from the French text):

"NEW PEAK DEMAND RECORD: on December 18, 1978 at 17:00 hours the temperature was -13°C, at this time the load demand reached a peak of 15,747 MW exceeding the previous record demand of 14,879 MW set on December 12, 1977."

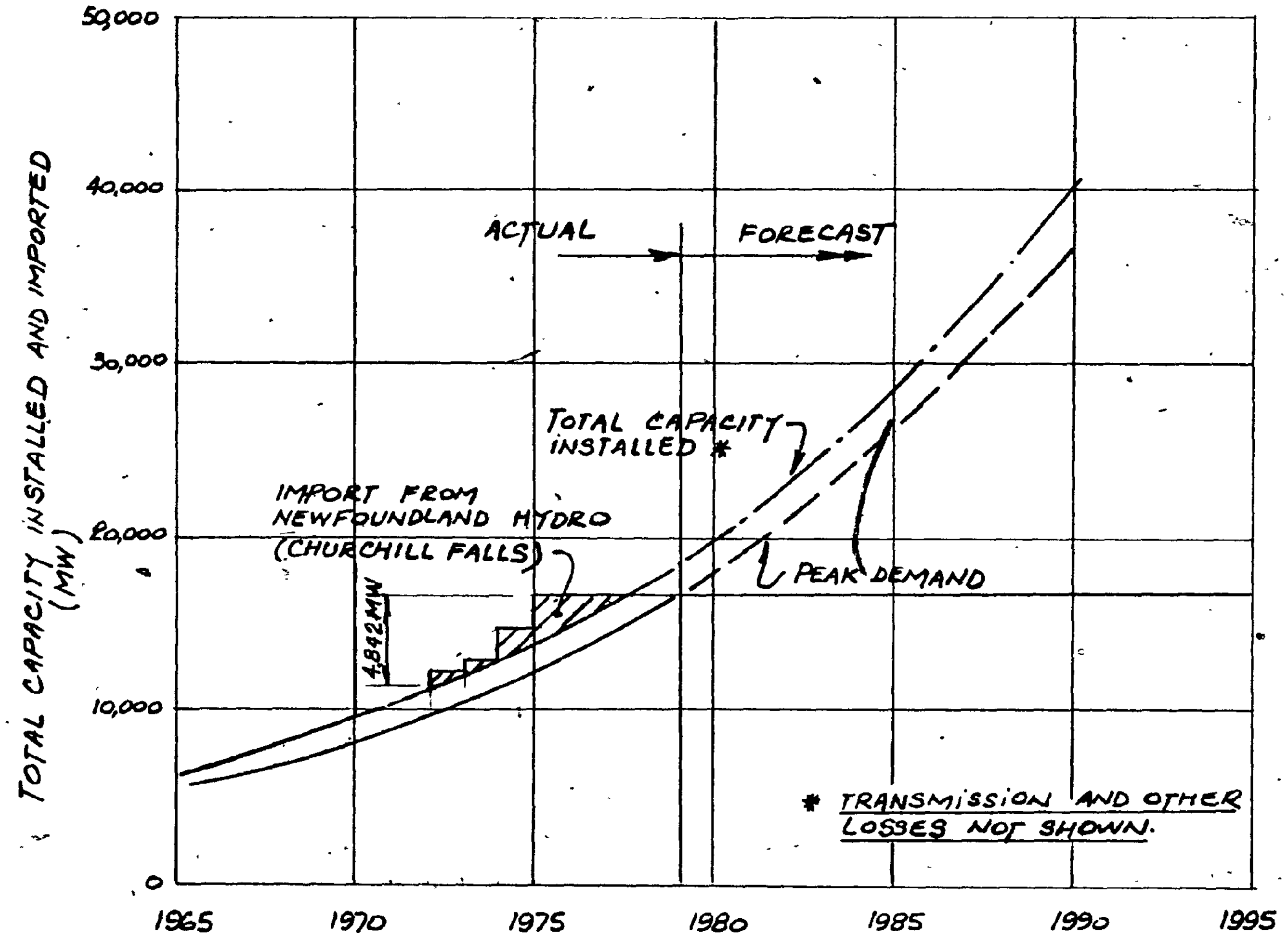


Fig. 3 - TOTAL CAPACITY AND PEAK DEMANDS, HYDRO QUEBEC SYSTEM 1965-1990

(PLOTTED FROM DATA OBTAINED FROM HYDRO QUEBEC. MARCH 1979)

Although Table 1 shows that the total capacity of the system in 1978 was 17,748 MW (including 4,842 MW import from Newfoundland Hydro's Churchill Falls plant) this capacity was not fully available because:

a) the Tracy thermal power station of 600 MW was out of operation.

b) the Gentilly 1 experimental nuclear power station of 266 MW was also inoperative and has been so for a number of years due to corrosion problems. This power station is still owned by the Atomic Energy of Canada Limited, however, transfer is expected for take place in the near future.

c) the capacity figures do not indicate electrical losses in the transmission network, which amount to about 7%.

It must also be realized that the total capacity can not be counted on entirely for local consumption because Hydro Quebec has contractual agreements with the U.S. and with Ontario, the latter amounts to some 10,455 GWH per year(13). However, on the date referred to above Hydro Quebec had to stop exporting power and started to import it, including some 200 MW from Ontario.

Therefore, in summary, it can be stated that:

1) There exists, at the moment, in the Province of Quebec a deficit in peaking power during the winter months, under certain circumstances.

2) Hydro Quebec is planning to install peaking power capacity in the form of gas turbines to satisfy the need until 1986 and that between 1986 and 1990 the present planning indicates an additional 4,600 MW of peaking capacity installation.

It is not exactly known what type of generating method will be used for this purpose, however, it is safe to assume that it might include some form of energy storage system. Hydro Quebec had studied various sites with the view of establishing conventional pumped storage hydro plants. One of the potential sites is situated some 30 miles north of Hull in the Gatineau hills where evidently there is a potential site on Proulx Lake with an ultimate capacity of some 4000 MW[16]. During the past 10 years Hydro Quebec has met with a great deal of hostility from environmentalists whenever it had investigated the possibility of constructing conventional pumped storage hydro plants. Some of the proposed sites were either protected natural parks (Mont St-Hilaire) or near bird sanctuaries (Lake Memphremagog, Lake St. Joachim) or located on some of the few remaining true wilderness areas (Jacques Cartier River in the Laurentide Park). It is safe to assume that the continued desire to protect the environment will prevent Hydro Quebec from constructing economically feasible conventional pumped storage hydro plants. Therefore, two possible other alternatives to generate peaking power are:

1) Underground pumped hydroelectric energy storage; and

2) Compressed air energy storage

since neither of these involve extensive above ground installations or flooding of river valleys and, thus, should be more acceptable from the environmental point of view. They can also be placed near the major load center of Montreal thereby eliminating the costly long transmission lines which, apart from economical consideration, would also attract the attention of the environmentalists who are of the opinion that transmission lines create "visual pollution".

CHAPTER II

UNDERGROUND PUMPED HYDROELECTRIC ENERGY STORAGE (UPH)

2.1 General Concept

The general characteristics of a UPH plant are similar to those of conventional pumped storage hydroelectric plants - with the exception of the location of the lower reservoir (Fig. 4).

Table 2 shows the characteristics of some existing and proposed conventional pumped storage hydroelectric plants. The most important items for comparison being the generating and pumping net hydraulic heads.

UPH employs the same basic principles as the conventional surface-sited pumped storage plant, except that the hydraulic head is created between the upper reservoir situated at ground surface and a lower reservoir located in cavities excavated in rock at depth.

The concept of UPH was documented in 1968 in a paper presented at the VII World Power Conference in Moscow, U.S.S.R. by Isaakson, Nilson and Sjostrand(4). Since that time, considerable development of the concept has taken place, a number of studies have been made and several papers were published.(3)(5)(6)(7)(8)

These have covered both single stage and two stage developments as illustrated in Figures 5 and 6.

Although pumped storage generation reduces efficiency, because more energy is required for pumping than the energy actually generated, it provides a means to satisfy excessive load demands.(15) The installation, therefore, consists, in essence, of an energy retiming mechanism composed of a hydraulic loop. A pumped storage hydraulic plant requires, on the average, three kilowatt hours of energy for each two kilowatts produced due to hydraulic, mechanical and electrical losses. However, favourable site arrangements, combined with the latest highly efficient generating

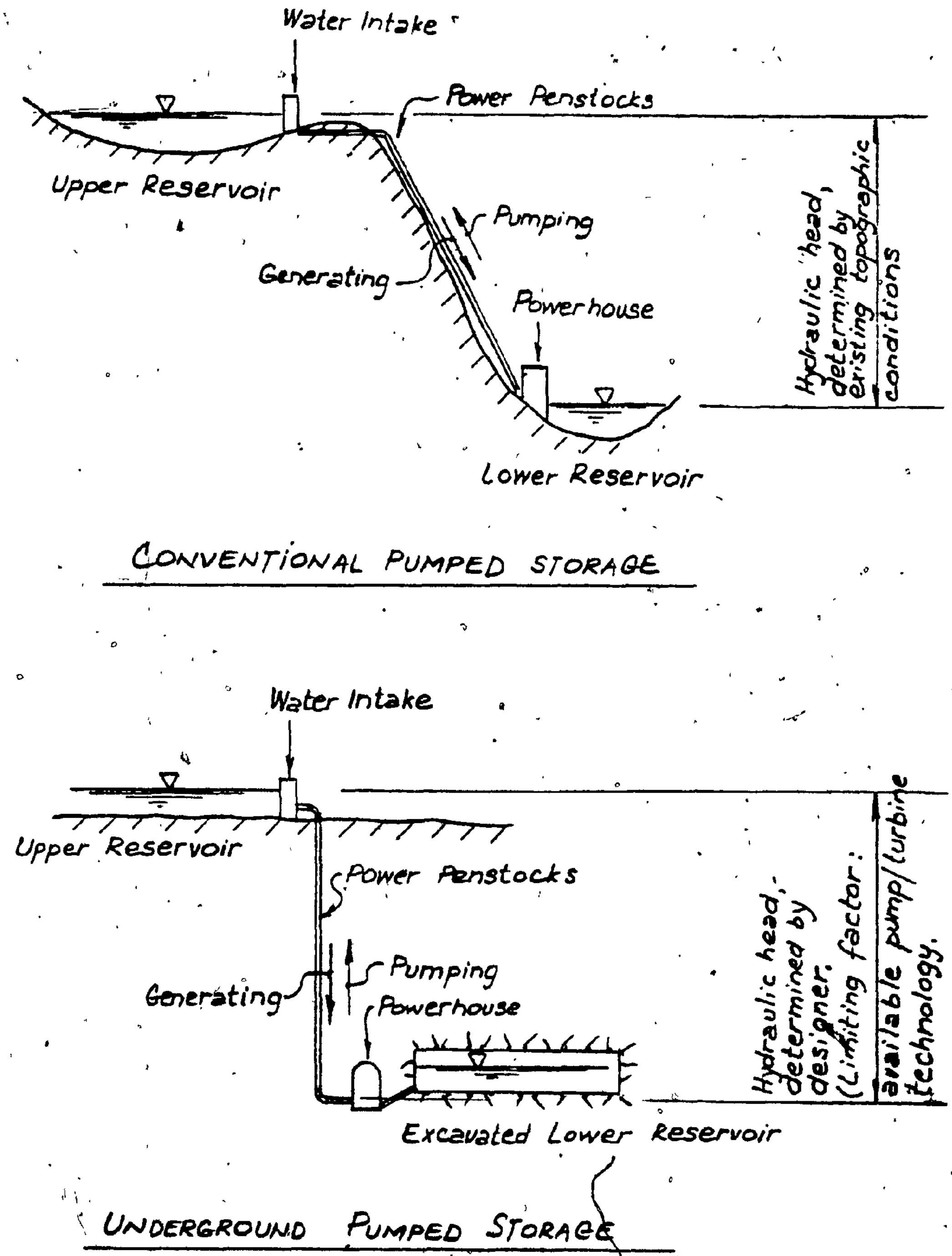


Fig. 4 - Characteristics of conventional and underground pumped hydroelectric energy storage.

TABLE 2

SOME EXISTING AND PROPOSED
CONVENTIONAL PUMPED STORAGE HYDROELECTRIC PLANTS
OF CHARACTERISTICS COMPARABLE TO THE
PROPOSED UPH PLANT

Country	Plant	Number of Units	Generating: Net head (ft.)	Generating: Installed cap. (MW)	Pumping: Net head (ft.)	Pumping: Flow (cfs)	Speed (rpm)	Year in Operation
U.S.A.	Blenheim-Gilboa	4	1,004	1,000	1,175	2,303	275	1973
Japan	Numappara	3	1,640	690	1,502	1,766	375	1973
Japan	Ohira	2	1,680	510	1,670	1,589	400	1975
Japan	Okuyoshino	3	1,725	621	1,535	1,391	514	1976
France	La Coche*	4	3,000	340	2,925	307	600	1976
U.S.A.	Castaic	6	899	1,500	1,063	1,872	257	1977
U.S.A.	Racoon Mtn.	4	1,000	1,700	941	4,270	300	1977
U.S.A.	Mount Hope	4	2,500	1,000	-	-	-	Proposed
U.S.A.	Stoney Creek	6	892	1,710	-	-	-	Proposed
Canada (Quebec)	Champigny**	4	1,400	1,000	-	-	-	Proposed

NOTES: * 5-stage reversible pump turbine
** Project has not been approved by Governmental authorities, following strong objections by environmentalists.

SOURCES: - Survey of pumped storage projects in the United States and Canada - IEEE Committee Report, 1975.
- Water Power - various publications

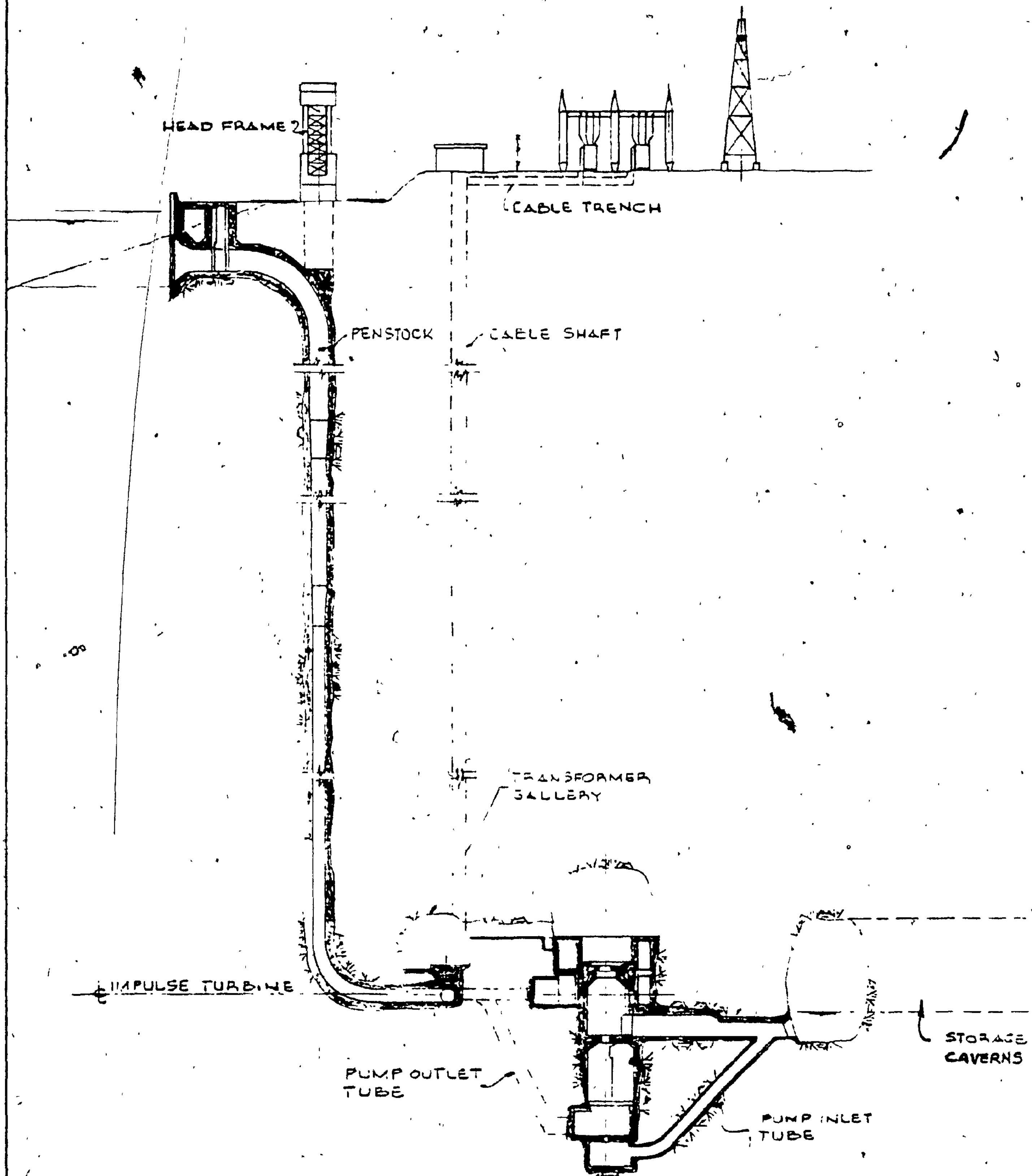


Fig. 5

HIGH HEAD, SINGLE STAGE SCHEME

IMPULSE TURBINES, SEPARATE MULTI-STAGE PUMPS

(Ref. 5)

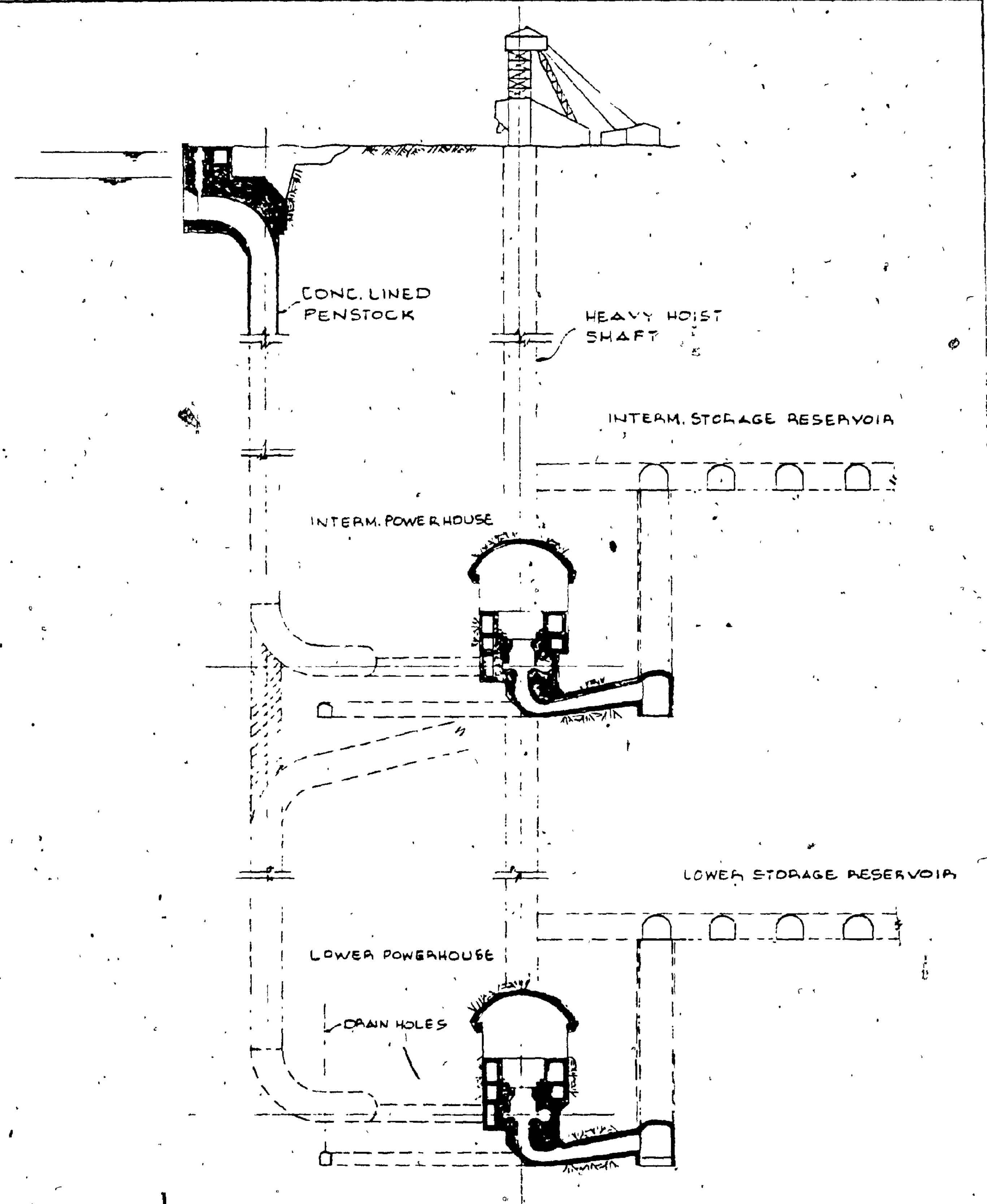


Fig. 6
HIGH HEAD, TWO STAGE SCHEME
REVERSIBLE PUMP-TURBINES
(Ref. 5)

equipment improves that ratio to three kilowatt hours of generation for every four kilowatt hours used for pumping, (the conversion efficiency of the Dinorwic conventional hydraulic pump storage project is 76%. This project is currently under construction in the United Kingdom). Therefore in this report the latter figures will be used. In summary, it can be said that although pumped storage does not conserve energy it improves the conditions of supply of available energy thereby increasing its utilization for the benefit of consumers.

The use of underground facilities for large scale storage of energy has evolved as an alternative solution to the increasing claims for groundlevel space by cultural, recreational, industrial and environmental needs and desires. In competition for such space, energy generating and storage complexes are being pushed further and further from urban load centers into areas rejected for other uses. Consequently energy production suffers increasingly the disadvantages of greater costs, remoteness from centers of service and rapid elimination of sites available for future expansion.

Topographical configurations of the site selected for a conventional pumped storage plant generally establish within a narrow margin the differential head under which the plant will operate. In contrast, when the lower reservoir is placed underground the vertical separation of reservoirs becomes a variable to be defined by the designer.

Where rock defects are not limiting factors, economics tend to encourage increasing the vertical separation to the maximum head under which available equipment will provide reliable operation.

The layout of power station facilities for a UPH plant is, in most respects, similar to an underground hydroelectric plant utilizing time tested arrangements for electrical, mechanical and hydraulic aspects. In April 1976 the Electrical Power Research Institute (EPRI) published a research report entitled "Underground Pumped Storage Research Priorities". The primary findings of this report were that there are

".... a number of aspects of the concept which will benefit from further development to improve its economics. These aspects relate primarily to the excavation of the lower reservoir cavern and to the further devèlopment of high head pump turbines to allow higher heads and hence smaller working volumes per unit of energy storage. This work can best be accomplished in the course of preliminary design of one or more specific projects......"

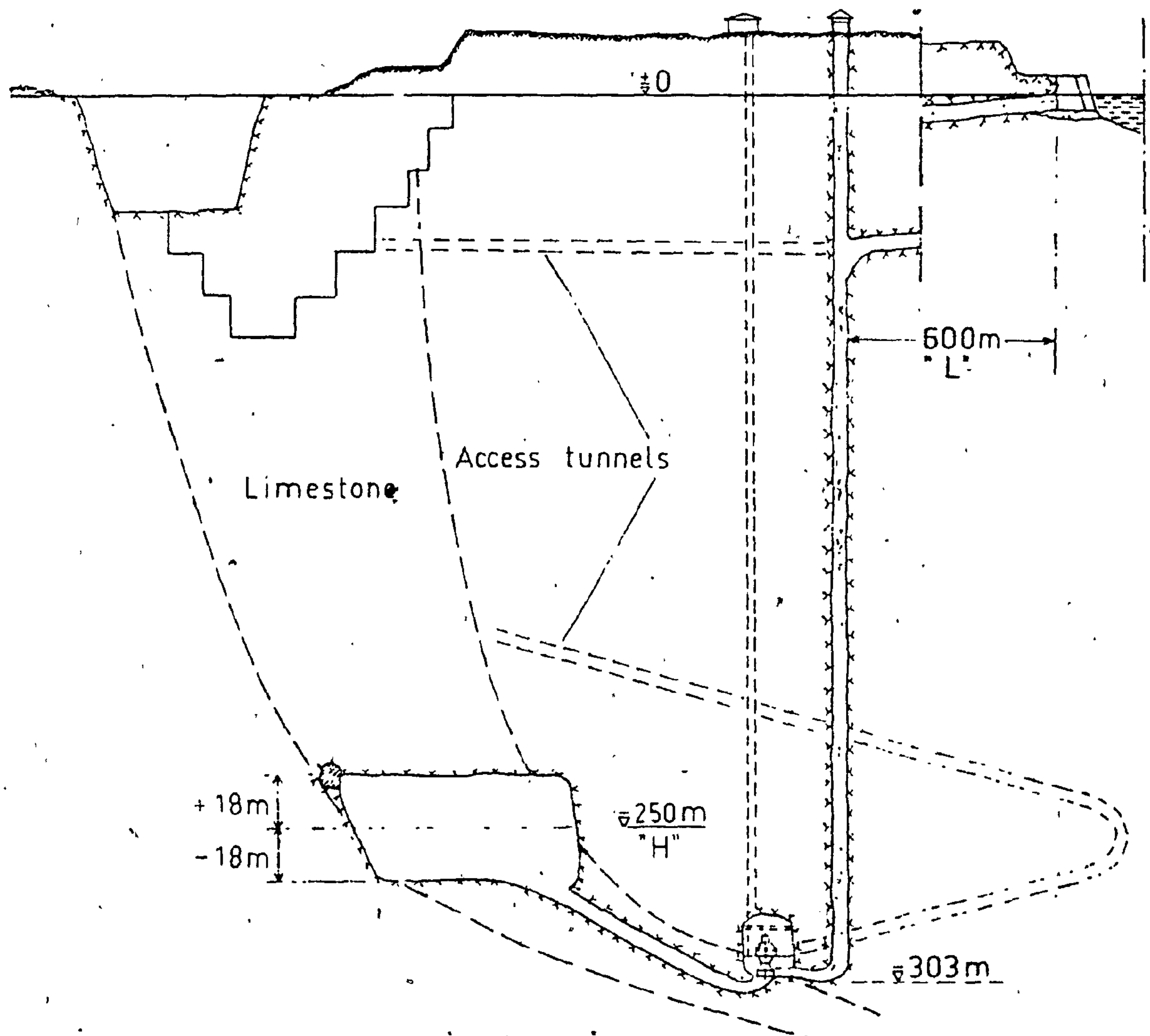
2.2 Comparable Existing and Proposed Developments

At the time of writing this report there is no existing UPH project anywhere in the world. The first such development would have been a 100 MW plant in Finland. This plant, referred to as the Parainen Project in a report given during the Syposium on Hydroelectric Pumped Storage Schemes held in Athens, Greece, during November 6 - 8, 1972 would have been situated adjacent to a limestone quarry and would have operated under a head of about 1000 feet utilizing the sea as upper reservoir (Figure 7). The construction of the access tunnels started in April 1972.

The excavation of the powerhouse and lower reservoir began in 1974 and the first unit was scheduled to be operating in 1977. However, work on the project stopped in 1977. Although no reason was given for the cancellation, it is assumed that shortage of funds was encountered.

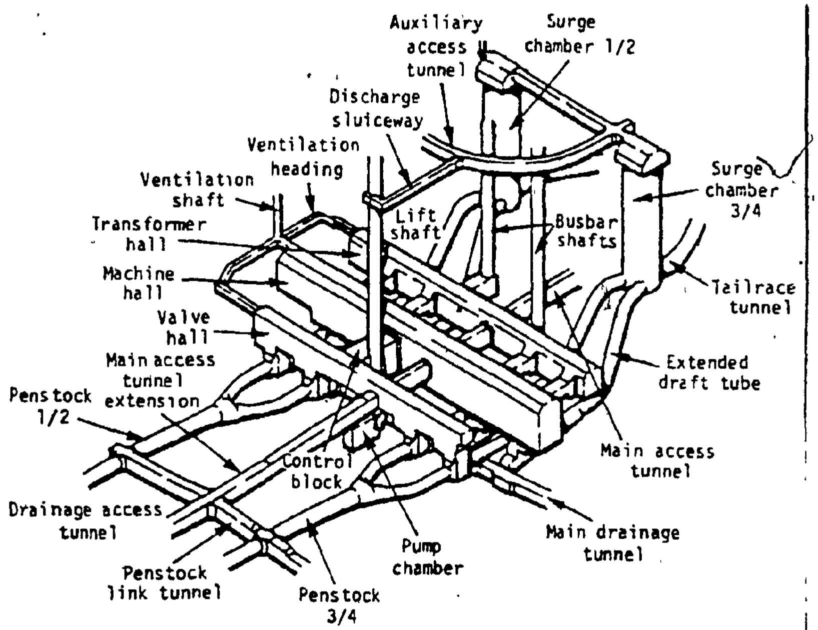
The Drakensberg pumped storage scheme presently under construction in South Africa can be considered as a hybrid because, although the lower reservoir is situated on the surface, the powerhouse is entirely located underground (Figure 8).

Figure 9 shows the general aspects of the Tuscarora Project at Niagara Falls, N.Y. to illustrate a conventional pumped storage hydroelectric plant.

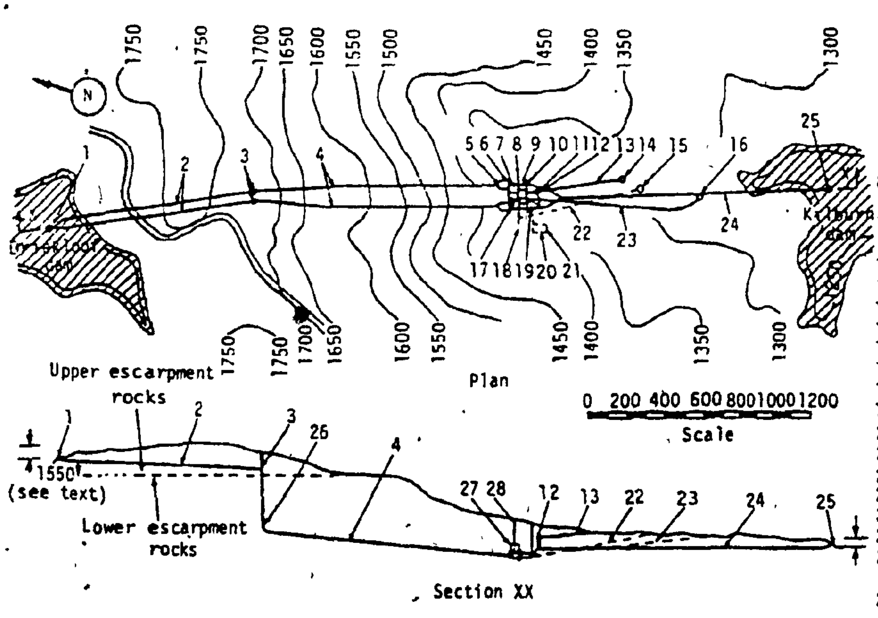


(Symposium on Hydroelectric Pumped Storage Schemes. Athens, Greece, Nov. 1972)

Fig. 7 - Parainen UPH Project, Finland



Underground Layout



1 Headrace tunnel intake
2 Headrace tunnels 2 No.
3 Surge shafts 2 No.
4 Pressure tunnels 2 No.
5 Penstocks 4 No.
6 Valve hall
7 Control block
8 Machine hall
9 Busbar tunnels 4 No.
10 Transformer hall
11 Busbar shaft 4 No.
12 Surge chambers 2 No.
13 Aux. access tunnel and link tunnel
14 Auxiliary access tunnel portal
15 Exploratory adit portal
16 Main access tunnel portal
17 Amenities block
18 Machine hall test enlargement
19 Busbar shaft
20 Plate bearing test adit
21 Penstock test chamber
22 Exploratory adit
23 Main access tunnel
24 Tailrace tunnel
25 Tailrace tunnel portal
26 Pressure shafts 2 No.
27 Ventilation tunnel
28 Lift shaft

Longitudinal Section and Plan of Works (*Tunnels and Tunneling Jan./Feb. 1979*)

Fig. 8 - Drakensberg Pumped Storage Plant, South Africa

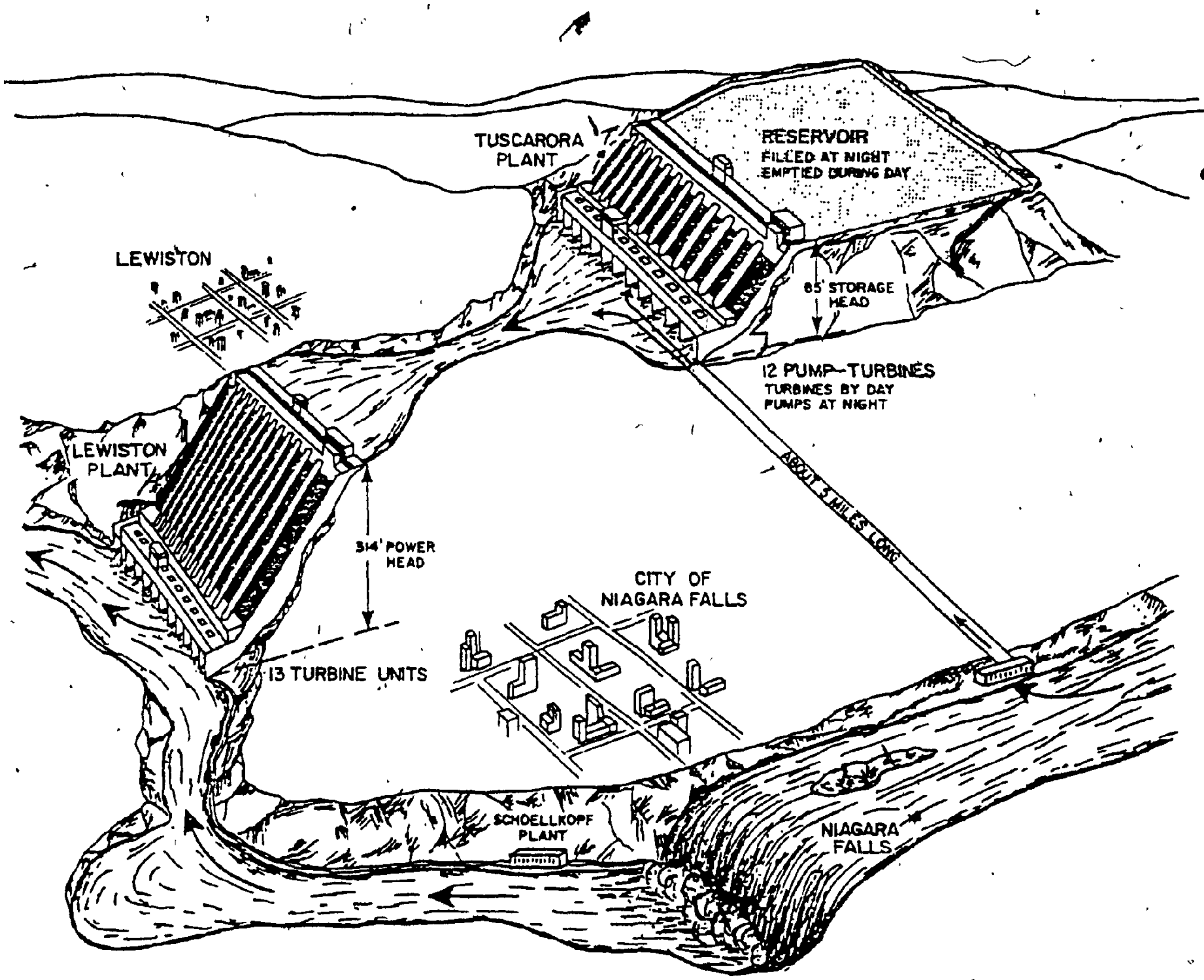


Fig. 9

TUSCARORA PUMPED STORAGE PROJECT AT NIAGARA FALLS CONSTRUCTED BY THE POWER AUTHORITY OF THE STATE OF NEW YORK *(Ref. 2)*

TABLE 3

SOME CONVENTIONAL PUMPING STATIONS
OF COMPARABLE HYDRAULIC AND GENERATING CHARACTERISTICS
CURRENTLY UNDER CONSTRUCTION

			Generating		Pumping			
Country	Plant	Number of Units	Net head (ft.)	Installed cap. (MW)	Net head (ft.)	Flow (cfs)	Speed (rpm)	Year in Operation
Yugoslavia	Bajina Basta	2	1,750	630	1,744	1,794	428.6	1979
Great Britain	Dinorvic	6	1,757	1,900	1,715	1,766	—	1980
U.S.A.	Helms	3	1,624	1,050	~1,500	2,401	360	1981
U.S.A.	Bath County	6	1,200±	2,100	-	-	-	1983

Table 3 shows the characteristics of some comparable conventional pumping stations currently under construction in Europe and North America.

2.3 Description of the Proposed UPH Project

Site Selection

Although a detailed site selection methodology is outside the scope of this report, following is a brief description of some of the requirements of a potential site:

- Favourable geological conditions at the lower reservoir level;

- Availability of a suitable upper reservoir, which will assure that the operation of the plant will not be impaired by technical, hydraulic or environmental problems;

- Proximity to the load center and to a suitable existing electrical transmission line in order to minimize construction costs associated with new lines and transmission losses which are directly proportional to the length of the line;

- Availability of sites within reasonable distance of the proposed plant, where the excavated materials could be disposed of without adversely affecting the environment.

The site proposed in this report is situated on Ile Ste. Therese and has the following characteristics - in general terms:

Geological conditions

In the general study area three distinct rock formations can be identified:

o intrusive and metamorphic rocks of precambrian age
o more recent sedimentary rocks, and the
o still more recent intrusive rocks

The available information(9) on these rocks indicate that they are competent at the desired depth of about 2000 feet. However, extensive geological exploration would be required at the site to determine the exact quality of rock, the nature of any geological faults, and the presence of water or gas concentrations.

In a report entitled "Etude Sédimentologique du Cambrio-Ordovicien des Basses-terres due St. Laurent" prepared by the Bureau d'Etudes Industrielles et de Coopération de l'institut Français du Pétrole (BEICIP) in 1975 reference is made to a number of deep drillings executed in search of natural gas and oil along the St. Lawrence river.

The report states that the geological formation located, generally, at the proposed lower reservoir level and called "Chazy formation" is considered mediocre as potential natural gas or oil reservoir due to its low permeabiltiy. This would indicate that this formation is well suited for the proposed lower reservoir.

Hydraulic Conditions

The annual mean flow of the St. Lawrence River at Beauharnois is 250,000 cfs. During flood periods over 300,000 cfs flows were observed.(10) The required flow for the proposed plant during the generating cycle is only 7,600 cfs.

Ice Conditions

In general, the ice cover on the St. Lawrence River is in the order of 1.5 - 3.0 feet. However, in certain locations, due to overlapping, the ice thickness can attain over 30 feet.(10)

The degree of severity of the ice condition directly affects the water elevation. Observations indicate that the water level may be 3 - 6 feet higher in the winter than in the summer for the same flow.(10)

Certain sections of the river remain free from ice cover during the winter. These sections are potential sources of frazil ice which is undesirable because of the possibility of severe icing on the trash racks of the water intake. Ice conditions at the proposed site are normal. If needed, an ice boom will be installed upstream of the water intake.

Sedimentation and Erosion

In the study area the St. Lawrence River does not carry significant amounts of suspended particles. However, dredging operations along the navigation canal might create undesirable conditions. Also, it is quite possible that the river banks might be exposed to erosion due to ice action.

Navigation

The navigation route in the study area is shown in Figure 10.

Between Caughnawaga and St. Helene Island, the Seaway constitutes the only navigable route. The depth of water in this canal is about 25 feet. This canal exits into the channel of the Port of Montreal where the depth of water is about 35 feet. At the eastern extremity of the Port of Montreal the Seaway follows the south bank of the river.

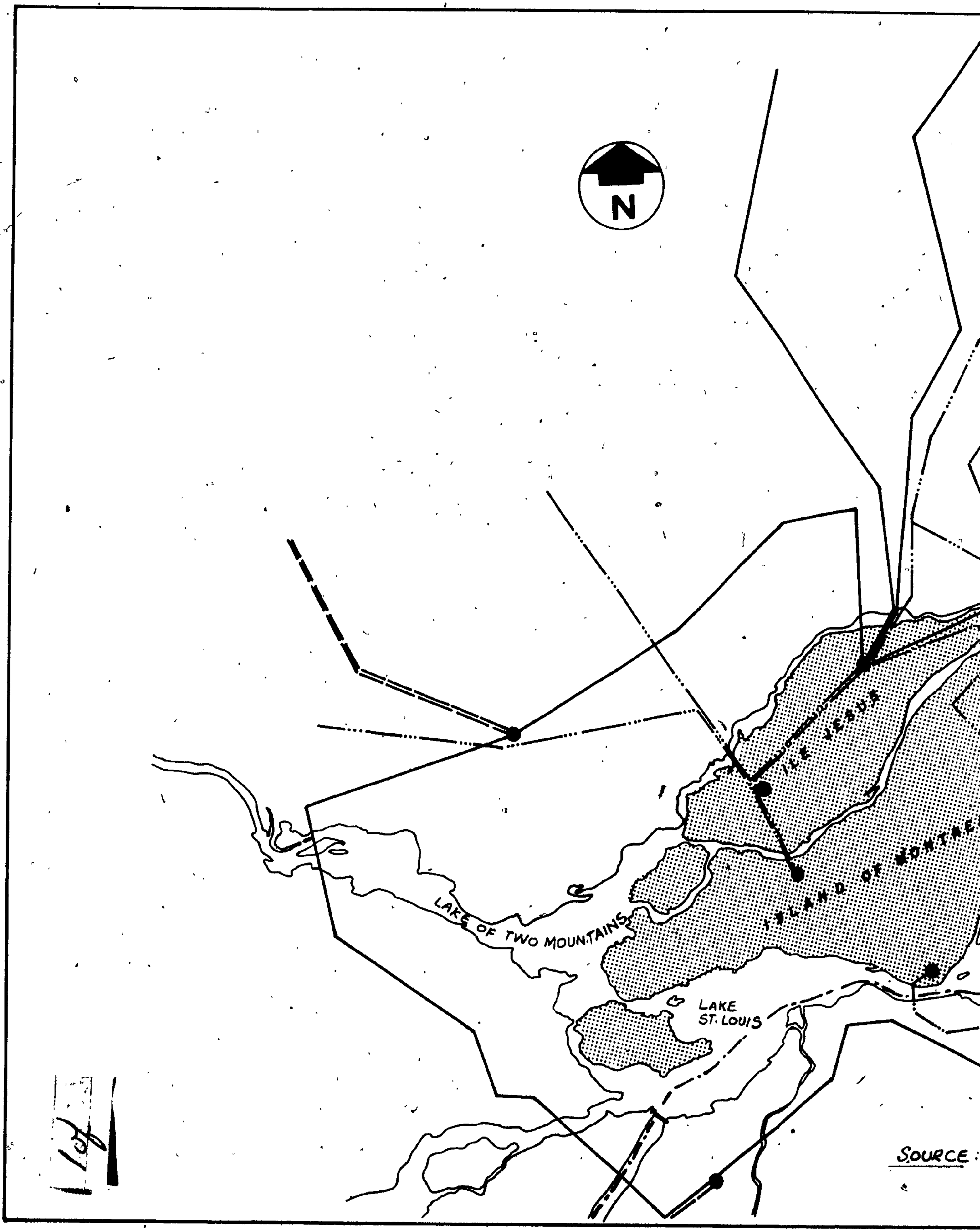
Existing Electrical Transmission Network

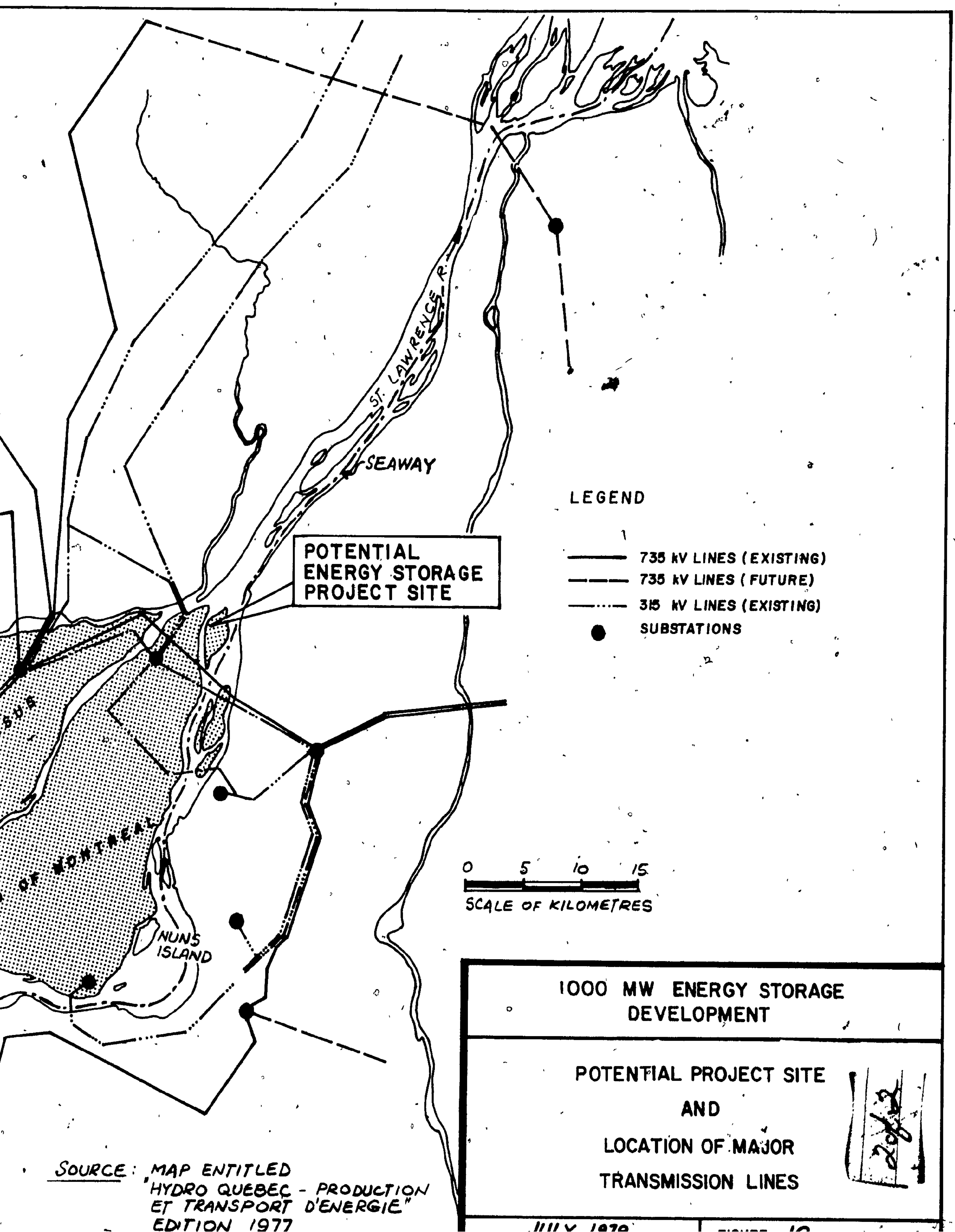
The Montreal region is encircled by a network of high and very high tension electrical transmission lines.

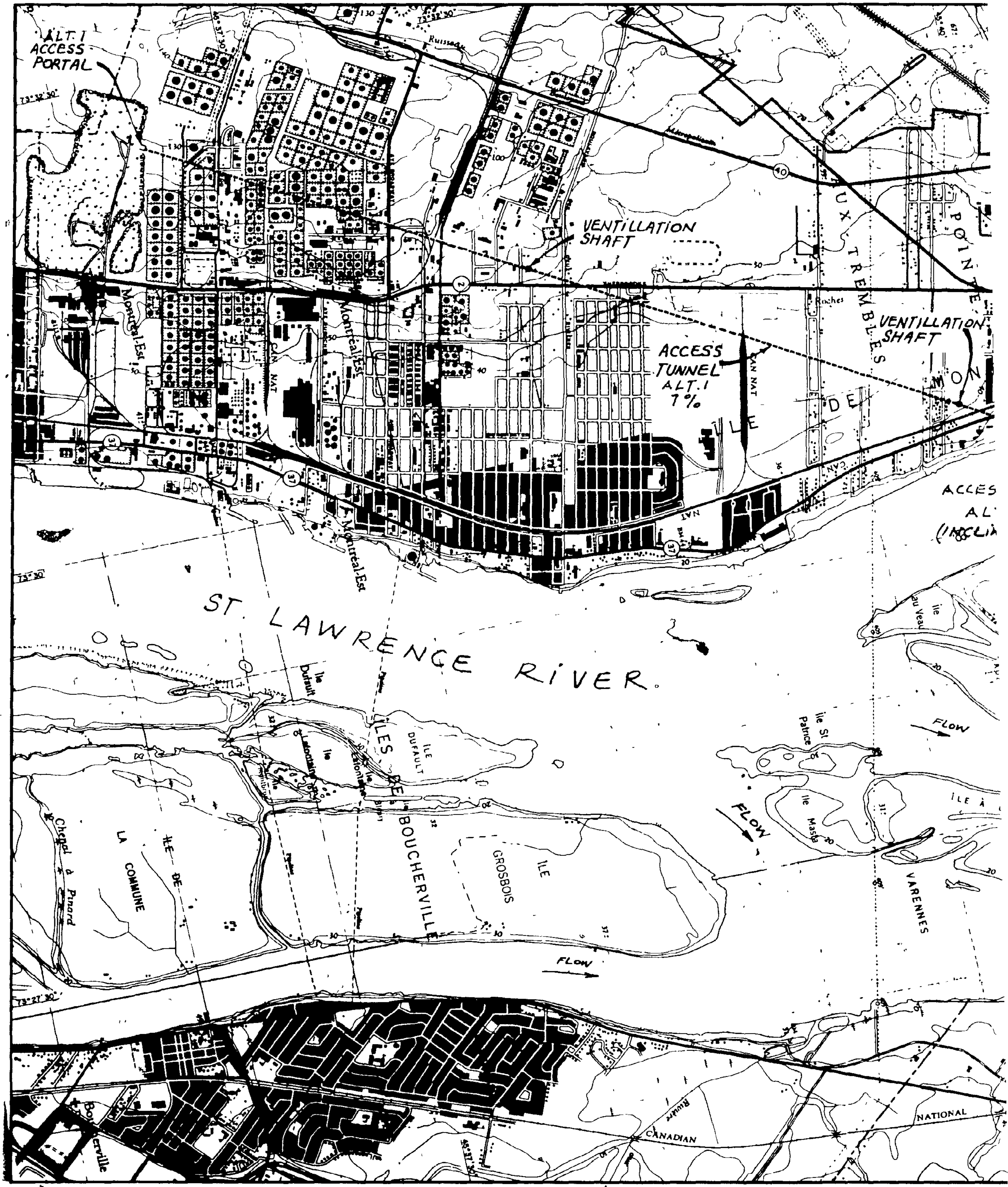
The 315 kV lines originate in the north-east region of the Province and the 735 kV lines bring electricity from the north shore and from the Churchill Falls Hydroelectric project in Labrador.

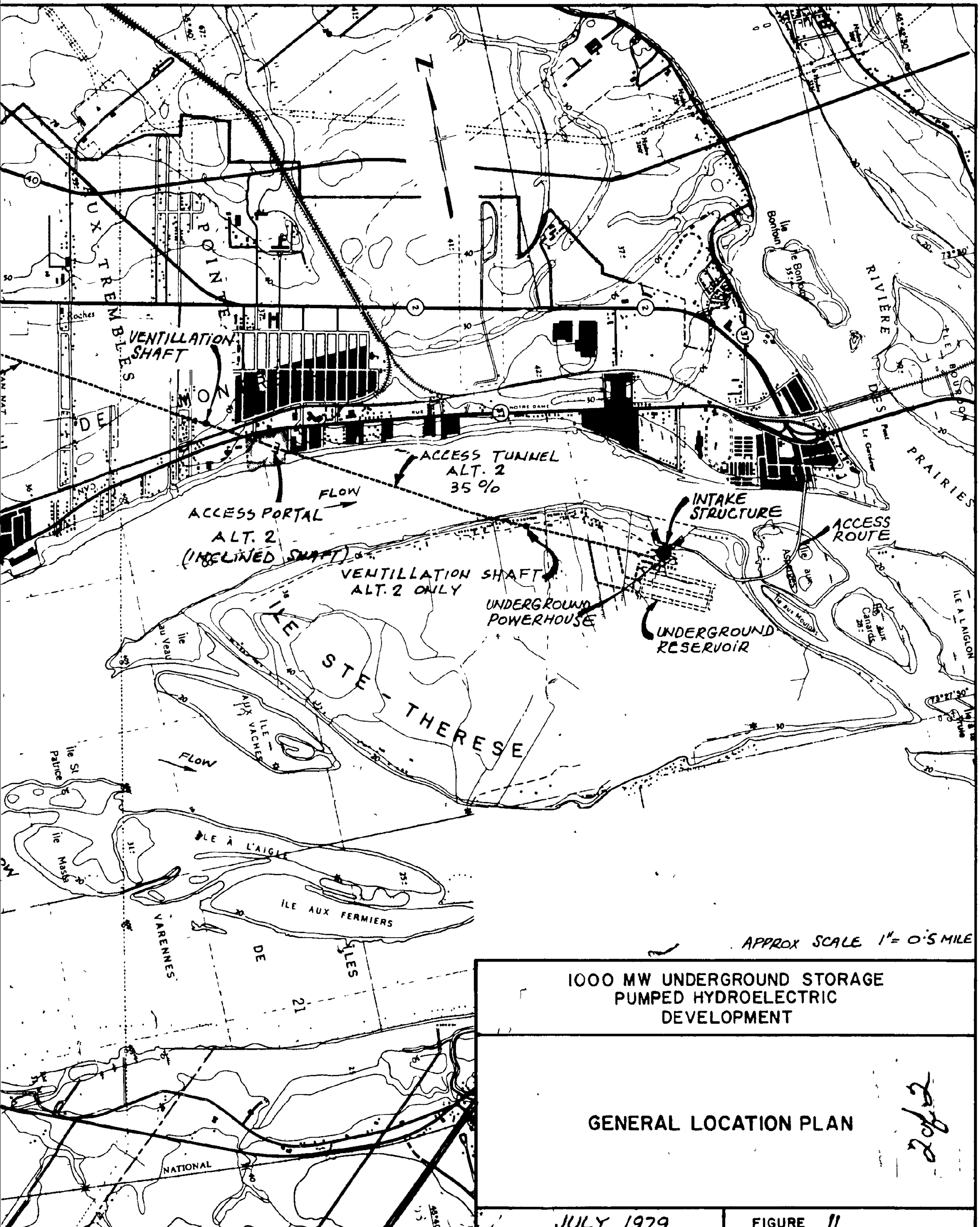
These two transmission line systems are shown in Figure 10.

The proposed energy storage project could be attached to the existing 315 kV network, with a very short transmission line.


N
ÎLE JÉSUS
ISLAND OF MONTRE
LAKE OF TWO MOUNTAINS
LAKE
ST. LOUIS
SOURCE :


ST. LAWRENCE R.
SEAWAY
POTENTIAL ENERGY STORAGE PROJECT SITE
NUNS ISLAND
LEGEND
735 kV LINES (EXISTING)
735 kV LINES (FUTURE)
315 kV LINES (EXISTING)
SUBSTATIONS
0 5 10 15
SCALE OF KILOMETRES
1000 MW ENERGY STORAGE DEVELOPMENT
POTENTIAL PROJECT SITE AND LOCATION OF MAJOR TRANSMISSION LINES
SOURCE: MAP ENTITLED "HYDRO QUEBEC - PRODUCTION ET TRANSPORT D'ENERGIE" EDITION 1977


ALT. I ACCESS PORTAL
VENTILLATION SHAFT
ACCESS TUNNEL ALT. I 7%
VENTILLATION SHAFT
ST. LAWRENCE RIVER.
FLOW
FLOW
FLOW
Montréal-Est
ILE DUFAULT
ILE GROSBOIS
ILES DE BOUCHERVILLE
LA COMMUNE
VARENNES
CANADIAN
NATIONAL
POINTE AUX TREMBLES
Ile St Patrice
Ile Masta

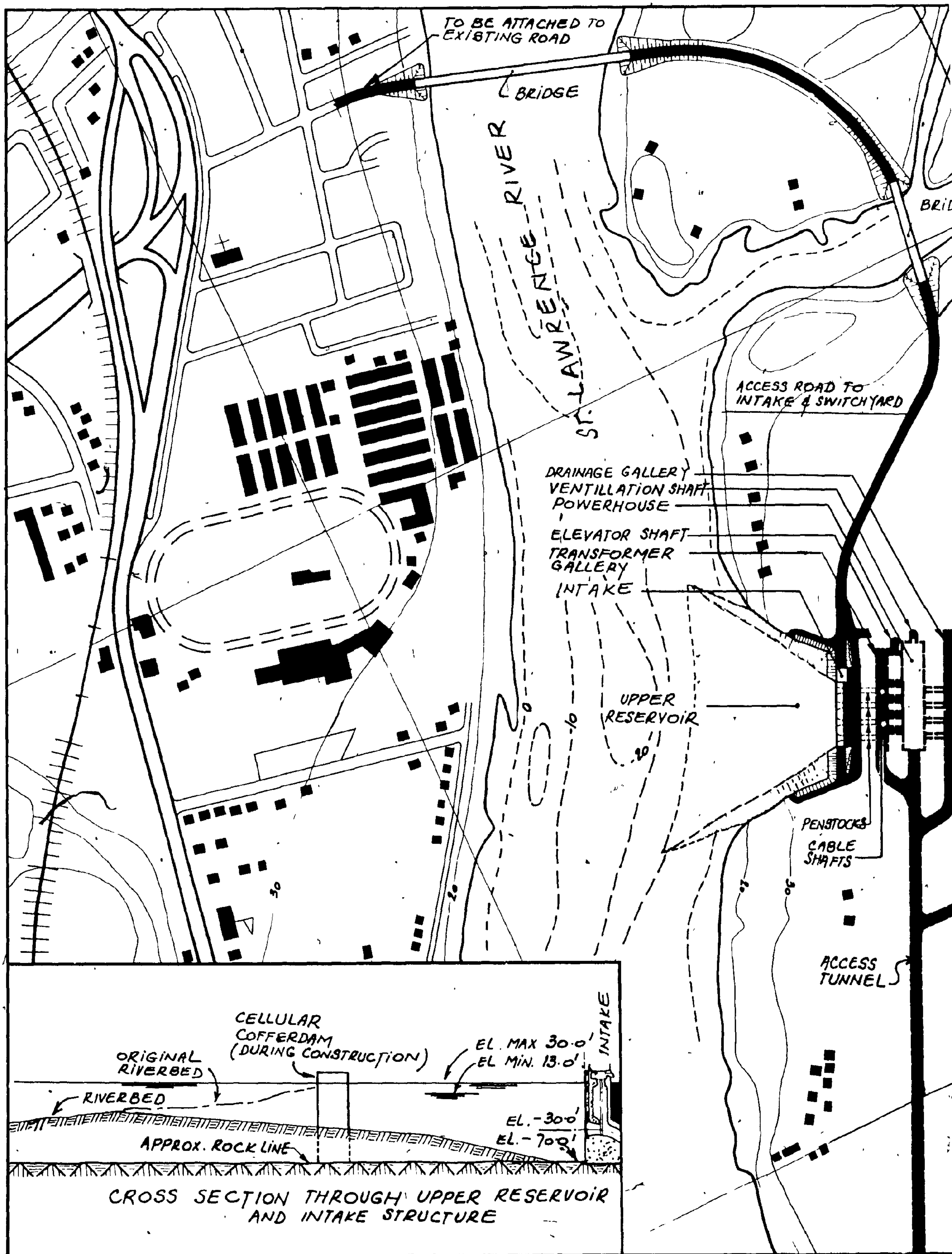


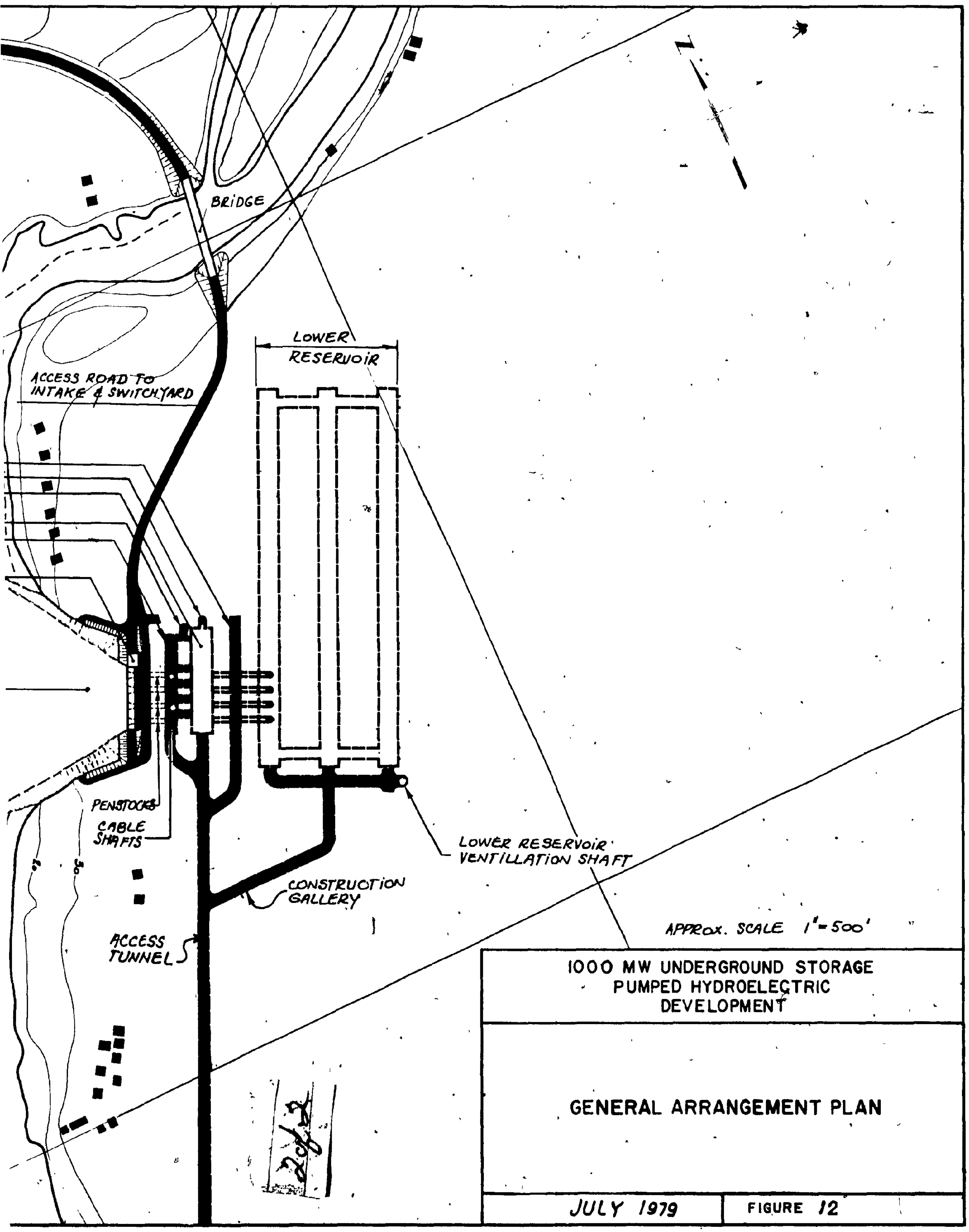
1000 MW UNDERGROUND STORAGE
PUMPED HYDROELECTRIC
DEVELOPMENT

GENERAL LOCATION PLAN

JULY 1979

FIGURE 11


TO BE ATTACHED TO EXISTING ROAD
BRIDGE
ST. LAWRENCE RIVER
BRIL
ACCESS ROAD TO INTAKE & SWITCHYARD
DRAINAGE GALLERY
VENTILLATION SHAFT
POWERHOUSE
ELEVATOR SHAFT
TRANSFORMER GALLERY
INTAKE
UPPER RESERVOIR
0
10
20
30
PENSTOCKS
CABLE SHAFTS
ACCESS TUNNEL
CELLULAR COFFERDAM (DURING CONSTRUCTION)
ORIGINAL RIVERBED
RIVERBED
EL. MAX 30.0'
EL MIN. 13.0'
INTAKE
EL. -30.0'
EL. -70.0'
APPROX. ROCK LINE
CROSS SECTION THROUGH UPPER RESERVOIR AND INTAKE STRUCTURE

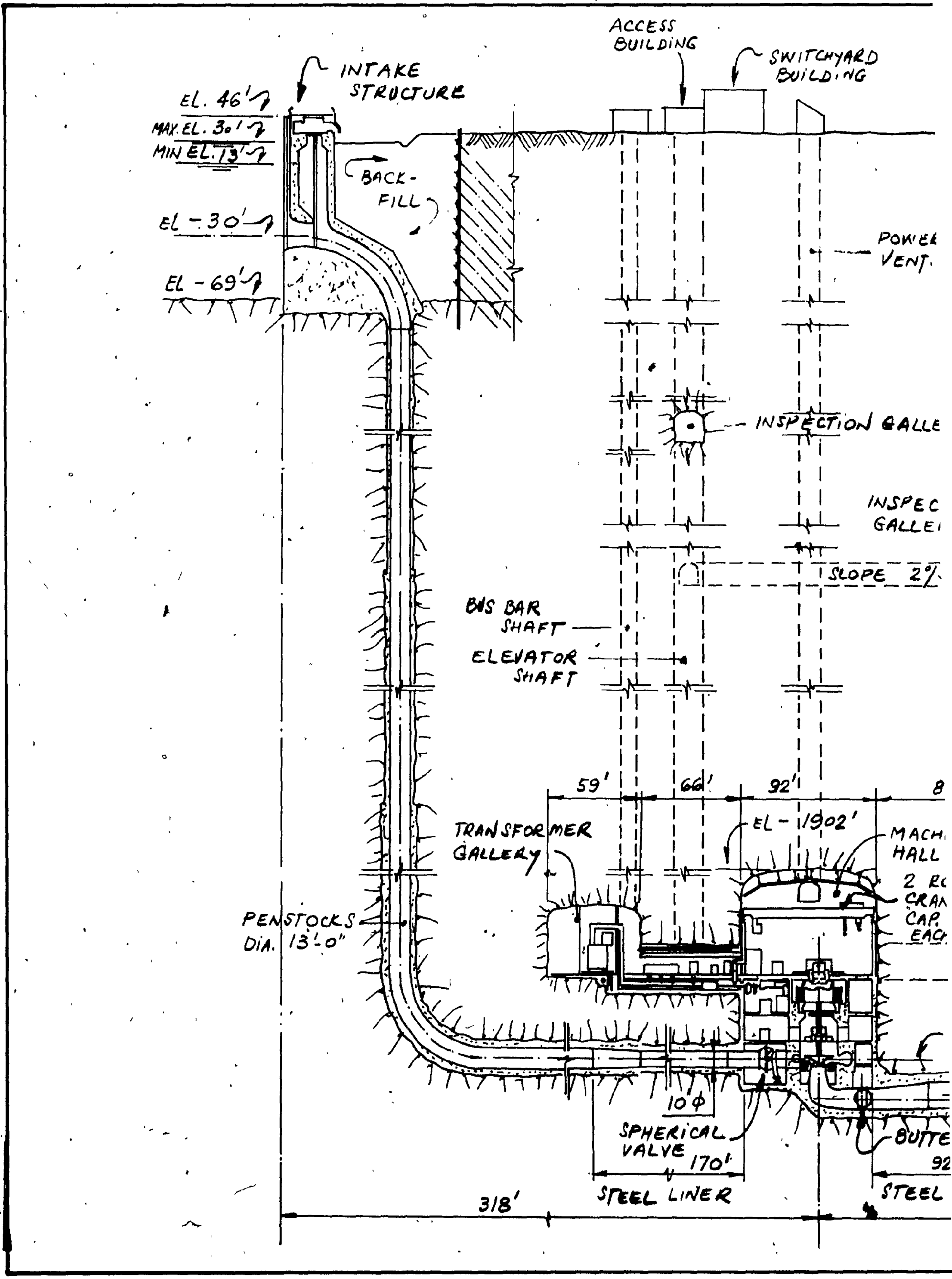


1000 MW UNDERGROUND STORAGE PUMPED HYDROELECTRIC DEVELOPMENT

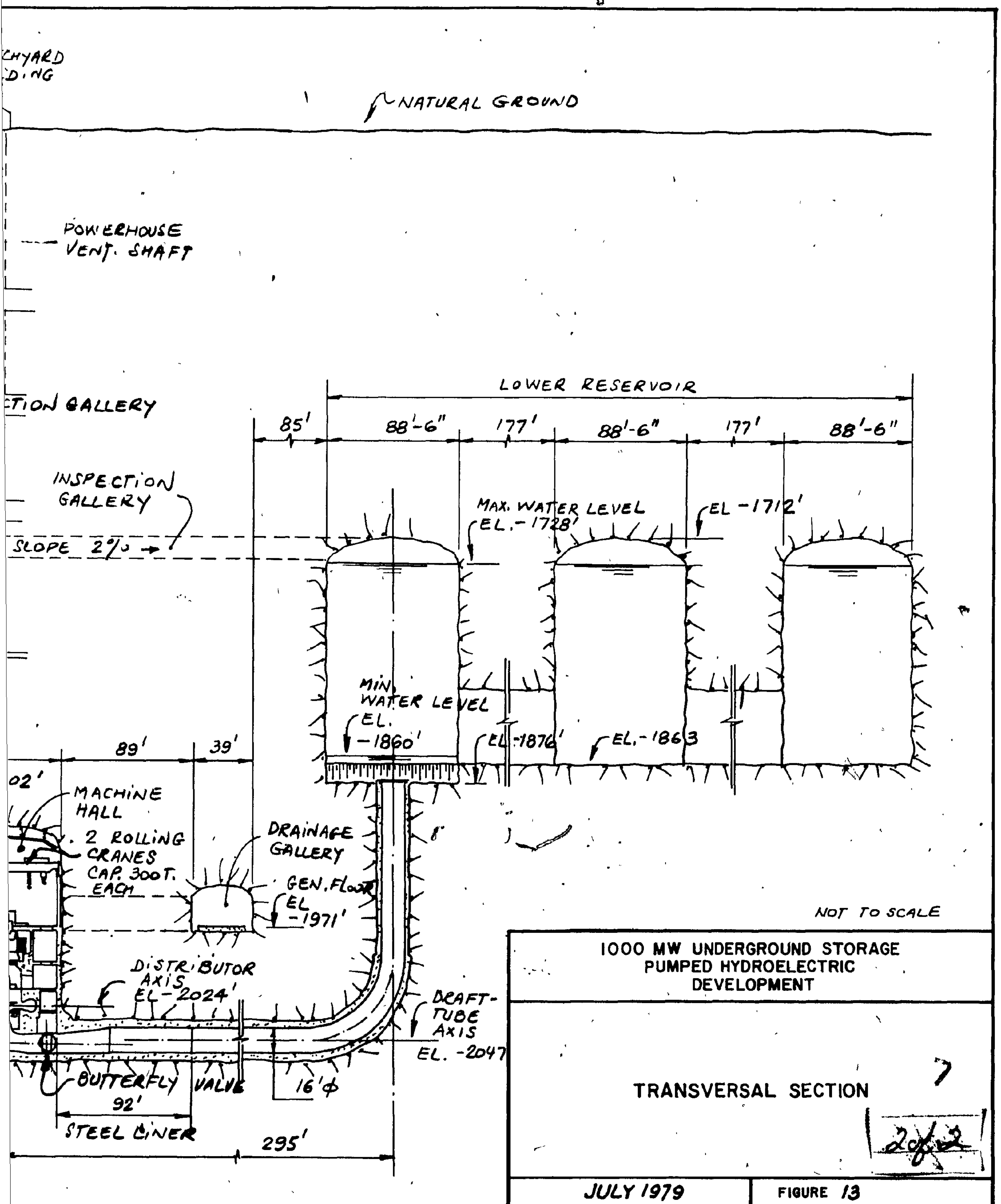
GENERAL ARRANGEMENT PLAN

JULY 1979

FIGURE 12



ACCESS BUILDING
SWITCHYARD BUILDING
INTAKE STRUCTURE
EL. 46'
MAX. EL. 30'
MIN EL. 13'
BACK-FILL
EL -30'
EL -69'
POWER VENT.
INSPECTION GALLE
INSPEC GALLE
SLOPE 2%
BUS BAR SHAFT
ELEVATOR SHAFT
59'
66'
92'
8
EL - 1902'
TRANSFORMER GALLERY
MACH HALL
2 R CRAN CAP. EAC
PENSTOCKS DIA. 13'-0"
10'φ
SPHERICAL VALVE
170'
STEEL LINER
318'
BUTTE
92
STEEL



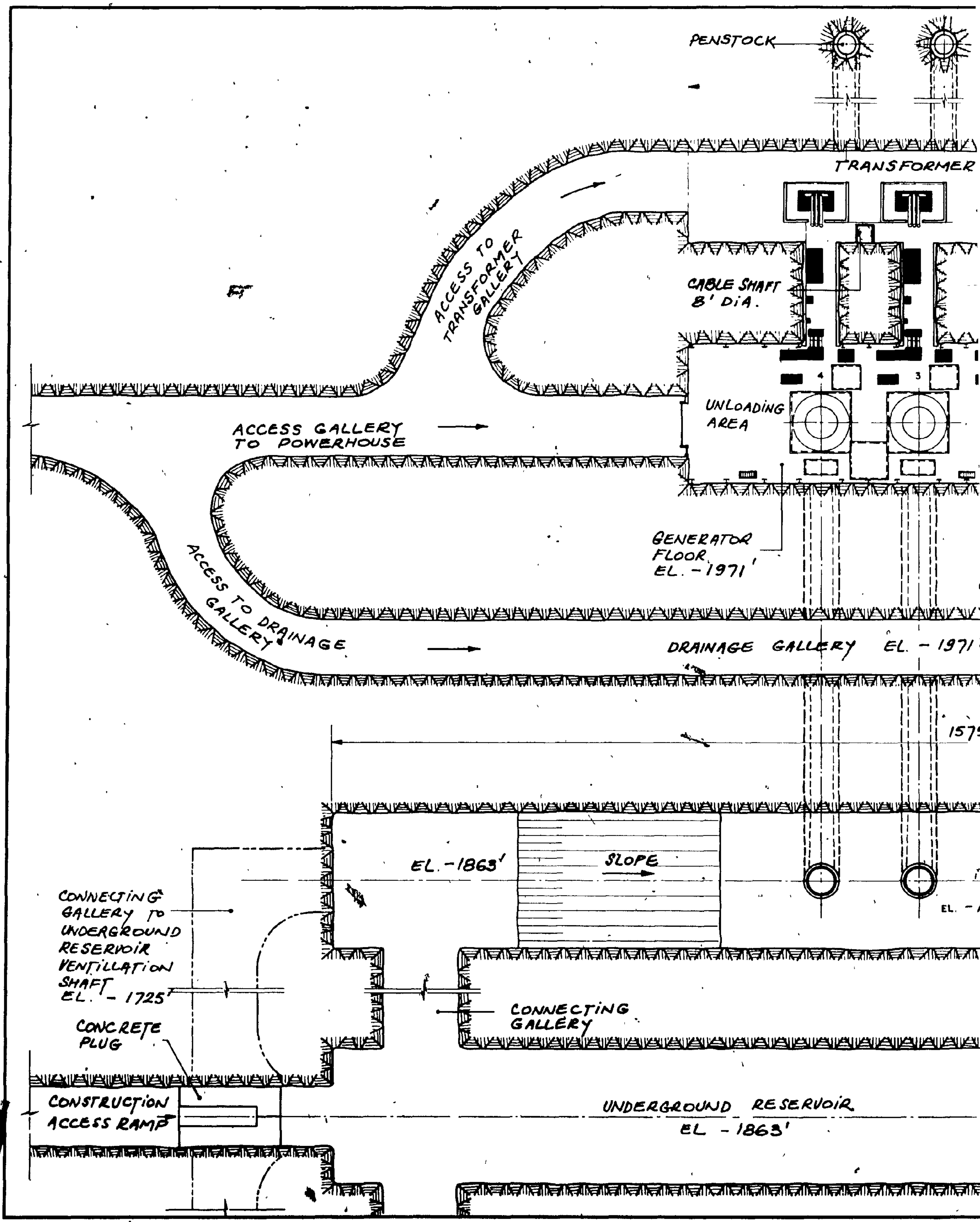
1000 MW UNDERGROUND STORAGE PUMPED HYDROELECTRIC DEVELOPMENT

TRANSVERSAL SECTION

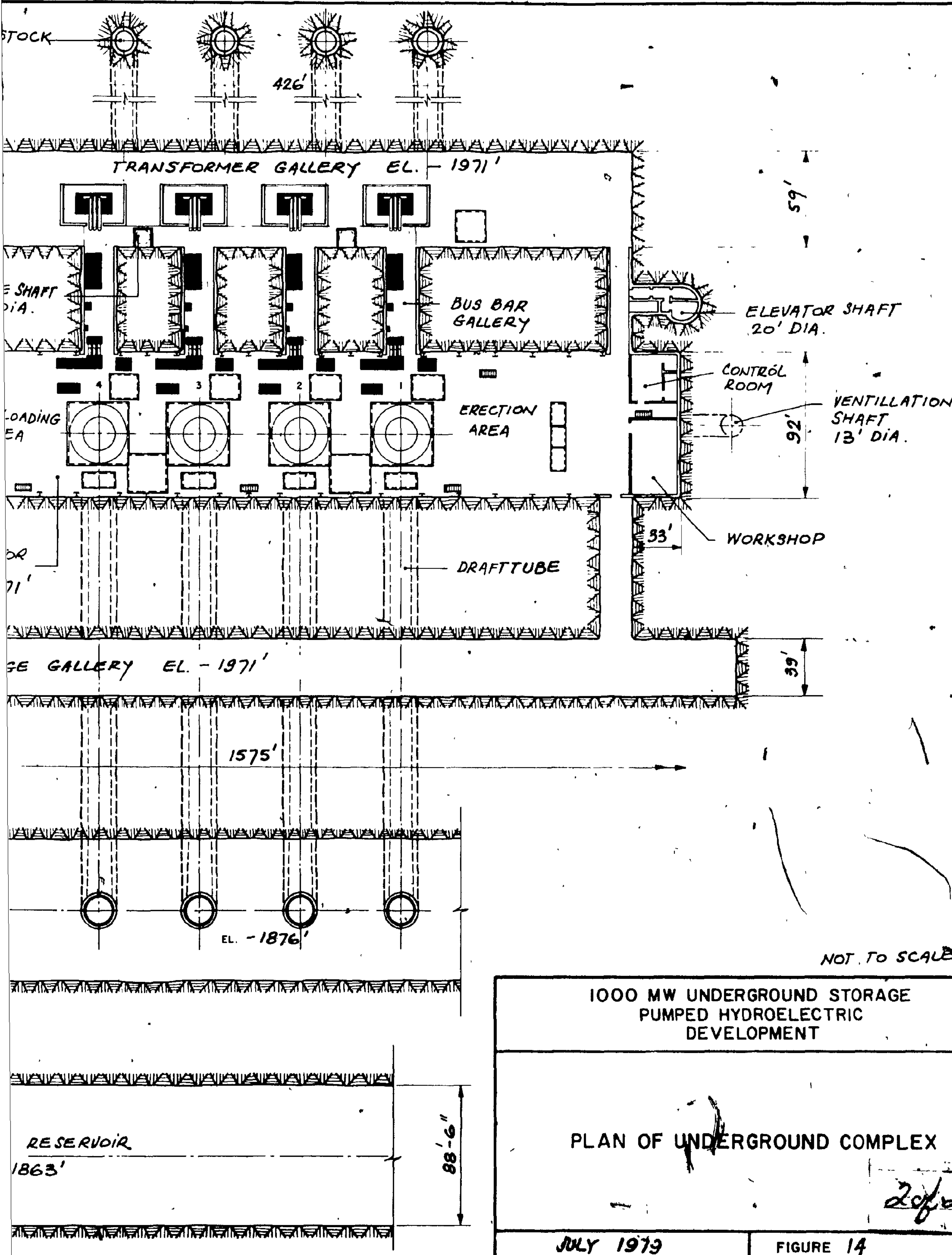
2 of 2

JULY 1979

FIGURE 13



PENSTOCK
TRANSFORMER
ACCESS TO TRANSFORMER GALLERY
CABLE SHAFT 8' DIA.
UNLOADING AREA
4
3
ACCESS GALLERY TO POWERHOUSE
GENERATOR FLOOR EL. - 1971'
ACCESS TO DRAINAGE GALLERY
DRAINAGE
DRAINAGE GALLERY EL. - 1971
157
EL. -1863'
SLOPE
CONNECTING GALLERY TO UNDERGROUND RESERVOIR VENTILLATION SHAFT EL. - 1725'
CONNECTING GALLERY
CONCRETE PLUG
CONSTRUCTION ACCESS RAMP
UNDERGROUND RESERVOIR EL - 1863'



NOT TO SCALE

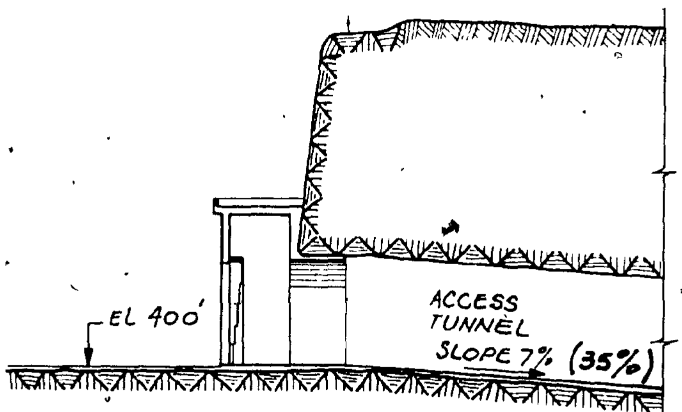
1000 MW UNDERGROUND STORAGE
PUMPED HYDROELECTRIC
DEVELOPMENT

PLAN OF UNDERGROUND COMPLEX

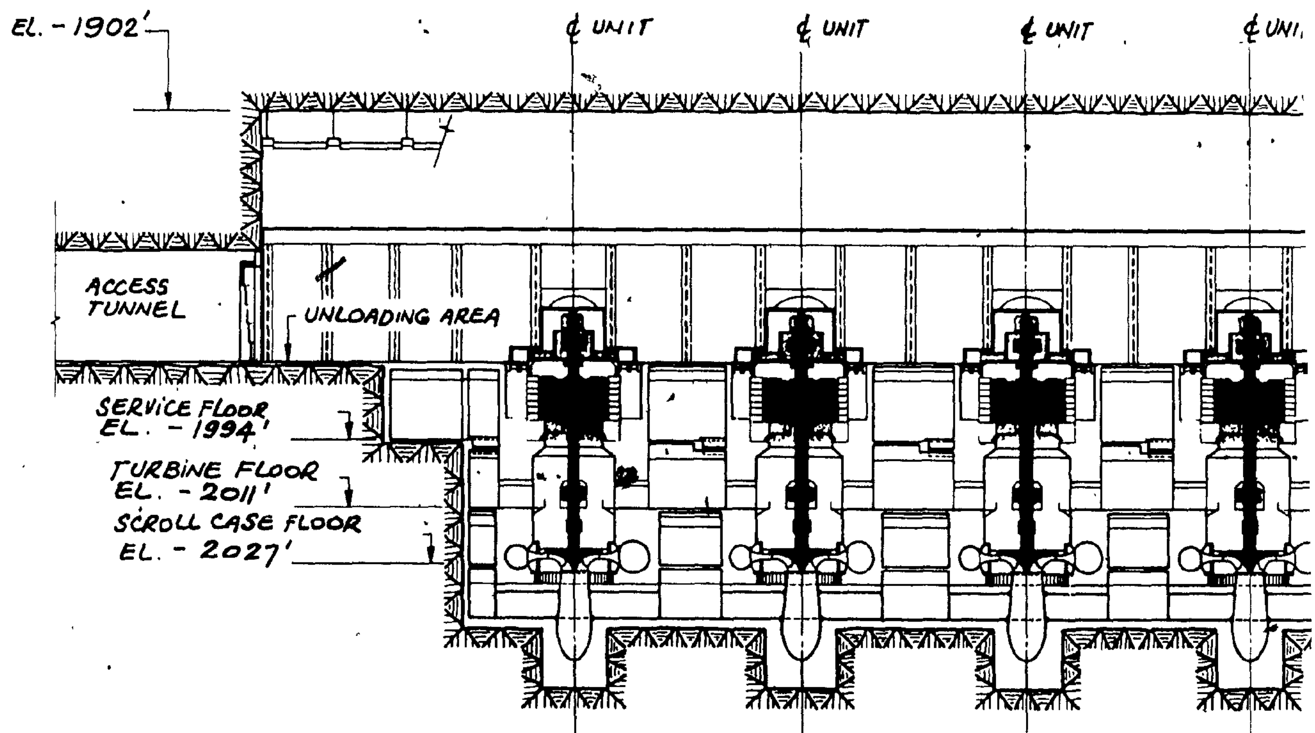
2 of 2

JULY 1979

FIGURE 14

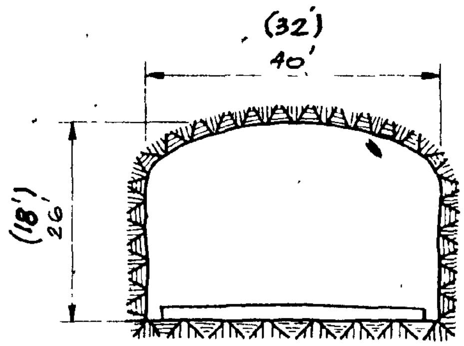


LONGITUDINAL SECTION
OF ACCESS PORTAL & TUNNEL

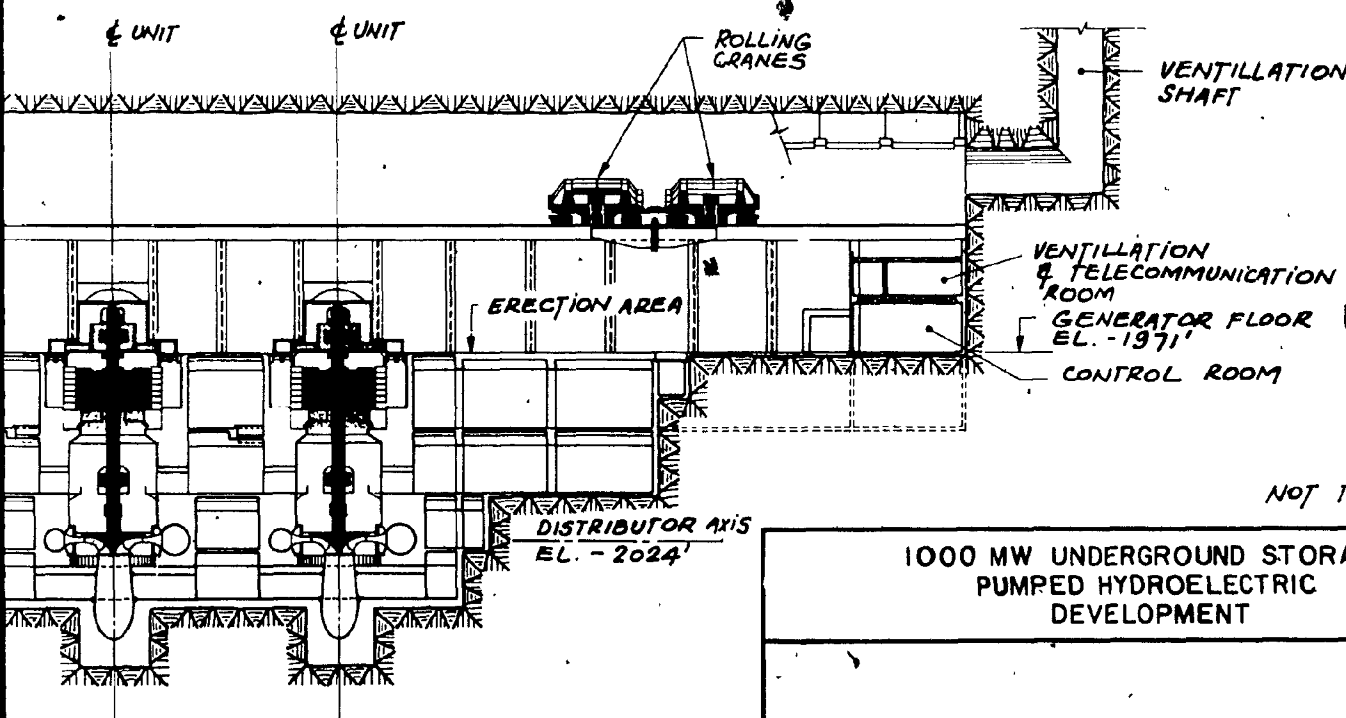


LONGITUDINAL SECTION THROUGH POWE

NOTE: FIGURES IN BRACKETS ()
REFER TO INCLINED SHAFT



TRANSVERSAL SECTION OF ACCESS TUNNEL



ON THROUGH POWERHOUSE

2 of 2

NOT TO SCALE

1000 MW UNDERGROUND STORAGE PUMPED HYDROELECTRIC DEVELOPMENT

LONGITUDINAL SECTION

THROUGH POWERHOUSE

JULY 1979	FIGURE 15

Surface Features

All work on the surface will be confined to an area of about 15 acres located on the west side of Ile Ste-Therese (Figure 11) with the exception of access roads, portal structure to the access tunnel, and the access tunnel ventilation shaft housing.

The access tunnel shown in Figure 15 will be ventilated by a vent shaft of 6 foot diameter.

The water intake structure will be designed to take into consideration the water level fluctuations of the river and the heavy ice cover during the winter months. The intake structure is shown in Figure 13.

The four vertical penstocks will be protected against floating debris by suitable trash-racks. If necessary the trash racks will be heated during the winter months.

There will be two verticle cable shafts situated at the switchyard east of the water intake structure.

Other surface features will consist of the housing for the elevator, the powerhouse ventilation shaft and the ventilation shaft of the underground reservoir, as shown in Figure 12.

An access road and a bridge will connect the installation with Montreal as indicated in Figure 12.

Underground Features

The penstocks will be concreted and the lower portions will be steel lined up to the spherical valves. The four reversible Francis turbines of 250 MW each will be isolated from the water storage by butterfly valves which will be installed in the elbows of the draft tubes. (Figures 13 and 14)

The control center, situated at one end of the machine hall, will be connected to the access building on the surface by an elevator located in a concreted shaft. The erection area and the powerhouse ventilation shaft are adjacent to the control center. The unloading area is situated at the other extremity of the powerhouse. A drainage gallery will protect the powerhouse from water infiltration from the water storage caverns.

The transformer gallery will be connected to the generator floor by the bus bar galleries.

The powerhouse, drainage gallery and the water storage caverns will be connected to the access tunnel by secondary galleries that might be isolated by installing watertight bulkheads. (Figures 13, 14, and 15)

The physical arrangement of the proposed project elements is shown in Figure 16.

The configuration of the underground installations would be selected to achieve the most tenable compromise between rock defects and costs, recognizing the desirability of facilitating mass-mining and quarrying excavation techniques.

The required lower reservoir volume was computed as follows(4):

$$V_m3 = \frac{3{,}600 \times Pmax \times T}{H_n \times g \times Na}$$

Where:

Pmax = maximum plant capacity = 1×10^6 kW

T = duration of generation = 2 hours

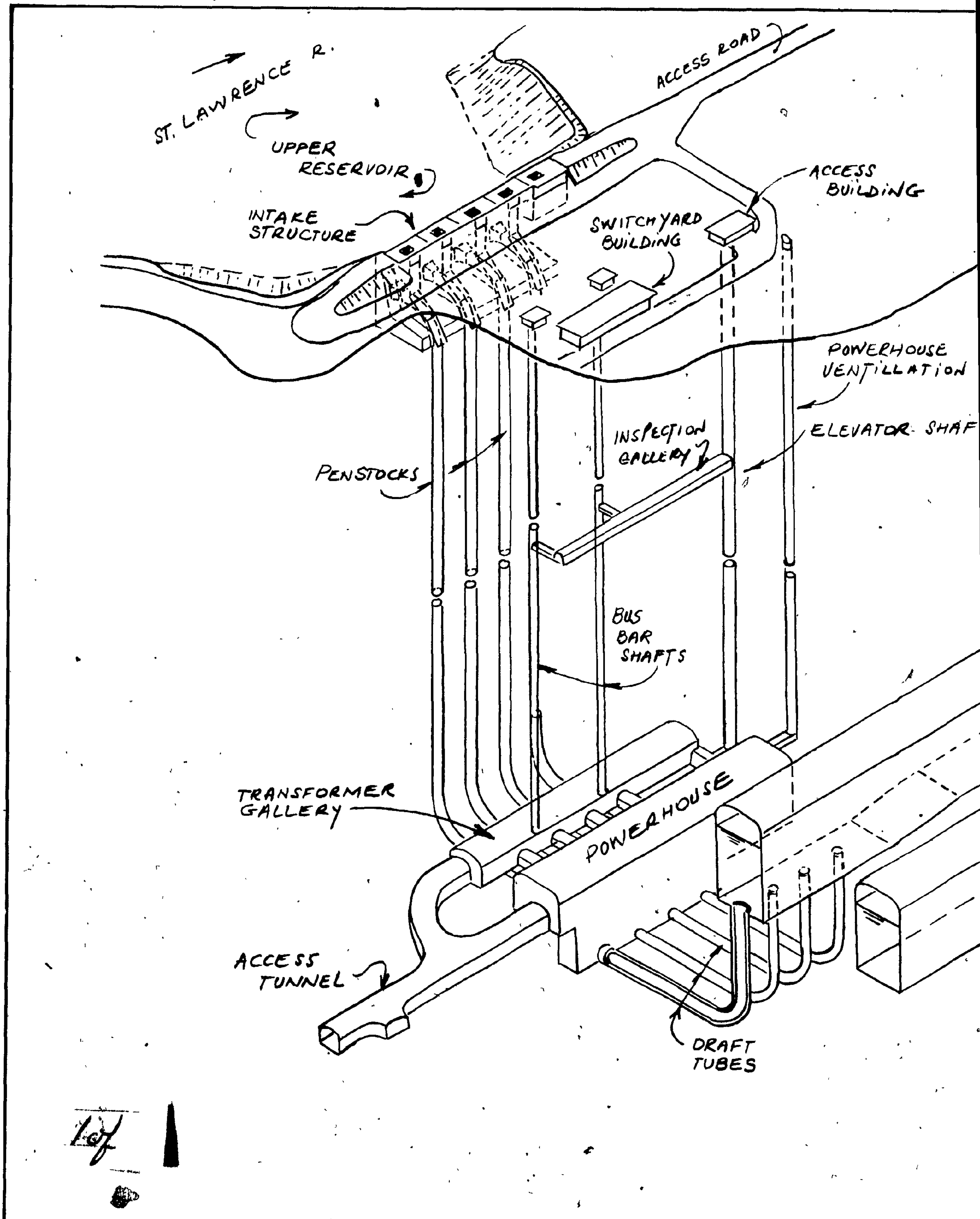
H_n = net hydraulic head = 540 metres

g = 9.81 m/sec^2

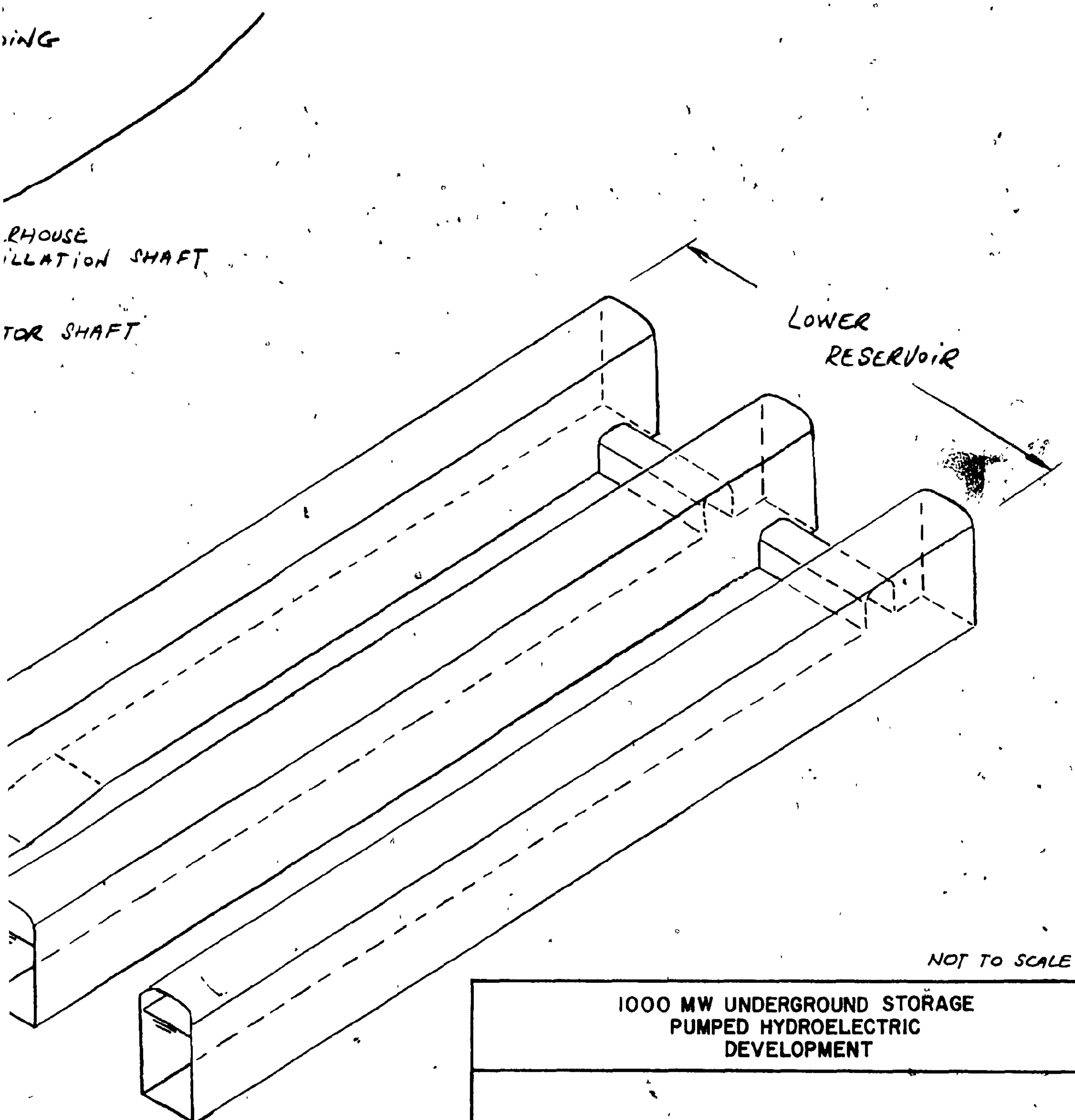
Na = average/combined efficiency of the pump turbine set and electrical equipment at power generation = 0.86

Therefore, the lower reservoir volume, in cubic metres is:

$$V_m3 = \frac{3{,}600 \times 1 \times 10^6 \times 2}{540 \times 9.81 \times 0.86} = 1{,}580{,}000 \text{ m}^3$$



ST. LAWRENCE R.
UPPER RESERVOIR
ACCESS ROAD
INTAKE STRUCTURE
SWITCHYARD BUILDING
ACCESS BUILDING
POWERHOUSE VENTILATION
ELEVATOR SHAF
INSPECTION GALLERY
PENSTOCKS
BUS BAR SHAFTS
TRANSFORMER GALLERY
POWERHOUSE
ACCESS TUNNEL
DRAFT TUBES



1000 MW UNDERGROUND STORAGE
PUMPED HYDROELECTRIC
DEVELOPMENT

ISOMETRIC VIEW OF PROPOSED

PROJECT ELEMENTS

2 of 2

Converting to cubic yards we have:

$$1,580,000 \times 1.3 = 2,055,000 \text{ cy.}$$

Orientation, height and width of openings and such details as the shape of the rock roof would be adjusted to minimize excavation problems and costs.

The centerline of the turbines is located well below the level of the lower reservoir as governed by submergence requirements during the pumping cycle. Such submergence is substantially greater than would normally be required during the generating cycle so the turbine operates under more than the usual back water pressure.

2.4 Optimum Depth of Lower Reservoir

For all practical purposes, the optimum depth is only a function of the cost of the civil works. The principal factors are the costs associated with the access tunnel and the shafts, as well as the cost of transportation of the excavated materials to the surface. All these costs increase with depth although the volume of the lower reservoir diminishes as the depth increases. The optimum depth was found to be around 2,000 feet measured from the surface of the upper reservoir. When the powerhouse is situated at less than 2000 feet the reduction of costs accociated with the access gallery, shafts and transportation of materials is inferior to the cost increment due to the larger water storage caverns required.

At depths greater than 2000 feet the decrease of the costs associated with the lower reservoir does not compensate for the increase in costs associated with the access tunnel, shafts and transportation of materials. Figure 17 illustrates graphically the sensitivity of capital cost to the positioning of the powerhouse below the upper reservoir.

The present state-of-art of single runner, reversible pump turbine performance limits a 250 MW unit to a net hydraulic head of about 1800 feet. Therefore this criteria governs over the optimization of excavation quantities. However, the two values are quite close. Improvement in pump-turbine performance can also be expected in the coming years. To illustrate, until 1968 the highest hydraulic head for a reversible Francis pump-turbine was 1280 feet installed at the Villarino project in Spain.

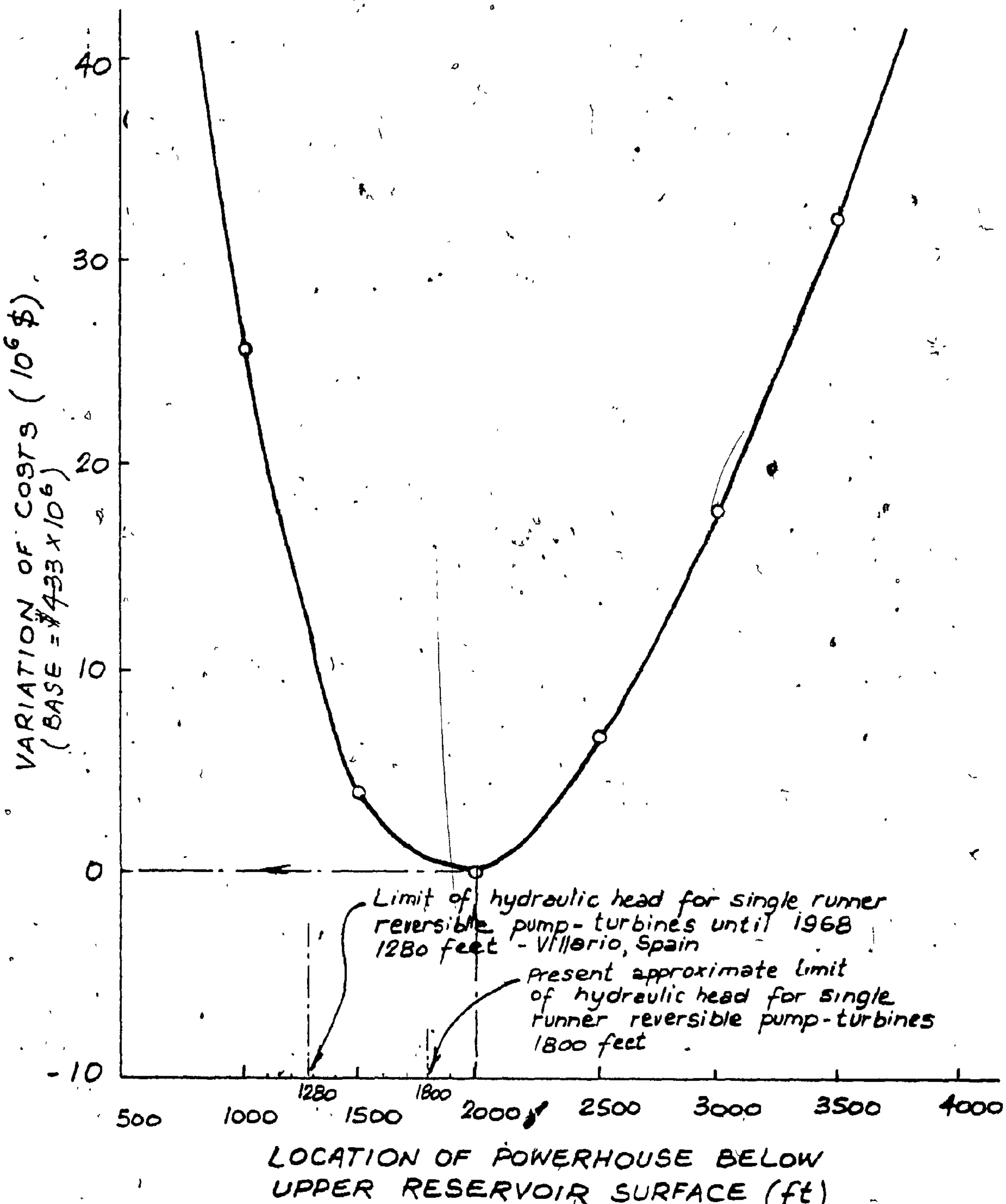


Fig. 17 - Variation of Costs versus Location of Powerhouse Below the Upper Reservoir

2.5 Excavation methods, transportation and disposal of excavated material

The galleries, the powerhouse and the underground storage caverns will be excavated by conventional methods of heading and benching. The arches will be consolidated by grouted rock anchors and shotcreting. For estimating purposes, the power penstocks will be excavated by the "Alimak" raise climbing system. This system is described in detail in Appendix B.

On the surface the excavation for the water intake structure and the shaft collars will present difficulties due to the presence of sensitive marine clays. Therefore the water intake structure will be excavated with the use of a cellular cofferdam system and the shaft collars will be constructed inside of caissons.

The excavated materials will be removed through an access tunnel of 35% slope with a conveyor system and will be transported to the disposal area - an abandoned rock quarry - by trucks.

This method was selected as a result of evaluating three alternatives. The methodolgy of optimization is described in Appendix A.

The main characteristics of the proposed project are shown in Table 4. Preliminary dimensions of the major project elements are summarized in Table 5. Construction costs, based on comparable projects like the Churchill Falls Hydroelectric Project, the La Grande 2 and 4 Hydroelectric Projects of the James Bay Complex, and escalated when appropriate are shown in Section 2.6.

TABLE 4

MAIN CHARACTERISTICS OF THE PROPOSED UPH PROJECT

INSTALLED CAPACITY	1,000 MW
NUMBER OF UNITS	4
GENERATING CYCLE	2 hours
GROSS HEAD	1,880 ft.
MINIMUM HEAD	1,750 ft.
NOMINAL HEAD	1,780 ft.
FLOW DURING GENERATING CYCLE	7,600 cfs
STORAGE CAVERN CAPACITY	2,055,000 c.y.

TABLE 5

PRELIMINARY DIMENSIONS OF THE PROJECT ELEMENTS (feet)

	Number	Diameter	Length	Width	Height
WATER INTAKE STRUCTURE	1		330	34	120
ELEVATOR SHAFT	1	20	2,035		
POWERHOUSE VENT. SHAFT	1	14	1,935		
CABLE SHAFTS	2	6	1,970		
PENSTOCKS	4	14	2,200		
POWERHOUSE	1		460	92	157
DRAFT TUBES	4	16	425		
LOWER RESERVOIR CAVERNS	3		1,575	88	150
LOWER RESERVOIR VENT. SHAFT	1	20	1,770		
DRAINAGE GALLERY	1	490	490	40	25
TRANSFORMER GALLERY	1		425	60	45
ACCESS TUNNEL	1		6,500	32	18
ACCESS TUNNEL VENT. SHAFT	1	6	1,000	-	-
SWITCHYARD	1		125	40	40

2.6 Summary of Cost Estimates

1000 MW Underground Pumped
Hydroelectric Energy Storage Project
2 hour generating cycle

Item	Description	Quantity	Unit	Unit Cost $	Amount 10^3 $
1.0	Access Route and Bridge	-	lump sum		4,000
2.0	Upper reservoir and intake structure, cofferdam, temporary and permanent sheet piling, excavation and concrete		lump sum		6,000
	Excavation in riverbed, piles, anchors, grouting, retaining walls, hydraulic passages, backfilling		lump sum		23,000
3.0	Inclined access shaft and conveyor.				
	Including excavation of access shaft and lower reservoir, conveyors, etc. as detailed in Appendix A.		lump sum		84,250
3.2	Vent shafts	1,500	c.y.	200	300
3.2.1	Overburden excavation	1,500	c.y.	200	300
3.2.2	Rock excavation	8,000	c.y.	80	625
3.2.3	Shotcreting	900	c.y.	350	315
3.2.4	Formed concrete	400	c.y.	325	130
3.2.5	Reinforcing steel	10	ton	1,000	10

Item	Description	Quantity	Unit	Unit Cost $	10^3\$
4.0	Penstocks and Shafts				
4.1	Penstocks - vertical				
4.1.1	Rock excavation	80,000	c.y.	80	6,400
4.1.2	Shotcrete	4,800	c.y.	350	1,680
4.1.3	Grouting	6,500	lin.ft.	25	160
4.1.4	Formed concrete	43,000	c.y.	200	8,600
4.2	Penstocks - horizontal				
4.2.1	Rock excavation	10,500	c.y.	60	630
4.2.2	Rock bolting	2,500	lin.ft.	15	38
4.2.3	Shotcreting	250	c.y.	350	88
4.2.4	Grouting	23,000	lin.ft.	25	575
4.2.5	Formed concrete	3,500	c.y.	200	700
4.2.6	Concreting-steel penstock section	4,000	c.y.	150	600
4.3	Elevator Shaft				
4.3.1	Overburden excavation	2,000	c.y.	150	300
4.3.2	Rock excavation	30,000	c.y.	80	2,400
4.3.3	Shotcreting	1,500	c.y.	350	525
4.3.4	Formed concrete	8,500	c.y.	250	2,100
4.3.5	Reinforcing steel	10	ton	1,000	10
4.4	Cable Shafts				
4.4.1	Overburden excavation	1,500	c.y.	200	300
4.4.2	Rock excavation	20,000	c.y.	80	1,600
4.4.3	Shotcreting	1,000	c.y.	350	350
4.4.4	Formed concrete	8,500	c.y.	250	2,100
4.4.5	Reinforcing steel	10	ton	1,000	10
4.5	Vent Shaft				
4.5.1	Overburden excavation	1,500	c.y.	200	300
4.5.2	Rock excavation	9,000	c.y.	80	720
4.5.3	Shotcreting	900	c.y.	350	315
4.5.4	Formed concrete	250	c.y.	250	60
4.5.5	Reinforcing steel	10	ton	1,000	10

Item	Description	Quantity	Unit	Unit Cost $	10^3\$
5.0	Galleries				
5.1	Construction and drainage galleries				
5.1.1	Rock excavation	210,000	c.y.	35	7,350
5.1.2	Rock bolting	90,000	lin.ft.	8	720
5.1.3	Shotcreting	3,800	c.y.	350	1,330
5.1.4	Drilling of drainage holes	12,000	lin.ft.	4	48
5.1.5	Concreting - invert	7,000	c.y.	100	700
5.1.6	Concrete plug	2,300	c.y.	70	160
5.1.7	Reinforcing steel	200	ton	600	120
5.2	Transformer Gallery				
5.2.1	Rock excavation	40,000	c.y.	35	1,400
5.2.2	Rock bolting	8,500	lin.ft.	8	68
5.2.3	Shotcreting	300	c.y.	350	105
5.2.4	Concrete - invert	2,000	c.y.	100	200
5.2.5	Reinforcing steel	25	ton	600	15
5.3	Bus Bar Galleries				
~~5.3.1~~	Rock excavation	5,000	c.y.	40	200
5.3.2	Rock bolting	1,600	lin.ft.	15	24
5.3.3	Shotcreting	70	c.y.	350	25
5.3.4	Concreting - invert & walls	400	c.y.	150	60
5.3.5	Reinforcing steel	5	ton	1,000	5
5.4	Inspection Galleries				
5.4.1	Rock excavation	18,000	c.y.	70	1,260
5.4.2	Rock bolting	6,500	lin.ft.	15	100
5.4.3	Shotcreting	70	c.y.	350	25
5.4.4	Concreting - invert	1,000	c.y.	125	125
5.4.5	Reinforcing steel	5	ton	600	3
6.0	Powerhouse and Draft Tubes				
6.1	Power house				
6.1.1	Rock excavation	180,000	c.y.	30	5,400
6.1.2	Rock bolting	21,000	lin.ft.	8	170
6.1.3	Shotcreting	500	c.y.	350	175

Item	Description	Quantity	Unit	Unit Cost $	$10^3$$
6.1.4	Grouting	3,500	lin.ft.	25	90
6.1.5	Formed concrete	25,000	c.y.	200	5,000
6.1.6	Reinforcing steel	1,400	ton	700	980
6.1.7	Structural steel	800	ton	1,500	1,200
6.2	Horizontal Draft Tubes				
6.2.1	Rock excavation	18,000	c.y.	65	1,170
6.2.2	Rock bolting	4,300	lin.ft.	15	65
6.2.3	Shotcreting	400	c.y.	350	140
6.2.4	Grouting	3,300	lin.ft.	25	82
6.2.5	Formed concrete	7,000	c.y.	200	1,400
6.2.6	Concrete - steel liner	4,200	c.y.	175	735
6.2.7	Reinforcing steel	250	ton	700	175
6.3	Vertical Draft Tubes				
6.3.1	Rock excavation	9,000	c.y.	80	720
6.3.2	Shotcreting	500	c.y.	350	175
6.3.3	Grouting	1,600	lin.ft.	25	40
6.3.4	Formed concrete	4,500	c.y.	225	1,000
6.3.5	Reinforcing steel	250	ton	750	188
7.0	Lower Storage & Vent Shaft				
7.1	Storage Caverns				
7.1.1	Rock excavation*				
7.1.2	Rock bolting	213,000	lin.ft.	8	1,700
7.1.3	Shotcreting	5,500	c.y.	350	1,900
7.2	Connecting Galleries				
7.2.1	Rock excavation	58,000	c.y.	55	3,200
7.2.2	Rock bolting	11,500	lin.ft.	8	90
7.2.3	Shotcreting	400	c.y.	350	140
7.3	Vent Shaft				
7.3.1	Overburden excavation	1,300	c.y.	160	210
7.3.2	Rock excavation	18,000	c.y.	70	1,260

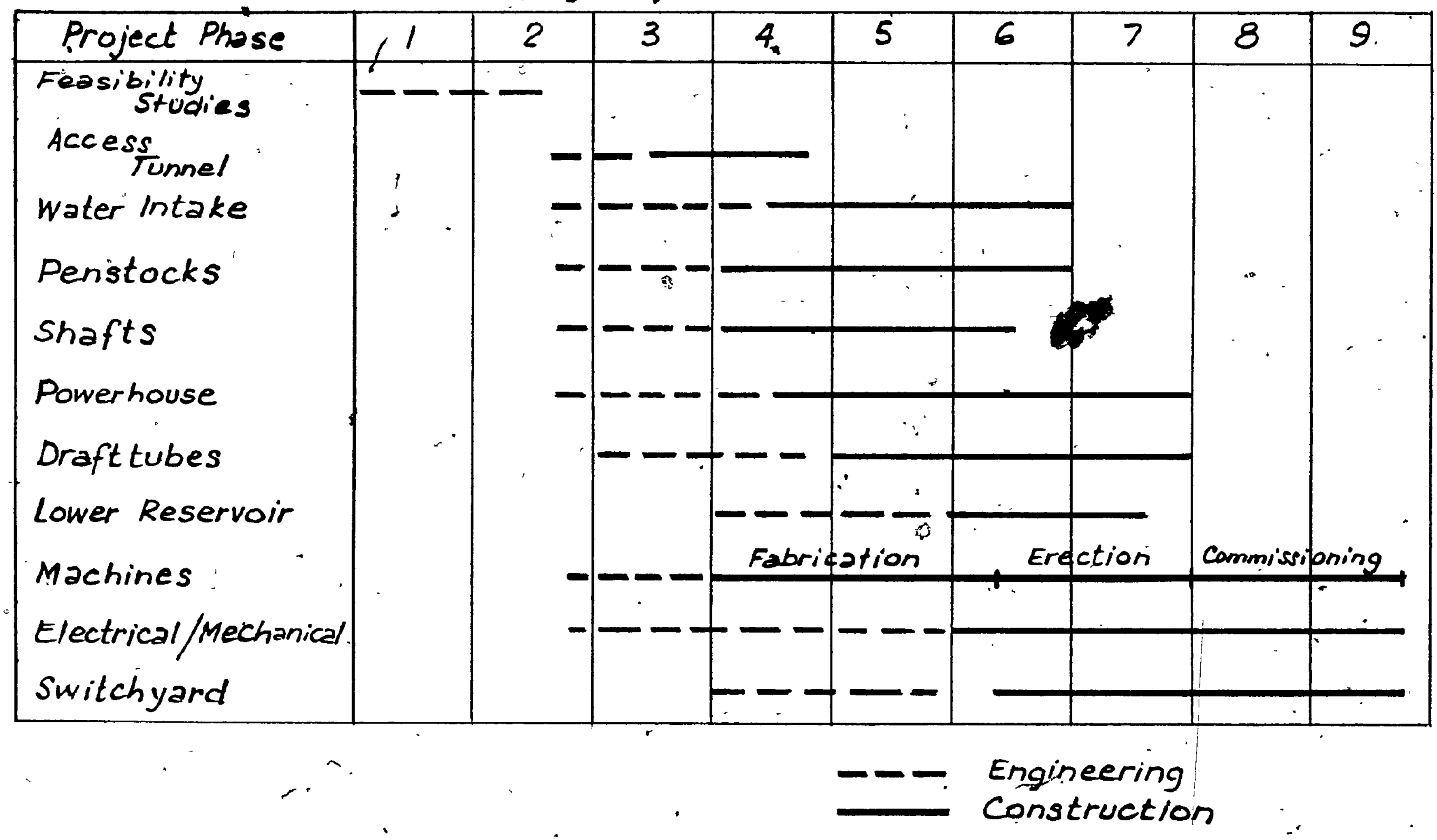
* Included in Item 3.0

Item	Description	Quantity	Unit	Unit Cost $	$10^3$$
7.3.3	Shotcreting	900	c.y.	350	315
7.3.4	Formed concrete	250	c.y.	300	75
7.3.5	Reinforcing steel	10	ton	1,000	10
8.0	Turbines & Generators				
8.1	Turbines				40,000
8.2	Generators				15,000
9.0	Mechanical Equipment				
9.1	Trashracks				180
9.2	Intake stoplogs				40
9.3	Intake gates				300
9.4	Steel liner - Penstocks				3,500
9.5	Spherical valves				14,000
9.6	Butterfly valves				2,000
9.7	Steel liner - Draft Tubes				700
9.8	Draft tube valves				80
9.9	Monorail				60
9.10	Powerhouse cranes				2,500
9.11	Elevators				2,000
9.12	Special Bulkheads				200
9.13	Compressors, filters, etc.				3,500
9.14	Heating, ventilating, pumping				5,000
10.0	Electrical Equipment				
10.1	Static excitation				1,000
10.2	Bus Bars				2,000
10.3	Disconnect switch				2,400
10.4	Main transformers				4,500
10.5	Auxilliary services				2,000
10.6	315 KV cables				3,000
10.7	Cable trays, conduits, etc.				1,500
10.8	Control, protection, communication				700
10.9	Grounding				100

Item	Description	Quantity	Unit	Unit Cost $	10^3 $
11.0	Switchyard & Access Building				
11.1	Equipment				3,500
11.2	Control and protection				100
11.3	Auxilliary services				50
11.4	Distribution, conduits, etc.				100
11.5	Grounding				10
11.6	Switchyard building				200
11.7	Access building				100
12.0	Exploration Work				2,000
13.0	Construction Services				24,000
		SUB-TOTAL (1979 dollars)			$ 327,370
		Contingency 15%			49,100
		Management and supervising - 15% of above			56,470
		TOTAL (1979 dollars)			$ 432,940
		SAY			$ 433,000

Capital Cost of Installations per kilowatt - $433

Preliminary Construction Schedule (UPH Project)
(in years)



Comparison of Capital Cost Estimate to Similar Projects

In the absence of existing UPH projects it is somewhat difficult to determine if the cost of $433/kW is a reasonable figure.

In the August 29, 1968 Engineering News Record (pp.36) the figure of $64/kW was quoted for a 400 MW UPH installation operating under a head of 1500 feet.

Assuming an inflation rate of 8 per cent per year this figure, in 1979 dollars would be

$$\$64\ (1.08)^{11} = \$150/kW$$

However it is unlikely that any hydroelectric project could be constructed for this amount in 1979.

The 5225 MW Churchill Falls Power Project completed in 1975 cost a total of 606.2 million dollars or $116/kW, however this is an extremely large generating facilitiy so the cost/kW would not be representative.

A better comparison would be the 1000 MW Champigny conventional pumped energy storage plant estimated by Hydro Quebec in 1973 to cost $235/kW.

Again, using an 8% inflation rate per year we would obtain for 1979:

$$\$235\ (1.08)^{6} = \$373/kW$$

The Bay of Fundy Tidal Power Review Board and Management Committee estimated the cost of conventional pumped storage plants at about $305/kW (1976 dollars) in the report entitled "Reassessment of Fundy Tidal Power".

In the capital cost estimate no attempt was made at crediting the potential value of the excavated material to the project.

Although it is realized that this material would be suitable for the production of crushed stone or concrete aggregates the value of such products depends on the market demand which vary from one year to another.

Therefore, for the purpose of this study, the revenue that might be realized from the excavated materials was not considered.

2.7 Economic Analysis - UPH Projet

Fixed Charge Rates Related to the Cost of Investment

Book Life (years) 50

Capital recovery factor (%)	5.806
Interim replacement (%)	0.41
Insurance (%)	0.10
Operation and maintenance (%)	0.60
Fixed charge rate (%)	7.016

Therefore the fixed annual costs of the proposed UPH project are:

($\$433 \times 10^6) \times 0.07016 = \$30,379,280$

Cost of Pumping

The generating facilities of Hydro Quebec consist virtually exclusively of hydroelectric plants. Energy used for the purpose of pumping would not generate any revenue during this time. Therefore in the calculation of cost of pumping, the full potential revenue producing value of $0.02/kWh is not justified, and a nominal amount of $0.005/kWh will be used to account for equipment wear during the pumping period.

Therefore, the annual energy used for pumping is:
$4/3 \times 1,000,000$ kW $\times$ 2 hrs/day $\times$ 365 days/yr =
0.973 GWh/yr

So the cost is: 973×10^6 kWh $\times$ $0.005 = $ 4,686,500

Total fixed annual costs:	$35,065,780
say:	$35,100,000

Note: Fixed charges associated with Hydro Quebec do not include taxes as it is a provincial utility.

Explanation of Fixed Annual Costs - UPH Project

Book Life

Major hydroelectric projects are assumed to have a service life of 100 years and this period is normally used in economic analyses. However in view of the fact that there is presently no data available on UPH projects the service life of the project was based on 50 years which is the life span used by Hydro Quebec for hydroelectric projects. (Source: Rapport annuel de l'Hydro Quebec 1977)

Capital Recovery Factor (crf)

This was based on real interest rate of 5½%. Real interest is defined, to a close approximation, as the difference between the actual interest rate (taking into account the borrower's credit rating and the risk involved) and the inflation rate.

This is the interest rate which was used in the 1977 Bay of Fundy Tidal Power Project evaluation:

$$\text{crf} = \frac{i\,(1+i)^n}{(1+i)^n-1} = \frac{0.055\,(1.055)^{50}}{(1.055)^{50}-1}$$

$$= 0.05906$$

$$= 5.906\%$$

The sensitivity of debt retirement to interest rates and service life is shown in Figure 18.

Interim Replacement

The use of sinking fund depreciation method does not provide for the replacement of those units of property included in the plant with life spans less than the adopted overall facility service life. Therefore, provision must be made for financing the cost of replacing such short lived units.

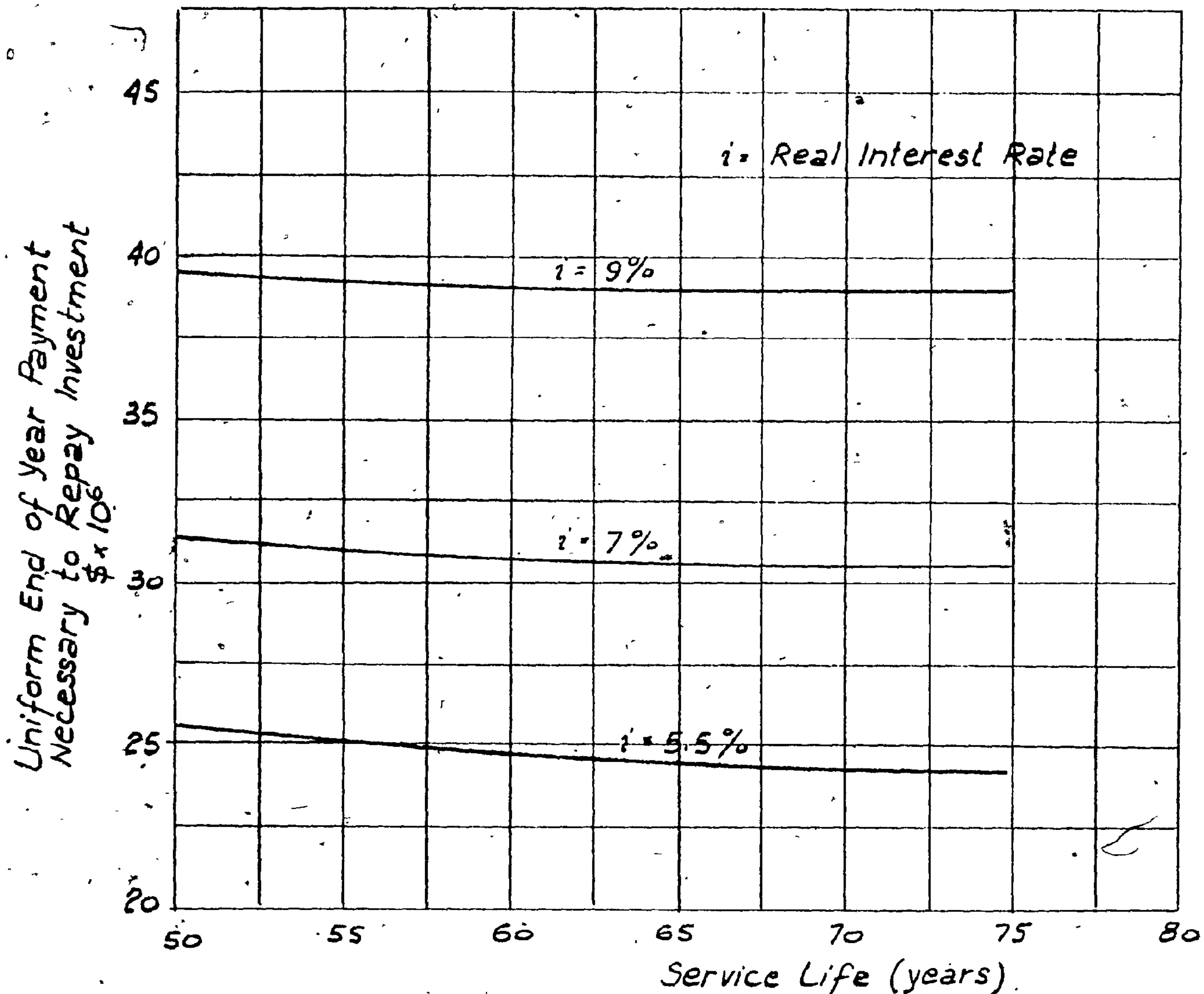


Fig. 18 - Sensitivity of Debt Retirement to Interest Rates and Service Life
UPH Project

For economic analyses of hydroelectric projects studies indicate that the appropriate annual amount for interim replacements would be 0.41 percent of total power investment.(23)

Insurance

The annual cost of fire, vandalism, machinery, public liability, property damage and other miscellaneous operating insurance applicable to electric utility facilities range from 0.01 to 0.35 percent of the total gross investment depending on the property involved, the location and management policies. A reasonable amount for hydroelectric projects is 0.1 percent of total gross investment.(23)

Operation and Maintenance

The annual operation and maintenance expenses per kilowatt capacity vary according to the size of plant and the type of operation. Automatic, remote controlled plants require addtional investment but reduce operating costs.

The Bay of Fundy Tidal Power Review Board and Management Committee obtained costs for pumped storage schemes during 1977 from power utilities in New Brunswick, Nova Scotia and the New England States and established this component at 0.6 percent of total gross investment.

CHAPTER III

COMPRESSED AIR ENERGY STORAGE (CAES)

3.1 Historical Background

The first compressed air storage scheme was constructed in the Striberg mine, Sweden in 1910 to provide compressed air to drilling equipment employed there. The volume of this air storage reservoir is about 1,100 cubic yards with the air stored at 7 atmosphere. This storage is still in operation.

Several other countries adopted this system in their mining operations.

The concept of Compressed Air Energy Storage (CAES) for energy generation was first introduced by Stal-Laval Turbine AB of Sweden in 1949.

Table 6 shows some of the existing and proposed Compressed Air Storage Schemes.

3.2 General Concept

CAES is a technique for supplying peak load power to electric utility systems. Although the basic idea of CAES has been discussed for a long time, only the technological advances made in the field of high pressure ratio, modified gas turbines make the economics of the plant attractive for consideration as a commercially feasible system for peaking power.(12)
The concept functions in a similar manner to a pumped storage hydroelectric plant. Electric energy is withdrawn from the utility system during off-peak periods to compress air during the pressurization or storage mode, and store it in an underground containment.

In the power generation mode the stored air is withdrawn from the containment, heated and expanded through suitable gas turbines to generate electric power.

TABLE 6

Some Existing and Proposed
Compressed Air Storage Schemes
and CAES Projects

Country	Location	Type	Vol. c.y.	Pressure(atm)	Year
Finland	Pyhasalmi*	Balanced	2,670	80	1973
Luxemburg	Vianden** (300 MW)	Balanced	133,000	50	proposed
Norway	Jukla*	Unbalanced	8,250	25	1974
	Kvilldal*	Balanced	133,000	43	under const.
Sweden	Striberg* Mine	Balanced	1,100	7	1910
	Glan** (230 MW)	Balanced	532,000	26	proposed
West Germany	Huntorf** (290 MW)	Unbalanced	400,000	70	1978

* Indicates compressed air storage schemes designed for the operation of mine equipment.
** Indicates CAES plants designed for peaking power generation.

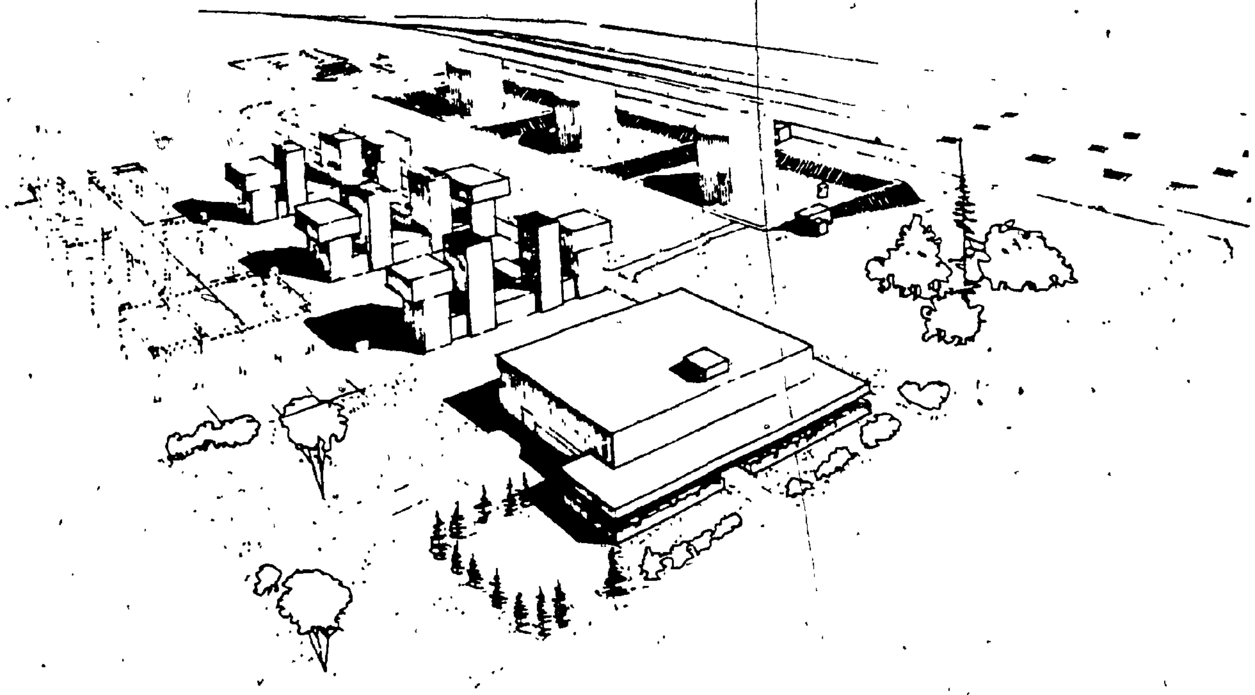
The consumption of fuel oil by a CAES facility can be between one half and one third of the oil consumption of conventional peaking power gas turbines (25) because the gas turbine is relieved of the duty of driving the compressor during generation to the power system and the full turbine output becomes available as net work.

In a conventional gas turbine the compressor consumes about two-thirds of the power output of the turbine. Figures 19 and 20 show the general layout and detail of a conventional gas turbine peaking power plant constructed by Hydro Quebec in Cadillac, Quebec in 1977. In the CAES system the energy transfer is accomplished by a motor generator attached by clutch drives to both the compressor and the turbine, as illustrated in Figure 21.

In the pressurization or storage mode the motor-generator drives an axial compressor that boosts air pressure to about 160 psi.

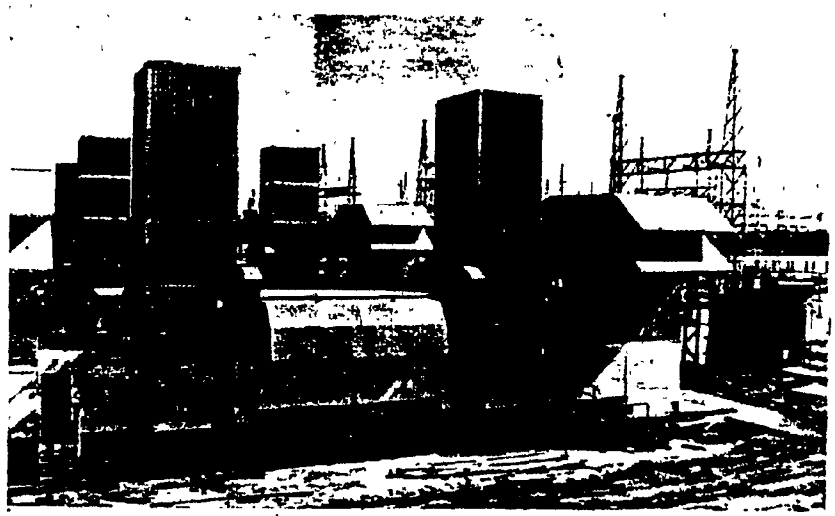
The air is then passed through a series of coolers and auxiliary centrifugal compressors that raise it to the final 1028 psi pressure at which it is stored in the underground storage cavern.

In the power generation mode, the compressed air is released from the storage cavern. The high pressure air is throttled to a pressure of approximately 600 psi and passed through a recuperator where it is heated by the gas turbine exhaust. It is then channeled to an expansion turbine that drives a 50 MW generator. After leaving the turbine, the hot, high pressure air travels to the gas turbine combustors where it is heated. The resulting very high temperature and high pressure air is then expanded through the gas turbine to drive a motor generator unit that produces an additional 150 MW of electric power. This concept, developed by General Electric [25] is illustrated in Figure 22. The CAES systems might operate at a constant pressure or at variable pressure.



(Source: LAVALIN-Montreal)

Fig. 19 - 162 MW Conventional Gas Turbine Peaking Power Plant Cadillac, Quebec. Owner: Hydro Quebec



(Source: LAVALIN-Montreal)

Fig. 20 - Detail of 162 MW Conventional Gas Turbine Peaking Plant, Cadillac, Quebec, Showing the Three Groups of 54 MW Units Under Construction and Part of the Switchyard.

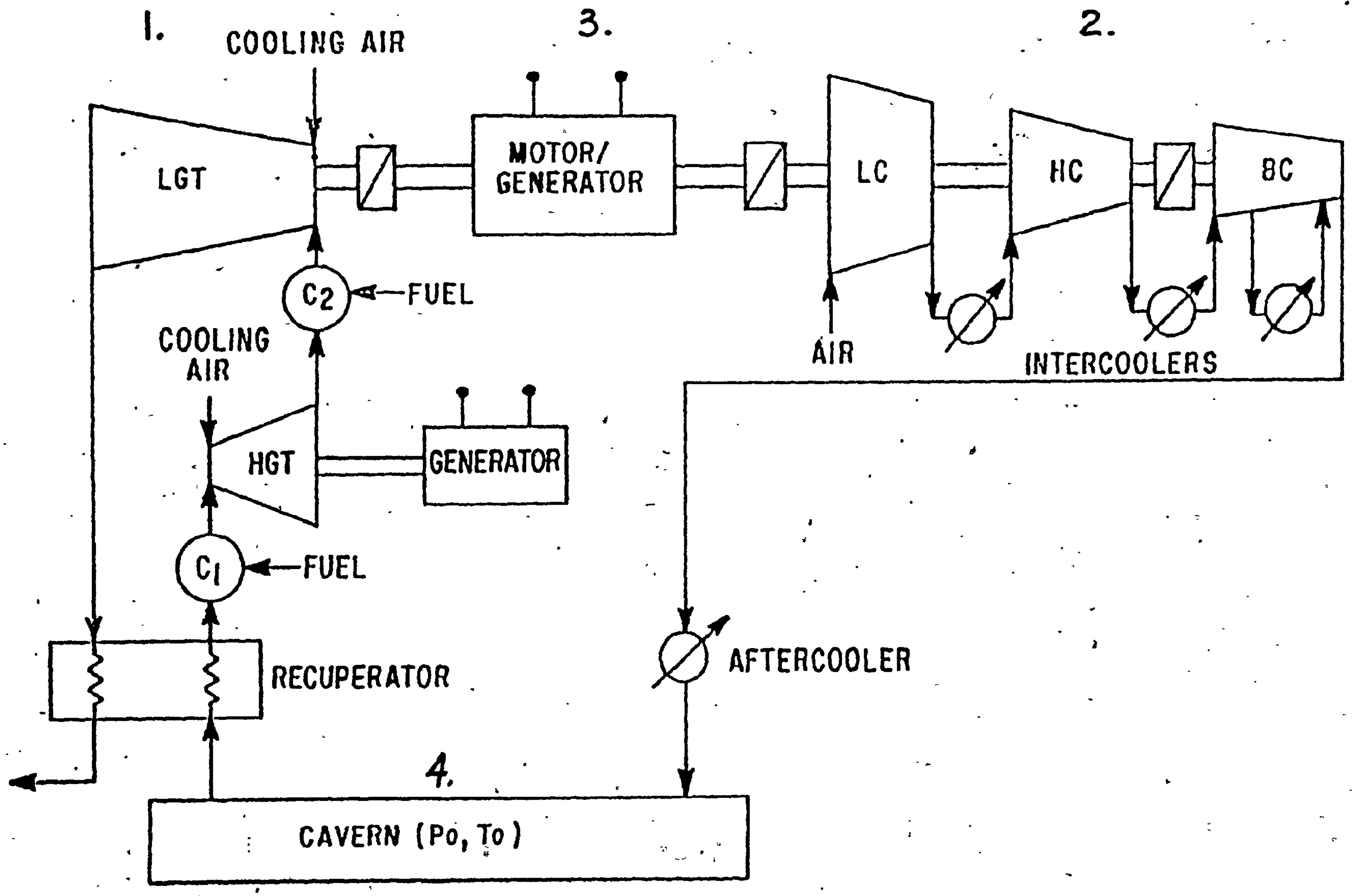


FIGURE 21 - Schematic Diagram of CAES Plant
(Ref. 28)

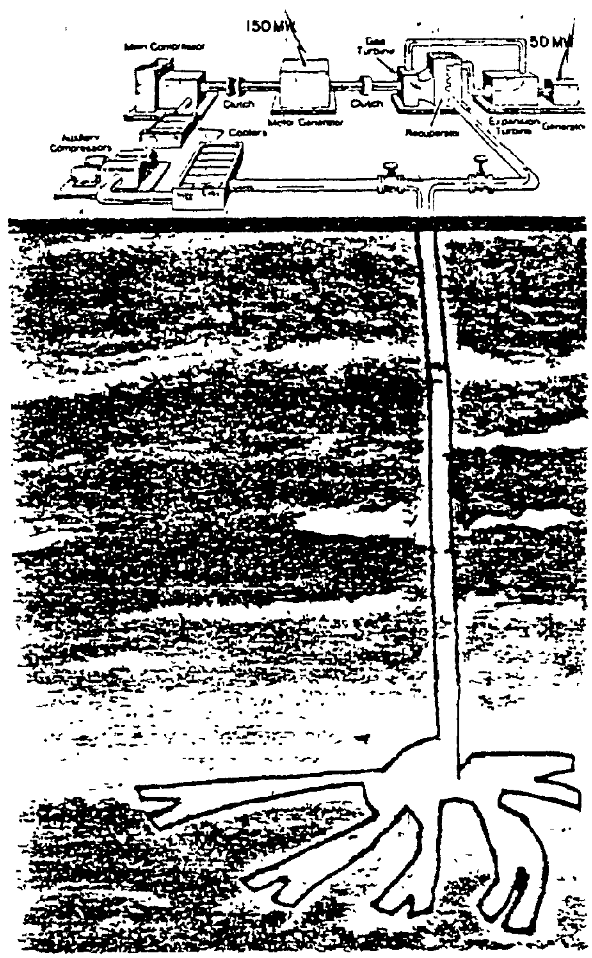


Fig. 22 - Compressed Air Storage
Power Plant Concept
(Ref. 26)

The Constant Pressure System

This system utilises a hydrostatically compensated lower reservoir to maintain a constant pressure during the cycle. During the compression period, water is displaced from the lower reservoir and forced through a shaft to a surface reservoir (Figure 23).

The Variable Pressure System

Stores air in an underground reservoir which acts as a simple pressure tank. Pressure and temperature in the cavern increase when compressing air into the fixed volume and decrease as air is fed to the gas turbine (Figure 24).

3.3 Subsystems of a CAES Plant

The plant consists of four subsystems (Figure 21)

1. Turbine system
2. Compressor system
3. Motor/generator
4. Underground air storage reservoir

The components of the turbine system are:

- low pressure gas turbine (LGT)
- High pressure gas turbine (HGT)
- two combustors
- recuperator

It is assumed that the LGT is a modified conventional gas turbine unit and the HGT is a modified steam turbine operating at gas temperatures of about 1000°F.

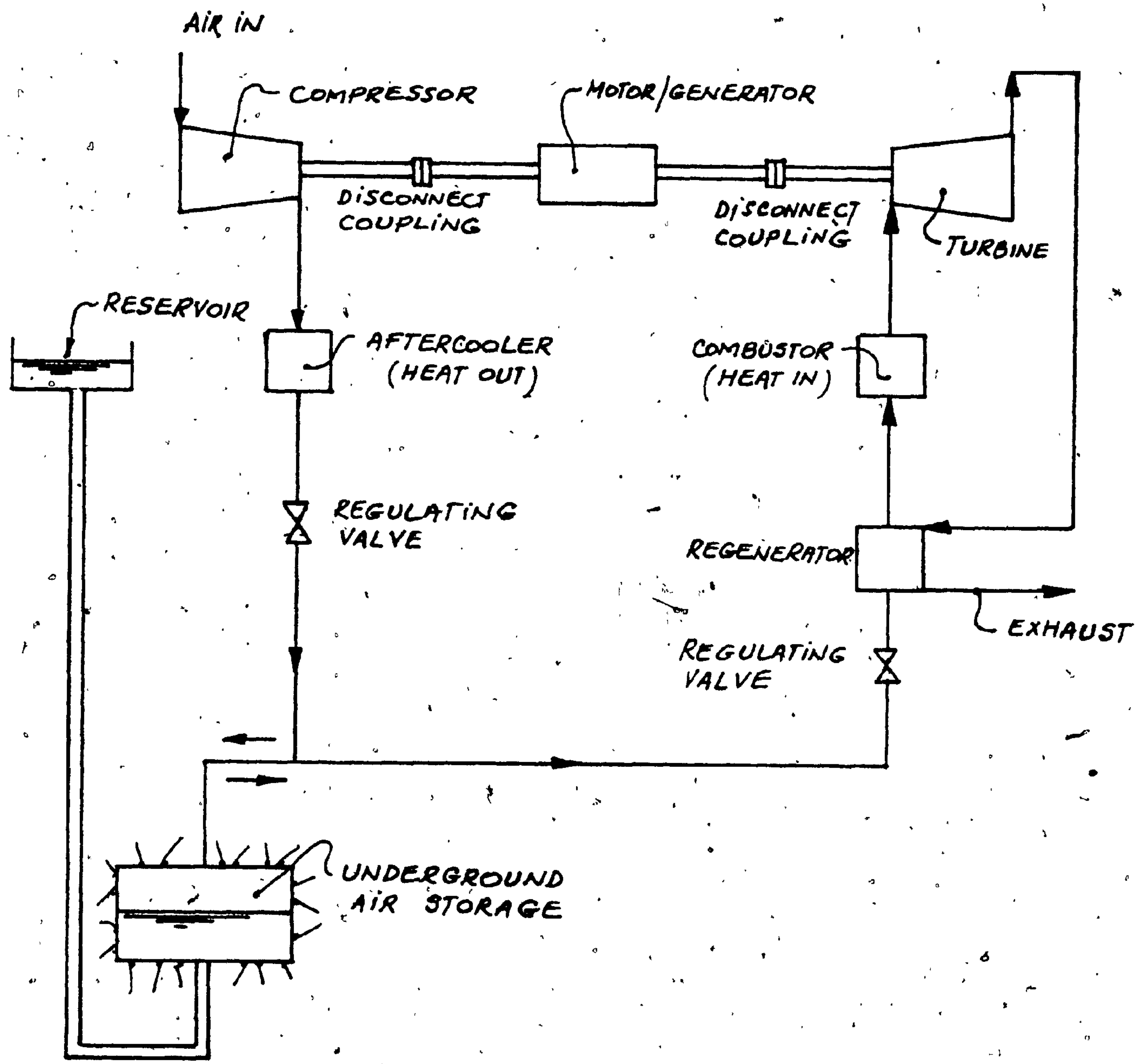


FIG. 23 - COMPRESSED AIR ENERGY STORAGE CONSTANT PRESSURE SYSTEM LINE DIAGRAM.

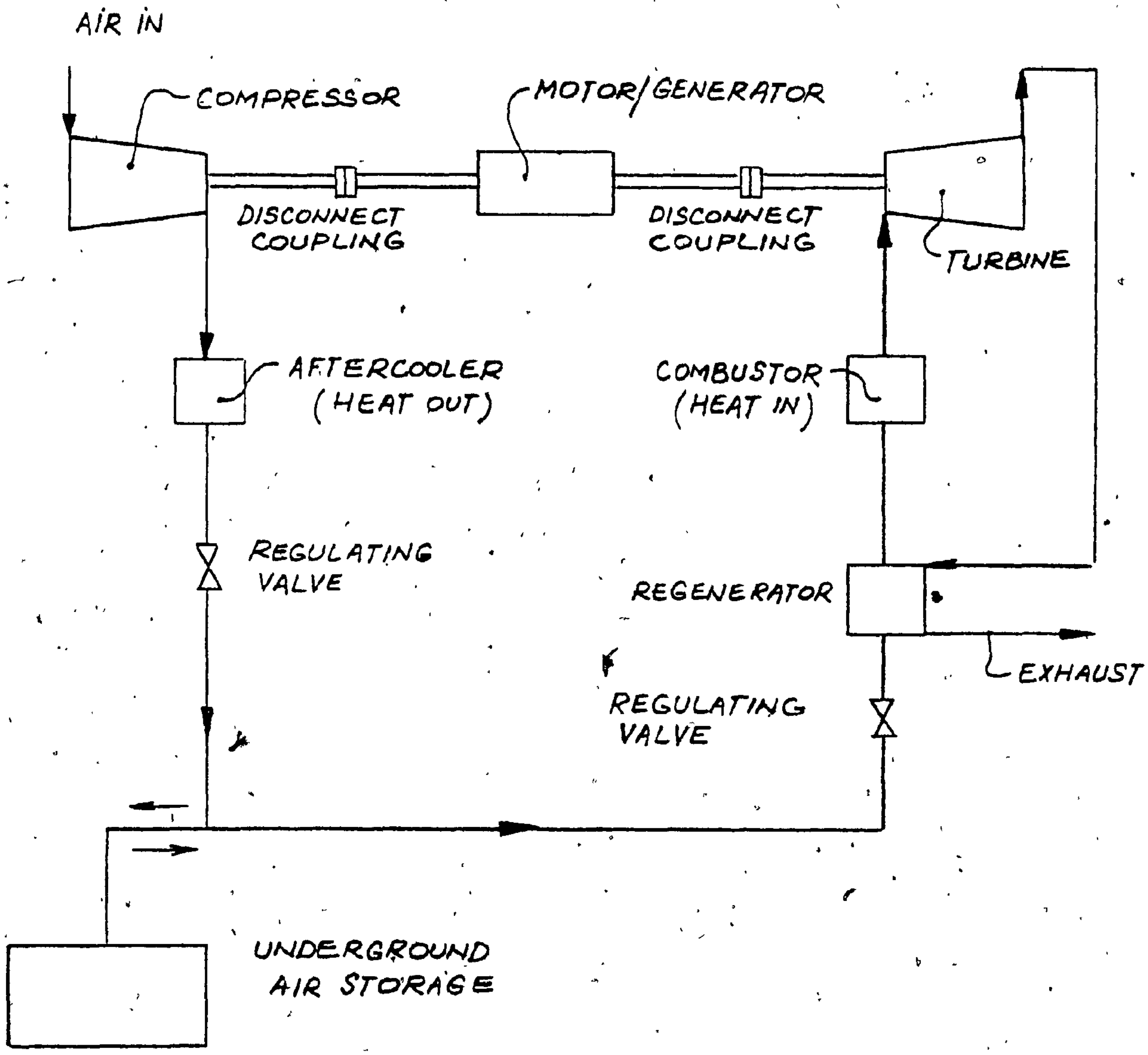


FIG. 24 - COMPRESSED AIR ENERGY STORAGE
VARIABLE PRESSURE SYSTEM
LINE DIAGRAM

The combustors are modified from conventional gas-turbine units whereas the recuperators will be designed specially for CAES operation. They differ from conventional units because of the high pressure of the storage reservoir.

The compressor systems consists of:

- o low pressure compressor (LC)
- o high pressure compressor (HC)
- o booster compressor (BC)
- o after cooler

Inter-cooling is necessary for the operation of the compressors within acceptable temperature limits.

The after cooler is used to cool the air entering the storage reservoir because of the possibility of thermal damage to the reservoir wall.

3.4 Specific Parameters of CAES Plant Performance

Four specific parameters characterise a CAES plant performance:

- o Specific air flow
- o Specific heat rate
- o Specific storage volume
- o Specific compression rate

Specific Air Flow

It is the mean flow rate of air supplied to the turbine system per kilowatt of power generated. This is the major factor in the sizing of turbines, compressors and the air storage reservoir. (Figure 25)

Specific Heat Rate

It is directly proportional to fuel consumption. It is the product of specific fuel consumption and the lower heating value of the fuel. Therefore it affects the turbine generating costs.

Specific Storage Volume

It is the volume of reservoir required per kilowatt of power generated. It depends on the specific air flow rate and the temperature of stored air. (Figures 26 & 27)

Specific Compression Rate

It is the energy equivalent of the power supplied to the compressor per kilowatt of power generated. This is the amount of off-peak energy required to operate the compressors.

The overall plant efficiency is equal to the total energy output from the turbines divided by the sum of the energy input from the fuel and off-peak energy to the compressors.

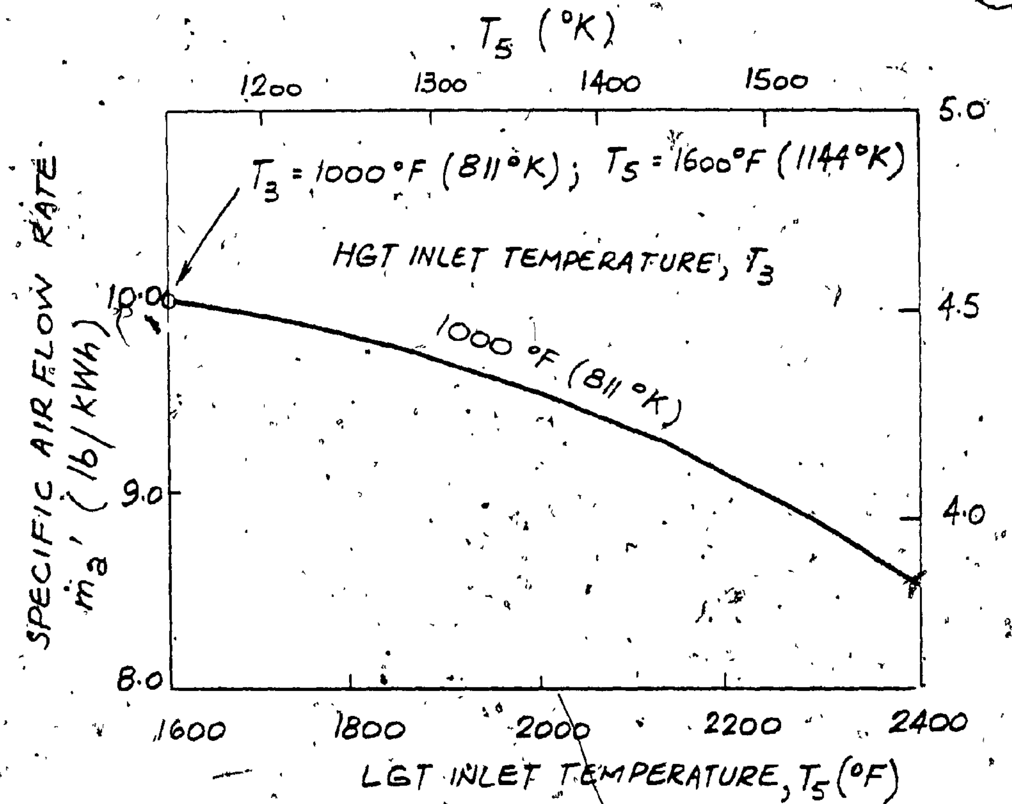


Fig. 25 - Effect of Turbine Inlet Temperature on Specific Air Flow Rate

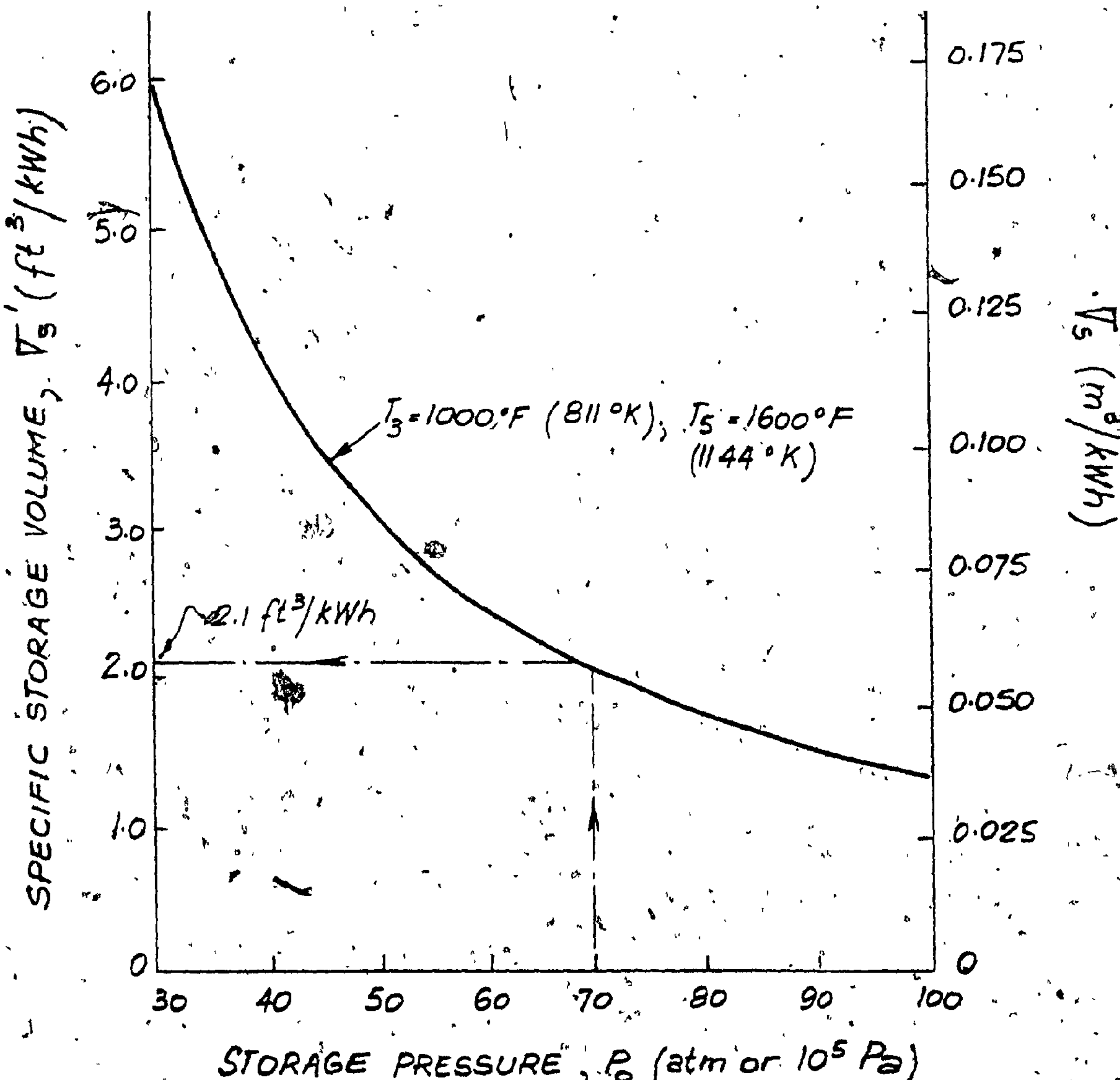


Fig. 26 - Effect of Storage Pressure on Specific Storage Volume

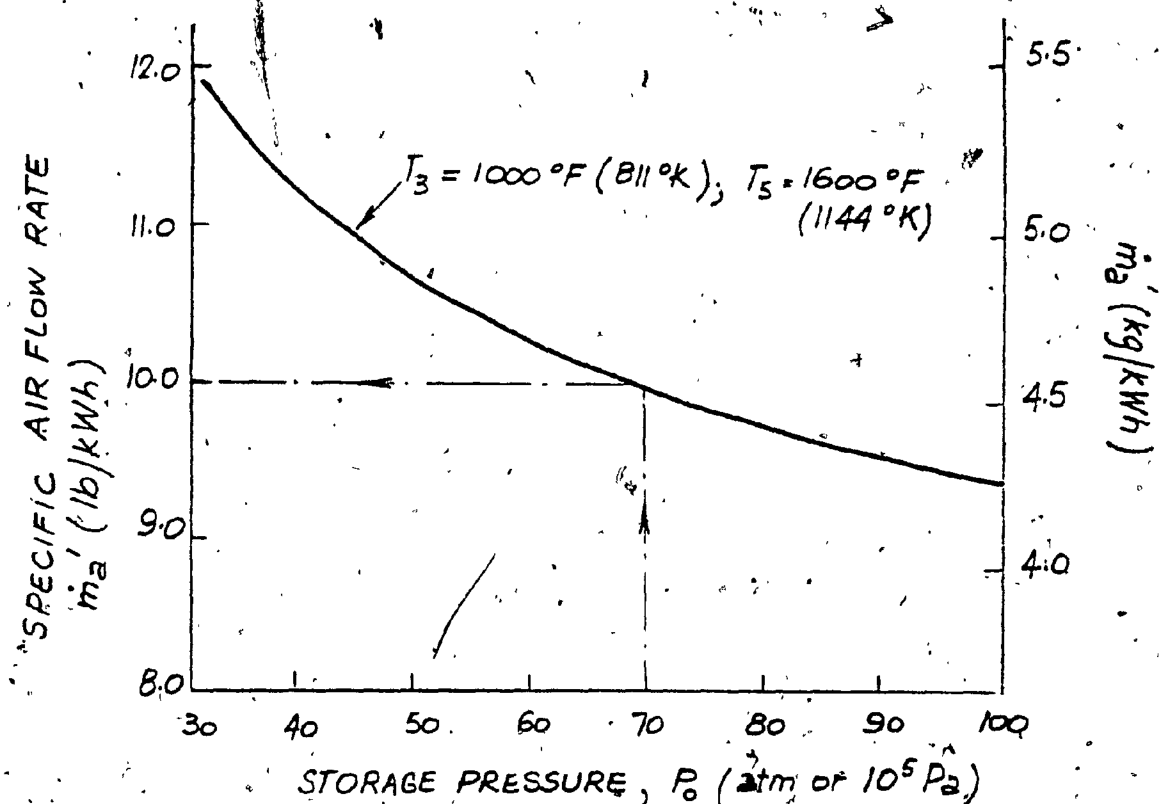


Fig. 27 - Effect of Storage Pressure on Specific Air Flow Rate

Turbines

$\eta_{LGT} = \eta_{HGT} = 0.9$

Recuperation effectiveness: = 0.8

Temperatures: T_3 = 1000°F (811°K) = LGT inlet temp.

T_5 = 1600°F (1144°K) = HGT inlet temp.

Pressure: P_5 = 16 atm. (1.6×10^6 Pa)

Power output of an LGT: W_{LGT} = 200 MW

i.e. for the required 1000 MW output five 200 MW units will be installed.

The efficiencies of turbines and combustors are based on the state-of-the-art values of available equipment.(28)

Compressors:

$\eta_{HC} = \eta_{LC} = \eta_{BC} = 0.90$ = adiabatic efficiency of compressors

Temperatures: T_{11} = 77°F

$T_{13} = T_{15}$ = 200°F

T_{19} = 120°F

Pressures: 11 = 1 atm

14 = 16 atm

The effect of storage pressure on the required specific storage volume is shown in Figure 26.

At the selected pressure of 70 atmospheres, 2.1 cubic feet of storage volume is needed per kilowatt hour of power generated.

Therefore, we have:

- Plant capacity: 5 - 200 MW units = 1,000 MW = 1,000,000 kW
- Operating period: 2 hours.
- Total kilowatt hours generated
  1,000,000 kW x 2 hrs = 2,000,000 kWh
- Storage volume required per 200 MW unit:
  2,000,000 x 2.1 cu. ft. = 4.2×10^6 cu. ft.

- Total storage volume required:

$$5 \times 4.2 \times 10^6 \text{ cu. ft.} = 21 \times 10^6 \text{ cu. ft.}$$
$$= 778{,}000 \text{ c.y.}$$

add 10% capacity margin

$$778{,}000 \times 1.1 = 855{,}000 \text{ c.y.}$$

In order to provide a valid comparison of the air storage reservoir of the CAES with the lower reservoir of the UPH system the cavern dimensions of 88-foot width and 150-foot height will be retained.

Therefore the required total cavern length for the air storage reservoir will be:

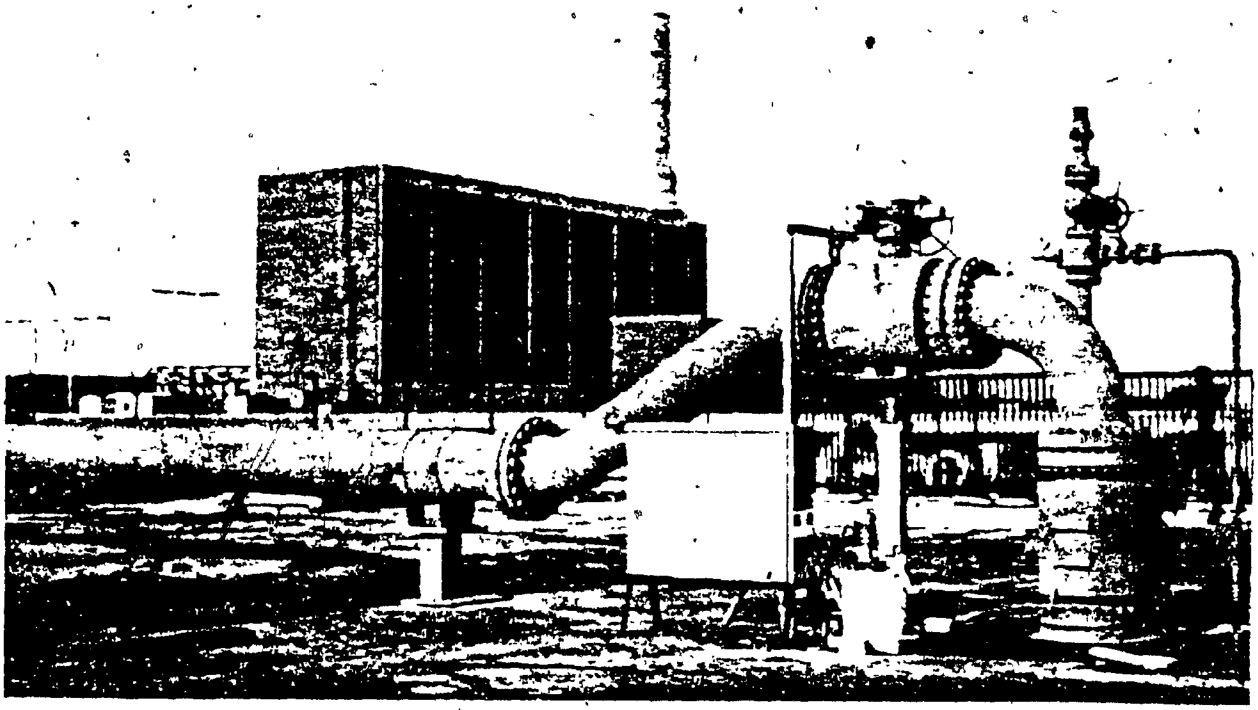
$$\frac{855{,}000 \text{ c.y.} \times 27 \text{ cu. ft./c.y.}}{88 \text{ ft.} \times 150 \text{ ft.}} = 1750 \text{ ft.}$$

Due to the comparatively low quantities of underground excavation associated with this project (855,000 c.y. versus 2,055,000 c.y. for the UPH project) the material will be removed by vertical hoisting through the watershaft and then trucked to the disposal area selected for the depositing of excavated materials for the UPH project.

The cost of transporting the excavated rock from the hoist to the disposal area is calculated in Appendix A.

3.5 Existing Development

The world's first CAES plant, expressly designed to generate peaking power was placed into operation in the fall of 1978 at Huntorf, West Germany, by the Nordwestdeutsche Kraftwerke AG (NWK). A general view of this plant is shown in Figure 28. The 290 MW system uses a two-cavern air storage system excavated by solution mining techniques in a salt dome. The total volume of the two caverns is about 400,000 cubic yards. The conceptual design took about two years. Construction of the plant and storage cavities was started in 1975. The caverns were completed two years later and the plant was put on stream for peaking power generation in October 1978.(13)



(Ref. 12)

Fig. 2.8 - 290 MW CAES Peaking Power Plant, Huntorf, West Germany, Air Production Well Head and Plant.

3.6 Description of the Proposed CAES Project

For the purpose of this study a water-compensated air storage cavern is considered, therefore the pressure variation in the cavern during the operating cycle is considered to be negligible.

In order to avoid discharging water of unacceptably high temperature into the river during the compression cycle the air temperature of the storage cavern (To) is assumed to be 120°F (322°K) and the air storage pressure (Po) is 70 atm (7×10^6 Pa) to minimize the cavern size.

Site Selection

In the U.S., Harza Engineering Company carried out site selection studies for potential CAES development as part of an overall national survey. In addition to the geologic and general aspects of the study, Harza also included the identification of regional markets, recommendations for further research and development and demonstration efforts required to make underground storage commercially attractive.

After considerable research and interpretation, Harza geologists prepared generalized maps of the U.S. that showed areas unsuitable for the development of CAES projects.

The rejected areas contained:

- unconsolidated sediments of great thickness;
- volcanic rock not sufficiently thick to contain the structures;
- geologically complex areas;
- areas of extensive major faulting;
- oil and gas fields - these were rejected because of the danger of residual hydro-carbons creating combustible mixtures or a possible chemical reaction causing oxygen deficiency.

At the proposed project site, described in this report the air reservoir would be situated in crystalline metamorphic rocks of precambrian age[9]

Bush, et al[26] reviewed the characteristics of various rock types for potential mined air reservoirs for CAES and concluded that this type of rock is one of the most suitable for this purpose.

Surface Features

The project will be constructed on a site of about 150 acres located on the west side of Ile St.Therese (Figure 11) with the exception of the access roads.

The permanent surface features include:

- water intake structure for the pressure compensating water column;
- administration and control building;
- plant building housing the air processing and compressor/generator equipment;
- switchyard;
- fuel storage tanks;
- air pipe system;

An access road and two bridges will connect the site with the Island of Montreal as shown in Figure 11.

Underground Features

The main permanent underground features of the project are:

- air storage cavern;
- pressure compensating watershaft and U-bend water seal.

The design of the U-bend water seal below the air reservoir is a special aspect of this system and requires careful consideration in order to avoid a potentially catastrophic blowout created by a phenomenon referred to as the Champagne Effect[17].

The Champagne Effect

The mechanism of the Champagne Effect can be described as follows.

Should the water in the cavern become saturated with air, it would remain in solution as long as the water remains at a pressure equal to or greater than that of the cavern. However, during the charging cycle, water in the cavern would be pushed up the shaft where it is exposed to reduced hydrostatic pressure. As the water reaches a level where the hydrostatic pressure is less than the saturation pressure the air would begin coming out of the solution. If a given volume of water were saturated at cavern pressure, then an incremental amount of air would be released from solution as soon as the given volume of water rose above the cavern level. This process would continue until that particular volume of water reached the surface at which point virtually all the dissolved air would have been released. As the particular volume of water rises, not only would the total mass of air released from solution increase with decreasing pressure, but the volume occupied by a unit mass of that air would correspondingly increase. For cavern pressures typical of those referred to in this report the air released from a unit volume of water is equal to or greater than that of the water in which it had been dissolved.

While the bubbles that would be released would tend to rise faster than the water, the net effect would be a two-phase column having a lower average density than a water column, resulting in a reduced hydrostatic pressure at the cavern level.

Even if charging of the cavern was to be stopped, there would still be an unbalanced buoyant force, tending to accelerate the water in the shaft. The water velocity would increase until frictional forces could counteract the difference between the cavern pressure and the hydrostatic head of the two-phase column.

At the same time, water leaving the cavern would increase the air volume of the cavern thereby reducing cavern pressure.

If cavern pressure were reduced far enough the water column would decelerate, eventually the velocity would reach zero, the bubbles would disengage and rise to the surface, and the resultant increase in hydrostatic head would cause the cavern air to be recompressed by a reverse flow of water into the cavern from the suface reservoir. Should the cavern be emptied of water before the water column is stopped, the air in the cavern would follow the water up the shaft, further accelerate the remaining water, destroy the water seal and blow out through the watershaft.

The scenario described is called the Champagne Effect.

At a minimum, it would cause a geyser of water above the compensating reservoir. It could also enable the air in storage to escape. The momentum of the water could cause serious damage to the water intake and any other structures in the path of the geyser.

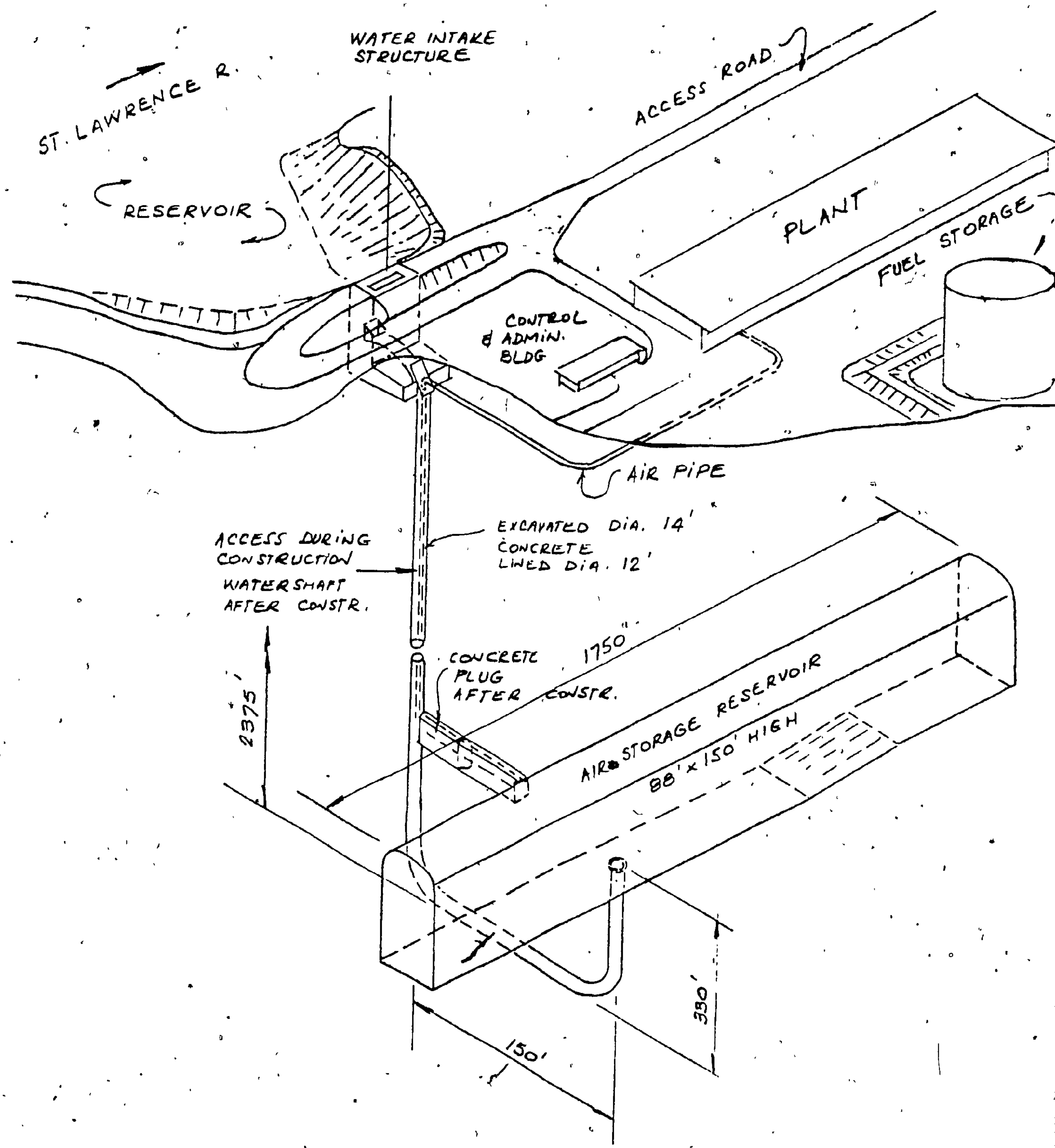
Figure 29 shows the surface and underground features associated with the project. The proposed system parameters are shown in Table 7.

Location of the Air Storage Reservoir

The siting of the underground air storage reservoir in the case of a variable pressure CAES system depends on the structural competence of the cavern rock and the thickness and quality of the overburden above the rock.

The project proposed in this report is a balanced, constant pressure CAES system where, in addition to the requirements of a variable pressure system, the designer must also satisfy the requirements of the pressure compensating water column imposed by the selected cavern pressure[18].

For the proposed project, the cavern pressure was selected at 70 atmosphere (1028 psi) in order to minimize the storage cavern volume.



1000 MW COMPRESSED AIR ENERGY STORAGE DEVELOPMENT

ISOMETRIC VIEW OF MAJOR PROJECT ELEMENTS

FIGURE 29

TABLE 7

Preliminary System Parameters of Proposed CAES Project

Cavern pressure	70 atm.
Cavern depth	2375 feet
U-bend depth	300 feet
Total shaft length	3110 feet
Shaft diameter - excavation:	14 feet
- concreted:	12 feet
Cavern volume	855,000 c.y.
Watershaft and U-bend volume:	17,750 c.y.
Construction adits - volume	11,000 c.y.

Therefore, the positioning of the cavern must be based on the height of the compensating water column that will be in equilibrium with the cavern pressure.

H_c = P = 1028 pounds per square inch (psi)

where: H_c = height of water column, ft.

P = pressure of air storage reservoir, psi.

weight of water = 62.4 lbs/ft^3, and

1 ft^2 = 144 in^2

So the weight of water per foot of hydraulic head is

$$\frac{62.4 \text{ lbs/ft}^3}{144 \text{ in}^2/\text{ft}^2} = 0.433 \text{ psi/ft}$$

Therefore, the height of the compensating water column will be:

$$H_c = \frac{1028 \text{ psi}}{0.433 \text{ psi/ft}} = 2{,}375 \text{ ft}$$

The air storage cavern invert, therefore, will be located 2,375 feet below the surface elevation of the water reservoir as shown in Figure 29.

Comparison of Capital Cost Estimate to Similar Projects

Although historical cost figures are not available for CAES plants in North America, since none were constructed so far, following are the Capital Cost estimates per kilowatt hour generated by Acres American Incorporated as a result of feasibility studies of CAES plant in California (In 1985 U.S. dollars)

705 MW	= CAES plant in porous media	\$ 464/kW
750 MW	= CAES plant in hard rock	\$ 385/kW

In comparison, the 290 MW Huntorf CAES plant constructed in 1978 in West Germany cost 400 DM/kW or about U.S.\$ 200/kW.

The recently (1977) completed 162 MW conventional gas turbine peaking plant constructed by Hydro Quebec in Cadillac, Quebec cost CAN $ 265/kW.

Kartsounes and Daley(30) have generated the following cost estimates for a CAES plant of similar characteristics to the one proposed in this report.

Capital Cost, $/kW:		Near Term Turbine System (1000,1600 °F)*
Turbomachinery, engines		40.8
Storage cavern**		87.0
Surface reservoir		8.1
Balance of plant		80.0
Indirect costs***		134.9
Total	U.S.$	350.8/kW
Operating Costs, mills/kWh		
Capital Charge		29.2
Fuel		9.5
Electricity		10.6
Operation & maintenance		2.0
Total	U.S.	51.3 mills/kWh

The cost of electricty (10.6 mills/kWh) shown under operating cost probably indicates that the CAES plant will use off-peak electricity generated by fossil fuel thermal plants during the compression cycle.

* Inlet temperature to high pressure and low pressure turbines, respectively.
** Water compensated, mined cavern
*** Contingency, engineering, escalation and interest

3.7 Summary of Cost Estimates

1000 MW Constant Pressure, Watercompensated CAES System
2 hour operating cycle

Item	Description	Quantity	Unit	Unit Cost $	Amount $10^3$$
1.0	Access Route and Bridge	-	lump sum	-	4,000
2.0	Water reservoir and intake structure, sheet piling excavation, retaining walls, hydraulic passage and backfilling etc.	-	lump sum	-	10,000
3.0	Watershaft, including U-bend				
3.1	Rock excavation	17,750	c.y.	92	1,633
3.2	Shotcreting	1,500	c.y.	350	525
3.3	Grouting	2,000	lin.ft.	25	50
3.4	Formed concrete	4,700	c.y.	444	2,100
3.5	Steel liner	385	ton	2,600	1,000
4.0	Construction adits				
4.1	Rock excavation	11,000	c.y.	40	444
4.2	Rock bolting	1,000	lin.ft.	8	8
4.3	Shotcreting	100	c.y.	350	35
4.4	Drilling of drainage holes	1,000	lin.ft.	4	4
4.5	Concreting inverts	250	c.y.	100	25
4.6	Concrete plugs	3,700	c.y.	70	260
5.0	Air storage				
5.1	Rock excavation	855,000	c.y.	42.90	36,000
5.2	Rock bolting	88,500	lin.ft.	8	708
5.3	Shotcreting	2,300	c.y.	350	805

Item	Description	Quantity	Unit	Unit Cost $	Amount 10^3 $
	Total access, reservoir, intake, watershaft and air storage				58,297
6.0	Turbomachinery equipment assume $50.0/KW				50,000
	Ducting and installation of turbomachinery equipment allowance: 25% of cost				10,250
7.0	Balance of plant Includes: clutches, motor/generator, recuperator, combustors, fuel storage, coolers, electrical power system, land and plant structure assume: $90/kW				90,000
8.0	Switchyard building and equipment				4,000
9.0	Exploration work				2,000
10.0	Construction services				15,000
		SUB-TOTAL (1979 dollars)			$ 229,547
		Contingency 25%*			57,386
					286,933
		Management and supervising 15% of above			43,040
		TOTAL (1979 dollars)			329,973
		say			330,000
		Capital cost of installation per kilowatt:		$330	

* A contingency figure of 25% is used considering the preliminary nature of estimate and the new technology involved.

3.8 Economic Analysis - CAES Project

Fixed Charge Rates related to the cost of Investment[22]

Book life (years) 35	
Capital recovery factor (%)	6.50
Interim replacement (%)	0.35
Insurance (%)	0.25
Fixed Charge Rate (%)	7.10

Therefore the fixed annual costs of the proposed CAES project are:

$(\$330 \times 10^6) \times 0.071 = \$23,430,000$

Operating Costs

	Mills/kWh	
Oil cost component	16.92	
Fuel inventory component	5.00	
Pumping cost component	6.53	
Operating and maintenance	3.00	
Total	31.45	
1,000,000 kW x 2 hrs/day x 365 days x $0.03145/kWh		$ 22,958,500
Total Annual Fixed and Operating Costs:		$ 46,388,500
say:		$ 46,400,000

Explanation of Fixed Annual Costs - CAES Project

Book Life

The estimated service life of modern generating facilities is from 30 to 35 years for thermal electric production plants. A 35 year life may be used for gas turbine peaking plants[23].

Capital Recovery Factor (crf)

Was based on the same assumption of real interest of 5½% as previously described for the UPH project, however using a service life of 35 years instead of 50 years used for the UPH project.

$$\text{crf} = \frac{i\,(1+i)^n}{(1+i)^n - 1} = \frac{0.055\,(1.055)^{35}}{(1.055)^{35} - 1}$$

$$= 0.065$$

$$= 6.50\%$$

Interim Replacement

Studies indicate that an average allowance of about 0.35 percent of the total investment is required for each year in the life span of a thermal electric plant(23).

Insurance

An annual allowance for insurance for thermal power production plants, excluding nuclear, is 0.25 of 1 percent of total gross investment(23).

Explanation of Operating Costs

Oil Cost component

A study by P.A. Berman of Westinghouse Electric Corporation(28) determined that this cost component for a CAES system with the parameters proposed in this report is 16.92 mills/kWh.

Annual Charges on Fuel Inventory Stock

A reserve fuel supply is normally maintained at major gas turbine peaking plants. Since fuel deliveries may be disrupted by production or transportation problems, a reserve supply is necessary to assure uninterrupted operation of the plant.

The annual charges on the investment in fuel stocks are part of the cost of producing power. Electric utilities reports indicate(23) that fuel stocks necessary for approximately 75 days of normal operations are maintained.

On the basis of a net plant heat rate of 8,800 Btu per kilowatt-hour, the annual fixed charges on fuel inventory stocks would be:

- Fuel stock required: 75 days
- Heat rate: 8,800 Btu/kWh
- Plant capacity: 1000 MW = 1,000,000 kW
- Operation period per day: 2 hrs.

75 days x 2 hrs/day x 1,000,000 kW x 8,800 Btu/kWh

$75 \times 2 \times 1{,}000{,}000 \times 8{,}800 = 1.32 \times 10^9$ Btu

Cost = \$2.85/Btu x 10^6

$$\text{Cost of fuel} = \frac{1.32 \times 10^9 \text{ Btu}}{1 \times 10^6 \text{ Btu}} \times \$2.85$$

= \$3,762,000

Interest @ 5.5% 206,910

Total annual cost of fuel inventory \$3,968,910

$$\text{Cost mills/kWh} \quad \frac{\$3{,}968{,}910}{1 \times 10^6 \times 365} = \$0.005$$

= 5 mills/kWh

Pumping Cost Component

The study referred to above also determined that 1.306 kW of energy is required during the off-peak compression cycle to obtain 1 kW of energy during the generating cycle.

If the cost of energy for the compression cycle is assumed to be 5 mills/kWh the pumping cost component is:

$$\frac{\text{kW compression}}{\text{kW out}} = \frac{1.306}{1} = 1.306$$

$$1.306 \times 5 \text{ mills/kWh} = 6.53 \text{ mills/kWh}$$

Operating and Maintenance Costs

In the absence of cost figures for a CAES system the figure of gas turbine 1.71 mills/kWh quoted for 140 MW units in the U.S. in 1968 was used and escalated 6% annually to arrive at 3.0 mills/kWh.

SENSITIVITY OF CAES TO INCREASE IN FUEL PRICES, 1980 - 2000

General Level of Inflation %

	1976-1980	1981-1990	1991-2000
High	9	8	8
Medium	7	6	6
Low	5	4	4

Increase in Fuel Prices %

High	11	10	10
Medium	9	8	8
Low	7	6	6

Cost of Fuel \$/kWh
(Base 1979 - Cost \$0.01692/kWh

	1980	1985	1990	1995
High	0.01878	0.03025	0.04871	0.07845
Medium	0.01844	0.02709	0.03981	0.05849
Low	0.01810	0.02423	0.03242	0.04339

The results are summarized in graphical form in Fig. 31.

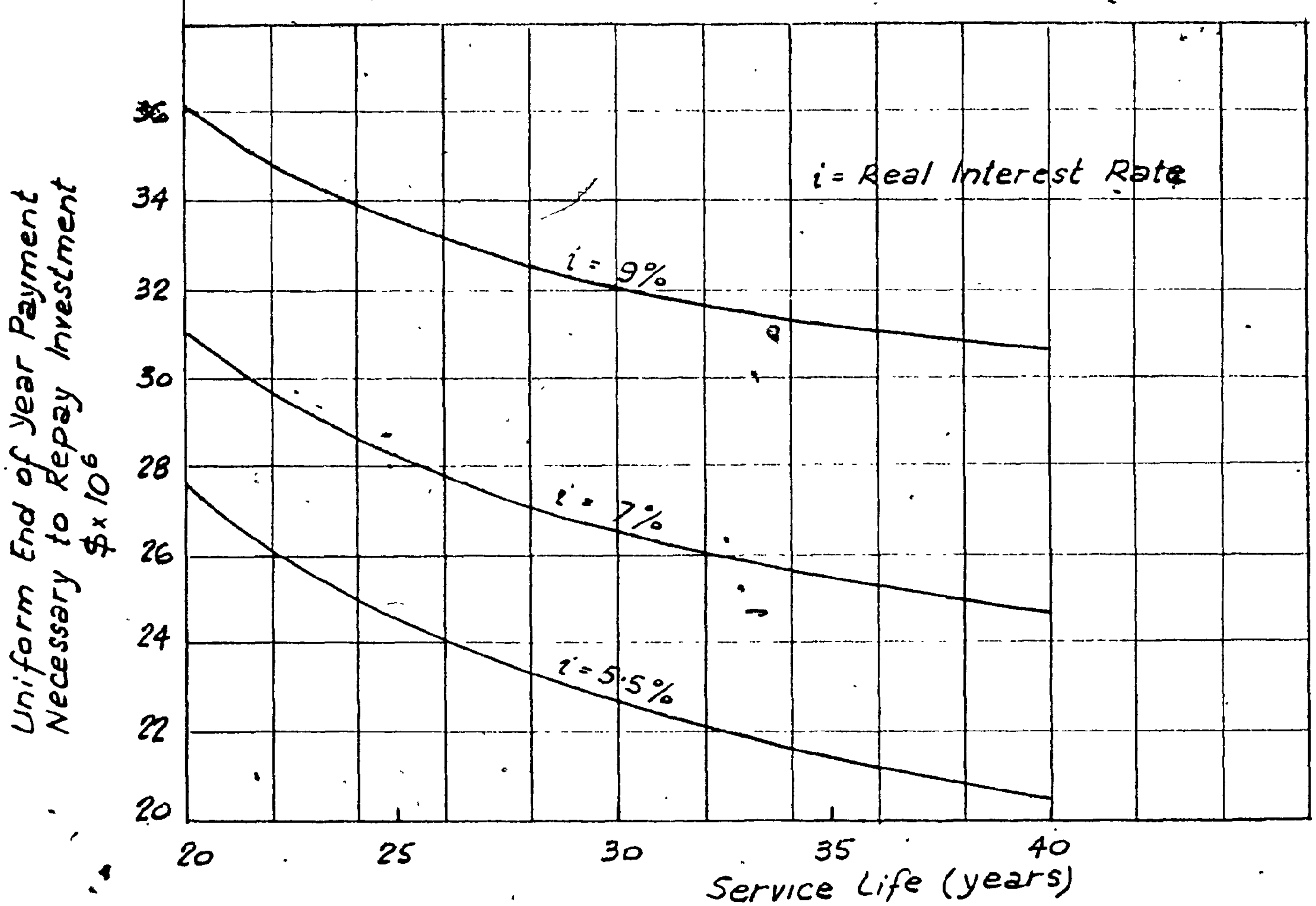


Fig. 30 - Sensitivity of Debt Retirement to Interest Rates and Service Life CAES Project

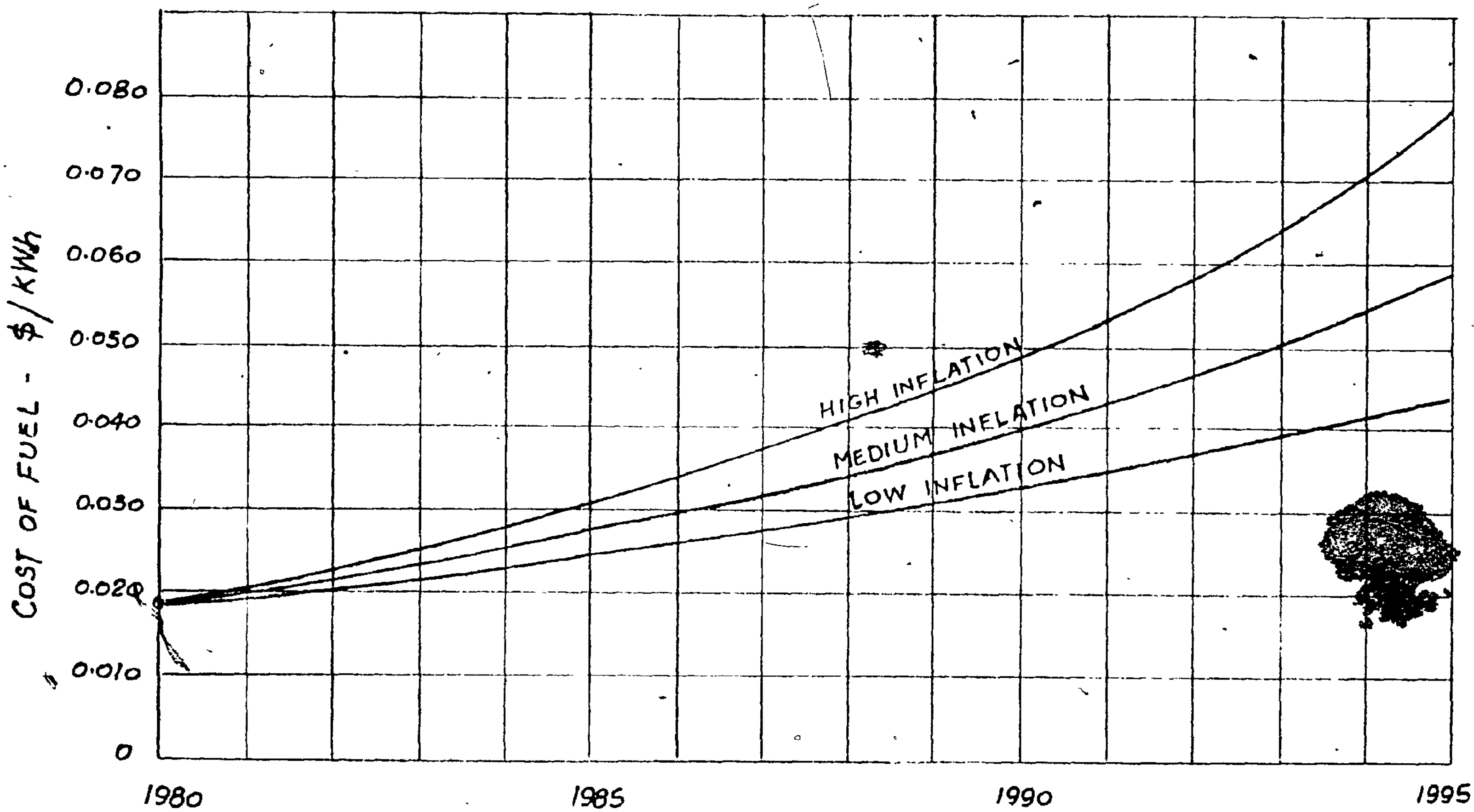
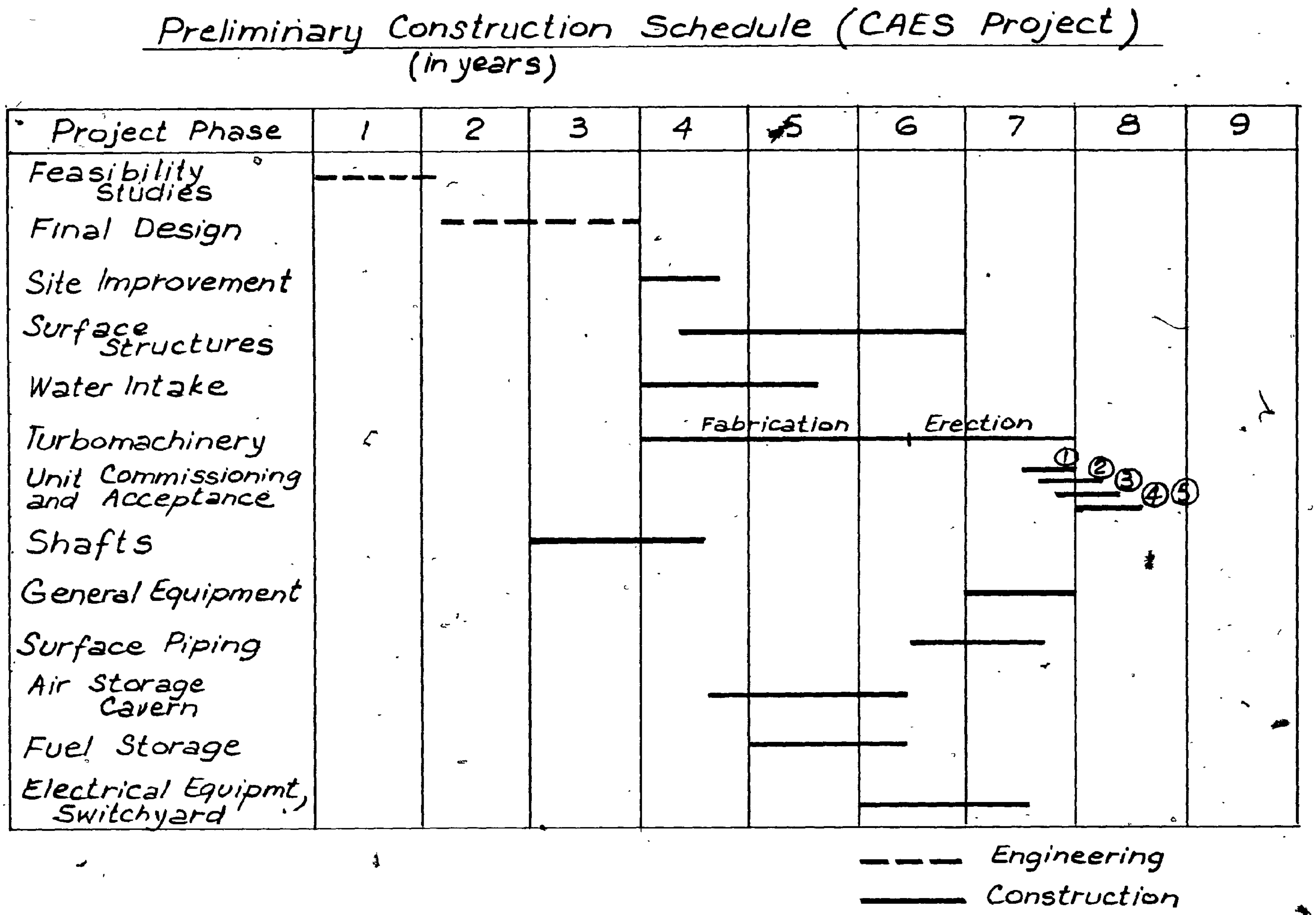


Fig. 31 - Sensitivity of Cost of Fuel to Inflation
CAES Project



Preliminary Construction Schedule (CAES Project)
(in years)
Project Phase
1
2
3
4
5
6
7
8
9
Feasibility Studies
Final Design
Site Improvement
Surface Structures
Water Intake
Turbomachinery
Fabrication
Erection
Unit Commissioning and Acceptance
1
2
3
4
5
Shafts
General Equipment
Surface Piping
Air Storage Cavern
Fuel Storage
Electrical Equipmt, Switchyard
Engineering
Construction

CHAPTER IV

COMPARISON OF ALTERNATIVES

In the previous chapters the two alternative methods of energy storage, each capable of supplying 1000 MW of power for a period of two hours daily, were described both from technical and economical viewpoints.

However, it is felt that the figures given may not adequately describe the alternatives and, therefore a set of qualitative terms were developed as criteria for further aiding in the selection of one of the technological options.

Although an attempt was made to include as many criteria as necessary to provide a complete list it should not be viewed as such, but rather as a very general guide.

4.1 Criteria for Selecting Technological Option

Complexity – the technology must be simple to operate, easy to maintain and simple to repair and generally it should be longlasting.

Dependability – the level of service to be provided with a specific degree of certainty must be an explicit component of design, construction and operation.

Timing – because the purpose of installing any technological option is to produce some desired outputs, an important consideration is the time required until the first outputs are actually produced. For a major project, using capital intensive methods of construction early completion will enable benefits from outputs to be derived earlier.

Cost – Central to all decisions regarding choice of technology are costs. These include:

- construction costs,
- operation and maintenance costs, together with replacement costs,
- administrative costs,

Included in all three costs are equipment, materials and supplies, energy, land and labour of all types.

It is the time stream of total construction, installation, operation, maintenance and replacement costs which is the most relevant criterion.

Related non-human input	– Because there may be physical constraints on the availability of some resources, such as fuel, oil, land – contraints which should be reflected in costs but for which costs are usually underestimated – it is useful to indicate the physical quantities of these inputs required for a technological option. An important consideration in costs is the amount of foreign exchange required for the technological option.
Cost effectiveness	– the ideal criterion for the evaluation of a technological option is net benefit. However, in many cases not all of the net benefits can be translated into monetary terms.
Management organization	– Critical to the success of the application of any level of technology is the existence of a management organization capable of providing the requisite trained manpower to supervise, operate and maintain the physical system and a financial structure capable of providing the requisite monetary resources for operation and maintenance and replacement over time.
Relation to other options	– Too often a particular technological option is viewed in isolation, rather than in relation to other options being developed.
Side effects	– Consideration must be given to whether or not the technological option can result in condition which exacerbate or conceivably, mitigate some existing problems.

Accuracy of estimates	- The choice of technology may hinge on the degree of accuracy associated with the estimate of both costs and results. Different levels of complexity of technology may well have substantial differences in the accuracy of the estimates of costs and results associated with them. On the other hand, the range in the accuracy of the estimate may be similar for both highly complex and simple technological options, but the consequences of inaccuracy in estimation may be much greater for the former.
Political consideration	- Regardless of economic costs, the ultimate locus of choice is the political arena. The decision makers are likely to consider the technological option in terms of the priority of the benefits perceived to flow from it in relation to other local problems; in relation to its impact, if implemented, on intergovernmental relations; and in relation to public acceptance.

TABLE 8

RELATIVE MERITS OF THE TWO PROPOSED

ENERGY STORAGE ALTERNATIVES

	CRITERIA	UPH	CAES
1.	Complexity	3	2
2.	Dependability	3	2
3.	Timing	2	3
4.	Costs	3	2
5.	Related non-human inputs	3	1
6.	Cost effectiveness	3	2
7.	Management organization*	3	3
8.	Relation to other options	2	1
9.	Side effects	2	1
10.	Accuracy of estimates	3	2
11.	Political considerations	2	1
	Ratio of total points to maximum possible total:	29/33 (0.878)	20/33 (0.606)

(0 to 3, 3 highest - all criteria have equal weight)

* It is assumed that the project will be managed by Hydro Québec. This utility is considered one of the very best in North America from the management point of view.

4.2 Capacity Probability Analysis (29)

Many utilities use the probability theory in figuring out their probable forced system outages* to arrive at a suitable reserve capacity. Let Q_1, Q_2, Q_3, ..., Qn be the forced outage rates of Unit No. 1, 2, 3...., n, expressed as the ratio of number of days outage to the number of days in the year. Similarly, let P_1, P_2, P_3, ..., Pn be the operating rates of Unit No. 1, 2, 3, ..., n, expressed as the ratio of number of days of running to the number of days in the year. Then $P + Q = 1$ for any unit by definition. From the probability theory the product P_1P_2 is the probability of Units No. 1, and 2 being in operation simultaneously over any given period; the product $P_1P_2P_3$ is the probability of Units No. 1, 2 and 3 being in operation simultaneously over any given period. The product $Q_1\ Q_2\ Q_3$ is the probability of Units No. 1, 2 and 3 being out of service simultaneously.

To find the probability of different combinations of units out of service and in service, we use

$$(P_1 + Q_1)\ (P_2 + Q_2)\ (P_3 + Q_3).....(Pn + Qn) = 1$$

If all the units have the same service and outage probabilities P and Q, this equation reduces to:

$$(P + Q)^n = 1$$

The probability of forced outages for the two schemes is plotted in Fig.32 The plot shows that the four unit UPH system has a lesser probability of maximum outage than the five unit CAES system.

The probability of 0 MW loss (continuous operation) is 0.98 for a single 250 MW UPH unit; this falls to 0.92236 for the four 250 MW units. This, however, is not the basic criterion for selecting a system for continuous operation. The probable outages are significant in this respect: The single unit is out of service 2 percent of the time but the four unit system would be out of service only 0.000016 percent of the time.

* As opposed to planned outages (eg. maintenance, replacement of certain components.)

Forced outage calculation

a) UPH System

1000 MW capacity
4 - 250 MW units

The operating probability for all units is P = 0.98; and the forced outage probability rate is Q = 0.02.

Therefore for the four 250 MW units we have:

$$(P + Q)^4 = (0.98 + 0.02)^4 = 1$$

$$P^4 + 4P^3Q + 6P^2Q^2 + 4PQ^3 + Q^4 = 1$$

$$0.98^4 + (4 \times 0.98^3 \times 0.02) + (6 \times 0.98^2 \times 0.02^2) + (4 \times 0.98 \times 0.02^3) + 0.02^4 = 1$$

Summarizing, we have the following tabulations:

Capacity out of service or forced outage, MW	Probability
0	0.92236816
250	0.07529536
500	0.00230496
750	0.00003136
1000	0.00000016
	1.00000000

b) CAES System

1000 MW capacity

5 - 200 MW units

The operating probability for all units is P = 0.9 and the forced outage probability is Q = 0.1.

Therefore, for the five 200 MW units we have:

$$(P + Q)^5 = (0.9 + 0.1)^5 = 1$$

$$P^5 + 5P^4Q + 10P^3Q^2 + 10P^2Q^3 + 5\,PQ^4 + Q^5 = 1$$

$$= 0.9^5 + (5 \times 0.9^4 \times 0.1) + (10 \times 0.9^3 \times 0.1^2) + (10 \times 0.9^2 \times 0.1^3) + (5 \times 0.9 \times 0.1^4) + 0.1^5 = 1$$

Capacity out of service or forced outage - MW	Probability
0	0.59049
200	0.32805
400	0.07290
600	0.00810
800	0.00045
1000	0.00001
	1.00000

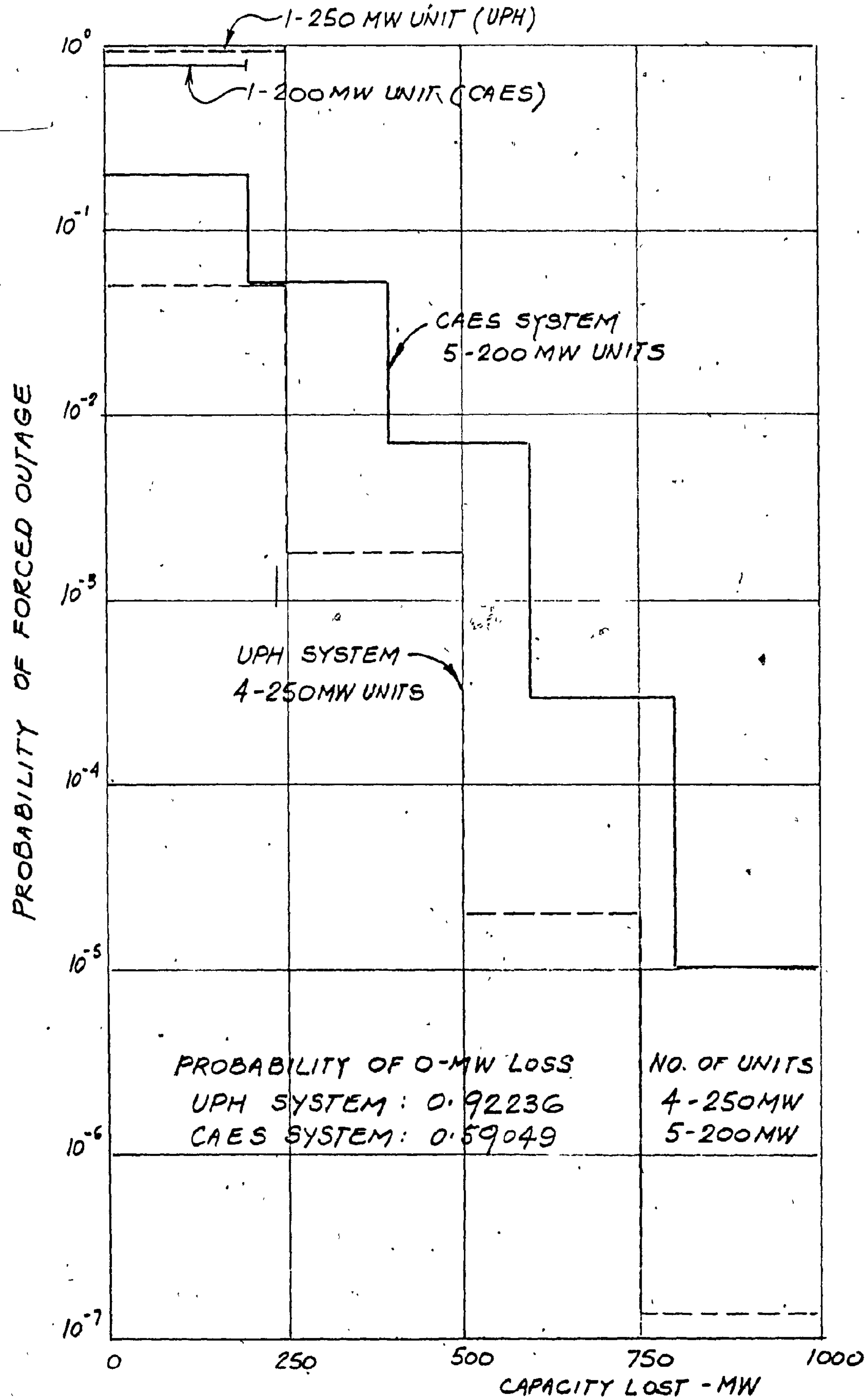


Fig. 32-CAPACITY LOSS PROBABILITY OCCURANCE DUE TO FORCED OUTAGE, 1000 MW UPH AND CAES SYSTEMS

4.3 Summary Statement

Based on the foregoing it would seem that the UPH project would be better suited for consideration as a source of peaking power than the CAES project.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The foregoing preliminary analysis indicates that:

a) A 1000 MW UPH project could be constructed in Montreal in 1979 for about $433 per kilowatt installed.
The fixed annual costs of the project would be $35,100,000.

b) A CAES plant of the same capacity would require a capital expenditure of $330 per kilowatt installed and the total fixed annual costs would be $46,400,000.

In order to further aid the decision makers in the selection from these two alternatives the following information is provided.

UPH Project

- The concept utilizes electrical and mechanical equipment similar to conventional hydro projects successfully operating around the world.

- The reliability of the equipment is well known and its behaviour is predictable.

- The cost figures generated in this report are based on current actual figures and are thought to be accurate to within $\pm$ 10%.

- The surface area occupied by the project is relatively small and would require only about 15 acres for the permanent structures.

- After having placed the project into operation, it would require a minimum amount of maintenance, it would not pollute the air and it would be virtually noiseless.

CAES Project

- The concept utilizes mechanical equipment of relatively new design. This equipment would require an extensive research and development program in order to assure compatibility of the system components. To date there is only one existing plant in the world utilizing this concept. This plant is relatively small - 290 MW - compared to the 1000 MW installation discussed in this report.

- The reliability of the equipment is not known to the same degree as that of hydro equipment.

- The cost figures generated in this report are, for the most part, based on conventional gas turbine plants. The accuracy of the figures for the mechanical components is probably + 20%, - 5%.

- The surface area occupied by the project is large, being about 150 acres. This figure is a preliminary estimate and was based on the La Citiere conventional gas turbine peaking plant of 284 MW capacity presently under construction near Laprairie, Quebec by Hydro-Quebec on a 68 - acre site. Since the proposed CAES project useds only 35% of the fuel required for conventional gas turbines, the fuel storage area was reduced by 65%. Also units of 200 MW capacity were used in place of the smaller units that would require greater area for the same installed capacity.

In spite of extensive efforts to equip a gas turbine installation with silencers, there is considerable noise during the generating cycle, comparable to a medium size airport. Attempts to silence the equipment beyond a certain level would be impractical because the turbine would have to work against increasing back pressure that would reduce its efficiency.

- Air pollution is present both by the discharge of exhaust fumes during normal operation and by the occasional discharge of compressed air directly into the atmosphere from the storage reservoir. The latter operation might discharge a certain amount of rock particles, natural gas and other possible impurities contained in the storage cavern.

- Although more fuel efficient than a conventional gas turbine, the CAES system still uses imported fuel during the generating cycle and therefore it is exposed to the effects of the ever present fuel cost escalation.

- The extremely high storage cavern pressure could, conceivably, cause a blowout under certain circumstances endangering life and property. From this point of view the construction of such a project might be found objectionable near built-up areas.

5.2 Recommended Program of Additional Work

The following recommendations apply to both projects:

1. Design Criteria and Impact on Existing Power System

- Literature search and survey of available components.
- Develop cycle for optimum utilization in the existing Hydro-Quebec system.
- Prepare Design Criteria documents.

2. Site Selection and Establishment of Site Characteristics

- Develop site selection methodology.
- Access to site.
- Prepare site selection report.
- Surface exploration program.
- Subsurface exploration program.

3. Formulation of Design Approaches

- Develop performance requirements for compressors, heat exchangers, turbines, reservoirs, shafts, etc.
- Subcontracts for development of specific components (confirm feasiblity, performance characteristics, cost estimates etc.).
- Integrate all sub-systems into a coherent configuration.
- Estimate preliminary construction costs and schedules.

- Identify further research and development requirements.

- Prepare the design approach report.

4. Assessment of Environmental and Safety Aspects

- Perform safety evaluation (inside plant and outside plant boundaries).

- Prepare Preliminary Safety Analysis Report.

- Perform environmental evaluation.

- Prepare preliminary Environmental Assessment Report.

5. Preparation of Preliminary Design of Plant

- Prepare facility/component packages.

- Refine construction costs and schedule estimates.

- Perform cost/risk study (identify risks, determine probabilities, identify associated costs and tradeoffs).

- Prepare licensing package (identify requirements, applications, assemble available data).

- Prepare Plant Design Report (final report).

GLOSSARY OF TERMS AND EQUIVALENTS

Base load - the minimum load imposed on an electrical system over a specified period of time. A baseload generation unit is dedicated to meeting a more-or-less continuous electrical demand.

Capacity of hydroelectric station - Total generating capacity of all the units of a hydropower station under given conditions. A distinction is made between the installed capacity and the guaranteed capacity.

Cofferdam - A temporary structure, often of steel sheet pilings, erected to exclude water from an area that would normally be submerged to facilitate the construction of foundations under dry conditions.

Constant dollar - Values are expressed in unit prices considered to prevail at a particular point in time. In this report, constant dollar values have been established on the basis of prices prevailing in March 1979.

Current dollar - Values are expressed in unit prices considered to prevail at the actual time that expenditures are incurred or revenues received. In this report, future current dollar values have been estimated by increasing the constant dollar prices of March 1979 by price inflation factors pertinent to the period and subject under construction.

Design head - Smallest working head with which the turbine must develop a power equal to the installed capacity.

Draft tube - Element of a hydro-power station with reaction turbines designed to regain the kinetic energy of the flow leaving the runner by conversion into suction head.

Efficiency of the pumped storage cycle - Ratio of the power output from discharge to the power consumed for recharge (measured on the high voltage bus bars of the pumped storage hydro power station).

Firm capacity of hydro electric station - Minimum daily generating capacity of a hydro-power station which can be achieved with a given degree of security, which characterises the electricity output during a series of years with low water availability.

Frazil ice - Various ice crystals (laminated, round, lenticular, etc.) or their accumulation in the water as a spongy, opaque mass. It forms when the water is supercooled. Suitable conditions for the formation of frazil ice arise at the open water surfaces within non-moving ice cover or between iced sections on rivers and also in large ice fields in lakes. Accumulations of frazil ice form on the bottom (submerged ground ice) or on objects situated in the water, causing blockage of openings of hydrotechnical installations, canals, etc. Frazil ice floating on the surface together with other kinds of ice formations constitutes slush.

Hydropower unit of a pumped storage plant	- A unit which, when operating as a hydro turbine-generator, converts the hydro energy into electricity, and when operating as a motor driven pump converts electricity into potential hydro energy. Three schemes are normally used: - Scheme I - the whole unit comprising of the pump, motor-generator and the turbine, is mounted on one shaft. In some cases, it may also have a clutch connection and a starting turbine. Scheme II - the unit consisting of the pump-turbine (which can serve as pump or turbine) and the motor-generator mounted on one shaft. Scheme III - individual units of (a) the turbine and (b) the pump and motor.
Hydropower unit run-away speed	- Maximum speed (rpm) of a unit on tripping full load and with guide vanes fully open.
Installed capacity of hydroelectric station	- Sum of the nominal active capacities of all the generators of a hydropower station, including auxiliary power generators.
Load factor	- is the ratio of the average demand load to the maximum or peak demand load over a specified time period.
Net head of hydroelectric station	- Head of a hydro power station is defined as the difference in the specific energies of the water at the turbine inlet and at the outlet of the draft tube for reaction turbines, and at the middle outlet level of the jet from the runner for free jet action turbines.

Overburden - The overlying stratum of soil relative to a level of interest. Frequently used to refer to all soil materials overlying the bedrock.

Peak demand - is the maximum capacity demand of an electrical supply system over a specified period of time.

Penstock; pressure conduit - Pipe or duct along which the water flows under pressure.

Present worth - is the measure of value ascribed to investments and revenues in this report. It represents the value, in a base year, of a dollar value in any other year or a series of dollar values over a number of years, after adjustment for the effects of price inflation. The "base year" used in this report is 1979. Alternative descriptions for present worth commonly used are "present value" and "discounted value".

Reversible turbine (pump turbine) - Bladed hydro machine, able to work both as a reaction turbine and as a pump, with reversible or single direction of rotation.

Shore ice - Strips of ice bordering the banks of river when the remainder of the water surface is not frozen.

Specific speed-(specific speed of a turbine) - speed in rpm of a turbine, geometrically similar to the one being tested and operating under hydraulically similar conditions, required to deliver a power output of 736 watts (1 HP), under a head of 1 metre.

Stored volume of water	- (live storage capacity in a pumped storage plant) maximum quantity of water which can be pumped into the upper reservoir by a pumped storage power station in the course of a single cycle of regulation.
Trash rack	- Device installed at the inlet of a water intake structure for trapping large floating objects. According to the space between the bars, the screen may be safety, coarse or fine. According to the method of removal of objects trapped, the screen may be designed for mechanical cleaning, hand cleaning, disintegrators, etc.
Turbine efficiency	- Ratio of the power output to the power input.
Turbine run-away speed	- Maximum speed (rpm) which can be reached by a turbine with no load, uncoupled from the generator.
Water intake; water intake structure	- the water intake structure at the head of the conduit to which the water from the stream or reservoir is diverted.

EQUIVALENTS

Volume	-	1 cu. metre (m^3)	=	35.31476 cu. ft.
			=	1.30795 cu. yards.
Pressure	-	1 kilopascal (kPa)	=	20.88555 pounds/sq.foot
			=	0.14504 psi
Energy	-	1 kilowatt hour (kWh)	=	3412.13 Btu

MW - megawatt - 1,000,000 kilowatt (kW)

GWH - Gigawatt hour - 1,000,000 kilowatt hours (kWh)

Btu - British Thermal Unit. The amount of heat equivalent to 251.996 IT (International Tables) calories or 778.26 foot pounds.

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APPENDIX A

COST ESTIMATE - ROCK EXCAVATION AND TRANSPORTATION - LOWER RESERVOIR

Source of Costs:

1. Programmation et Contrôle des coûts (PCC) - Société d'energie de la Baie James; Montreal, Que.

2. Spino Construction Company; - Montreal, Que.

3. Revay & Associates Ltd., Construction Management Consultants, Montreal, Que.

4. Projects of similar nature, e.g. Churchill Falls Power Project. In these cases prices were escalated to 1979 using an inflation rate of 8% per year.

Summary of Direct Costs

	Cost per c.y. - 1979 dollars				
Alternative	Excavation	Hoisting	Conveyor	Transport	Total
A. - Hoisting	19.26	6.00	-	3.34	28.60
B. - Conveyor	19.26	-	4.96	1.33	25.55
C. - Access a) tunnel	21.07	-	-	2.78	23.85
tunnel b) reservoir	19.26	-	-	3.83	23.09

Estimated tendered prices with 50% mark-up for overhead and profit

A. - Hoisting		1.5 x $28.60 =	$42.90/c.y.
B. - Conveyor		1.5 x $25.55 =	$38.33/c.y.
C. - Access -	a)	1.5 x $23.85 =	$35.78/c.y.
tunnel	b)	1.5 x $23.09 =	$34.64/c.y.

Estimated Total Tendered

A. - Hoisting		2,055,000 c.y. x $42.90 =	$88,160,000
B. - Conveyor		2,198,000 c.y. x $38.33 =	$84,250,000
C. - Trucking	a)	1,160,000 c.y. x $35.78 =	$41,500,000
	b)	2,055,000 c.y. x $34.64 =	$71,180,000

Summary	Estimated Total Tendered $
A. - Hoisting - vertical shaft:	88,160,000
add heavy equipment hoist, operation and maintenance	9,000,000
	97,160,000
B. - Conveyor - 35% grade	84,250,000
C. - Access tunnel - 7% grade:	112,680,000

Therefore, the most economical method of removing the excavated material to the disposal area is by a 35% inclined tunnel equipped with a conveyor belt system combined with trucking from the tunnel to the disposal area.

Note: The tunnel was sized to enable the passage of heavy powerhouse equipment like turbines, generators and transformers. The cost of special equipment required to convey the equipment underground is not known, however, it is thought that the 25% contingency allowance will be sufficient to absorb the cost of modification necessary to the conveyor or the installation of a suitable cograil system and carrying platforms.

Determination of the Probable Duration of Excavation

Information concerning excavated volumes and actual duration of excavation were obtained for eight projects. All these excavations were performed in hard rock.

1. Helms Project - California, U.S.A.
   Conventional pumped storage

Excavated volume:	1,000,000 c.y.
Duration	31.2 months

2. Underground Nuclear Plant - California, U.S.A.

Excavated volume:	1,060,000 c.y.
Duration	34 months

3. Churchill Falls Project
   Powerhouse and Surge Chamber

Excavated volume:	713,900 c.y.
Duration	21 months

4. Churchill Falls Project
   Tunnels

Excavated volume	1,334,800 c.y.
Duration	33 months

5. James Bay Project, LG-2
   Powerhouse and Surge Chambers

Excavated volume:	813,210 c.y.
Duration	18 months

6. James Bay Project, LG-2
   Diversion Tunnels

Excavated volume:	1,121,330 c.y.
Duration	24 months

7. James Bay Project, LG-2

   Access Tunnel

   Excavated volume: 144,400 c.y.

   Duration 9 months

8. Nynashamn Project - Sweden

   Underground Oil Storage Caverns

   Excavated volume: 1,200,000 c.y.

   Duration 26.4 months

Linear regression analysis was performed to plot the best line through the data points. The results are summarized in Figure 1.

The coefficient of determination (r^2) was computed at 0.75 which indicates a fairly large scatter of the data points. The figure indicates that for the UPH project, having a cavern volume of 2,055,000 c.y. the duration of the excavation would be 48 months. However, all the projects used in the analysis were excavated on one face. In case of the UPH project three faces would be driven simultaneously, therefore the expected duration of excavation is 48/3 = 16 months.

On the other hand, the proposed CAES project cavern would be excavated by driving one face only. In this case the graph is valid and indicates an expected excavation duration of 23.22 months.

Therefore, it would appear that the excavation of the storage reservoir of 855,000 c.y. for the proposed CAES project could only be done in 1.5 years if there will not be any delays. Based on the information contained in Figure 1 a potential overrun of excavation time is indicated.

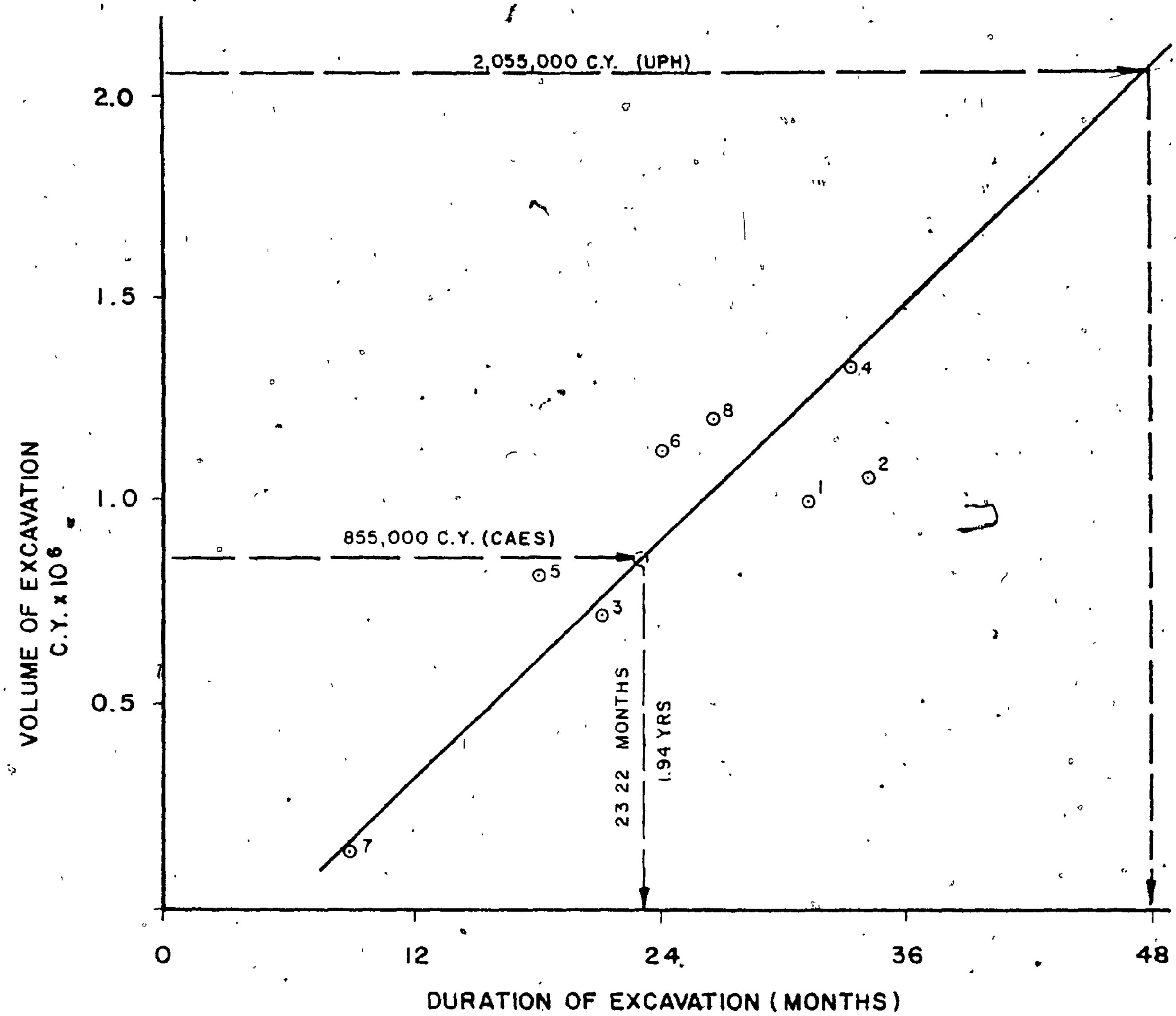


FIG. I DURATION OF EXCAVATION VS EXCAVATED VOLUMES
(HARD ROCK, UNDERGROUND)

1 HELMS PROJECT, CALIFORNIA, U.S.A.
2 UNDERGROUND NUCLEAR PLANT, CALIFORNIA, U.S.A.
3 CHURCHILL FALLS PROJECT - CANADA
POWERHOUSE AND SURGE CHAMBERS
4 CHURCHILL FALLS PROJECT - CANADA
TUNNELS
5 JAMES BAY PROJECT - CANADA
LG-2
POWERHOUSE AND SURGE CHAMBERS
6 JAMES BAY PROJECT - CANADA
LG-2
DIVERSION TUNNELS
7 JAMES BAY PROJECT - CANADA
LG-2
ACCESS TUNNELS
8 NYNASHAMN PROJECT - SWEDEN
UNDERGROUND OIL STORAGE CAVERN

Cost Estimate - Rock Excavation and Transportation

Lower Reservoir

1.0 Excavation of underground reservoir utilizing the following alternative methods of transporting excavated material to surface:

A. - Hoist and vertical shaft

B. - Conveyor and inclined shaft 35% grade

C. - Truck and ramp - 7% grade

2.0 Excavation of underground reservoir - Direct costs:

- Quantity excavated   2,055,000 c.y. x 2.2. tons/c.y.
  = 4,600,000 tons
- Duration   1.5 years
  = 1.5 x 220* = 330 working days

2.1 Top heading 4950 l.f.@ 60 c.y./ft. = 297,000 c.y.
(Fig.2 shows a typical top heading operation)

2.2 Working 3 shifts/day/face
220 working days per year

2.3 Advance/shift/face
Drilling 7 ft.
Advance 5 ft. = 1 round

2.4 Advance/day/face = 3 rounds = 15 ft.

2.5 Advance/year/face = 15 x 220 = 3,300 ft.

2.6 Advance/1.5 year/face = 4,950 ft.

2.7 No. of faces to be worked
$= \frac{4,950}{4,950} = 1$ face

2.8 Total advance per day
1 face x 3 shifts x 5 ft./face = 15 ft.

2.9 Advance per year:
220 days x 15 ft. per day = 3,300 ft.

* 220 working days/year assumed

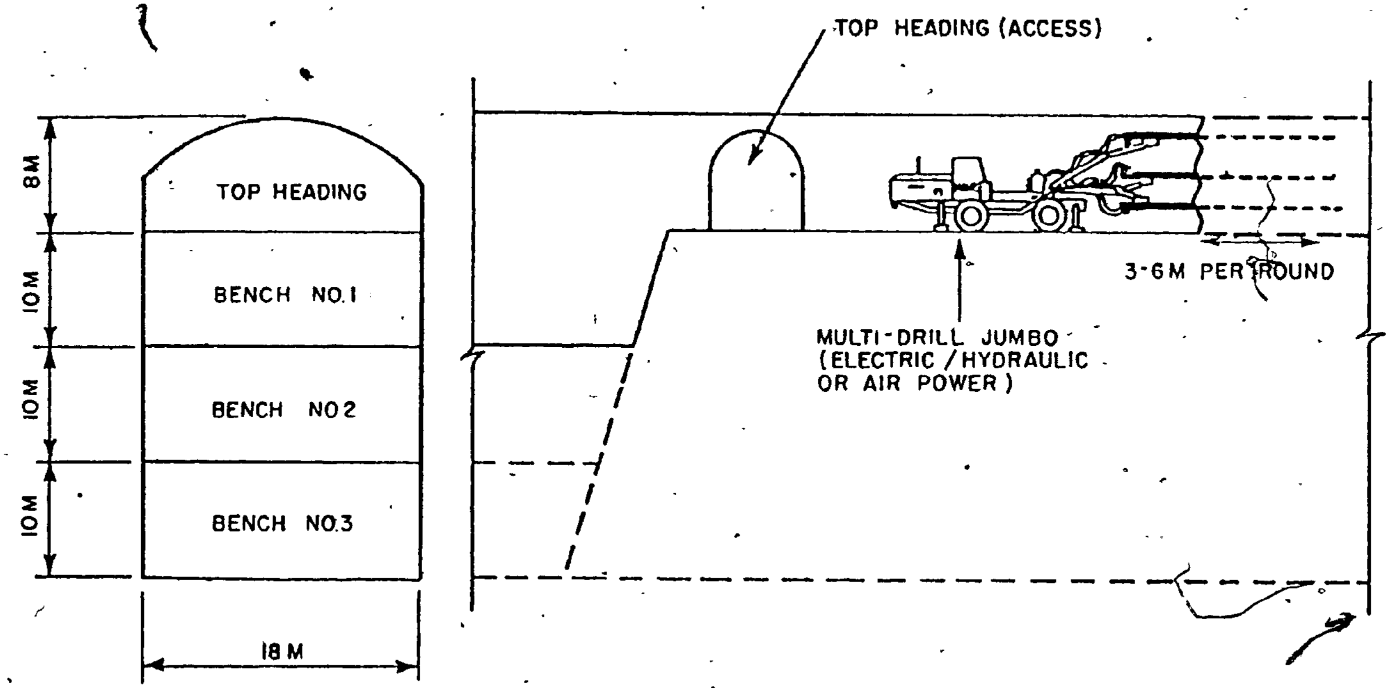


FIGURE 2. Typical Top Heading Drill-and-Blast Pattern
(Ref. 28)

2.10 Total time required:

$$\frac{4950 \text{ ft}}{3300 \text{ ft/yr}} = 1.5 \text{ years}$$

2.11 Total number of rounds:

$$\frac{4950 \text{ ft.}}{5 \text{ ft/round}} = 990 \text{ rounds}$$

2.12 Crews:

- Drilling and blasting
- Mucking and hauling
- Service

2.13 Drilling and Blasting crew:

No. of crews per shift = 1

2.14 1 shift crew production:

1 x 5 ft/shift x 60 cy/ft = 300 c.y./shift

2.15 Equipment:

2 - Jumbo's (5 drills each)

1 - Loader with 4.5 c.y. bucket

3 - 40 ton off-highway trucks

2 - Pickups

1 - Bulldozer

1 - 5 ton truck

Labour:

1 drill foreman

10 drillers

1 drill mechanic

1 bit grinder

2 labourers

1 service truck driver

2 powdermen

2 scalers

1 loader operator

3 off-highway truck drivers

2 truck spotters

1 excavation foreman

Total 27 men per shift crew

2.16 Cost of jumbos and ~~drill~~ material:

Purchase cost of jumbos

2 x $250,000 = $500,000

No. of hours used/round: 2

Total jumbo hours

990 rounds x 2 hrs = 1980 hrs.

Purchase cost per hour:

$\frac{\$500,000}{1980 \text{ hrs}}$ =	$252.00
Operation and maintenance per hour	
10 drills @ $5.00/hr.	$50.00
Cost of bits and steel	
300 c.y./hr x 4.5 ft/c.y. x $0.25/ft.	$338.00
Total drill equipment and material cost/hr	$640.00

2.17 Mucking cost

Purchase 1 - 992 Loader @ $300,000

Number of hours used:

$\frac{300 \text{ c.y.}}{150 \text{ c.y./hr.}}$ = 2 hours/round

Total hours used:

2 hours x 990 rounds = 1980 hours

Purchase cost per hour $\frac{\$300,000}{1980}$ =	$152.00
Operation and maintenance	50.00
Total Loader cost/hr.	$202.00
Cost per c.y. = $\frac{\$202. \text{ x } 2 \text{ hrs.}}{300 \text{ c.y.}}$ =	$1.35/c.y.

2.18 Hauling cost (to shaft or ramp)

Purchase 3 - 40 ton off-highway trucks

3 x $200,000 = $600,000

Purchase cost per hour

$\frac{\$600,000}{10,000 \text{ hours*}}$ =	$60.00

Operation and maintenance per hour

3 x \$35.00 = \$105.00

Total hauling cost per hour: \$165.00

Cost per c.y. $\frac{\$165. \times 2 \text{ hrs.}}{300 \text{ c.y.}}$ \$1.10/c.y.

2.19 Bulldozer cost

Purchase \$150,000

Purchase cost per hour $\frac{\$150,000}{10,000 \text{ hrs}}$ = \$ 15.00

Operation and mainenance 30.00

Total cost per hour \$ 45.00

Cost per c.y. $\frac{\$45. \times 2 \text{ hours}}{300 \text{ c.y.}}$ \$ 0.35 c.y.

2.20 Cost of pick-ups and service truck

Purchase	2 x \$7,000	=	\$14,000
	1 x \$9,000	=	\$ 9,000
	Total		\$23,000

Purchase cost per hour \$ 2.30*

Operation and maintenance 10.00

Total cost per hour \$12.30

Cost per c.y. $\frac{\$12.30 \times 4 \text{ hrs.}}{300 \text{ c.y.}}$ = \$0.2/c.y.

2.21 Labour cost

27 men x \$15.00 = \$405.00

Cost per c.y. $\frac{\$405. \times 8 \text{ hrs.}}{300 \text{ c.y.}}$ = \$10.80/c.y.

2.22 Explosives and accessories costs

Powder factor: 3 lb/c.y.

Cost per c.y. 3 x \$1.00 \$3.00/c.y.

* Life of equipment 10,000 hrs.

2.23 Total top heading direct cost

2.16	Drilling	$4.27/c.y.
2.17	Mucking	1.35
2.18	Hauling	1.10
2.19	Bulldozer	0.35
2.20	Service vehicles	0.20
2.21	Labour	10.80
2.22	Explosives	3.00
	Total direct costs	$21.07

3.0 Benching (Fig. 3 shows a typical excavation procedure of heading and benching

Total excavation: 1,760,000 c.y.

Total hours for 1.5 years:

1.5 years x 220 days x 3 shifts x 6 hours

= 6,000 hours

Excavation per hour: $\frac{1,760,000 \text{ c.y.}}{6,000 \text{ hrs.}}$ = 300 c.y./hr

Excavation per shift 300 c.y. x 6 hours = 1,800 c.y.

Excavation per day 1,800 c.y. x 3 shifts = 5,400 c.y.

3.1 Drilling

Using a 4-drill jumbo

2½" dia. holes @ 45 ft/hr

Drill factor 1.2 ft/c.y.

6' x 5' pattern + line drilling

+ 10% subgrade drilling

Drilling per hour (for one jumbo)

4 x 45 = 180 lin. ft.

Drilling/hour required 300 c.y. x 1.2 ft/c.y. = 360 lin.ft.

Number of jumbos required $\frac{360 \text{ lin.ft.}}{180 \text{ lin.ft.}}$ = 2 jumbos

7

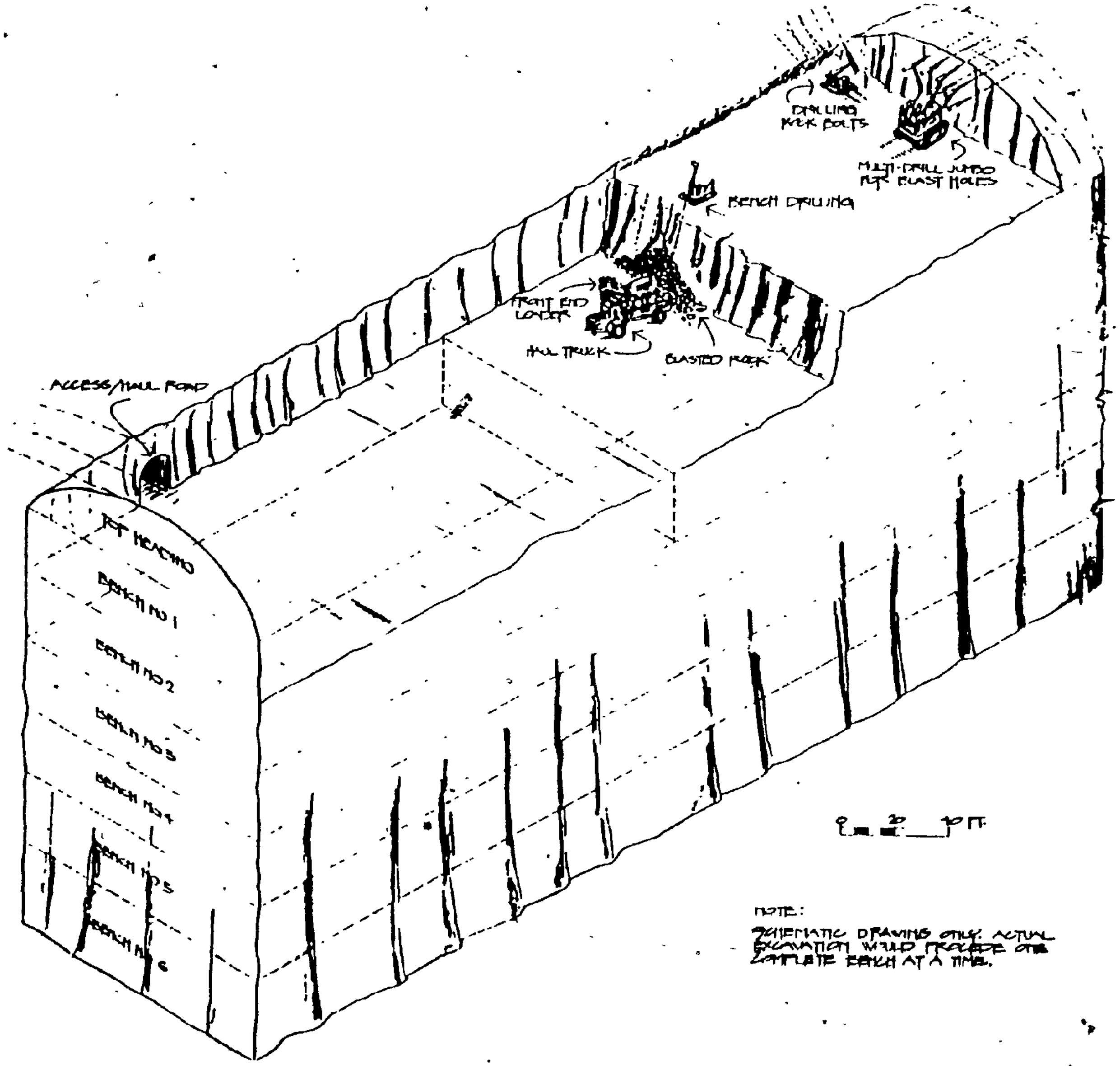


FIGURE 3. Typical Excavation Procedure - Heading and Bench

3.2 Drilling, Blasting, Mucking and Hauling Equipment:

2 - 4 drill jumbos
2 - 992 loaders
4 - 40 ton off-highway trucks
2 - bulldozers
2 - pickup trucks
2 - service trucks

Labour:

2 - drill foremen
8 - drillers
8 - drill helpers
1 - drill mechanic
2 - labourers
4 - powdermen
1 - blasting foreman
2 - loader operators
1 - excavation foreman
4 - off-highway truck drivers
2 - bulldozer operators
2 - service truck drivers
2 - truck spotters

Total 39 men per shift

3.3 Cost of drills and drill materials

Purchase cost of drills	
2 x \$200,000	\$400,000
Cost per hour:	
$\frac{\$400,000}{10,000\text{ hrs}}$	\$ 40.00
Operation and maintenance:	
8 drills x \$8.00/hr	\$ 64.00
Cost of bits and steel:	
300 c.y./hr x 1.2 ft/c.y. x \$0.25/ft	90.00
Total cost per hour	\$194.00
Cost per c.y. $\frac{\$194.00}{300\text{ c.y.}}$ =	\$ 0.70

3.4 Cost of mucking and hauling equipment (see 2.23)

Loader	1.35 /c.y.
Trucks	1.10
Bulldozer	0.35
Service vehicles	0.20
Total	$ 3.00/c.y.

3.5 Cost of labour crew — Cost/shift

39 men x $15.00/hr x 8 hrs/shift — $ 4,680.00

Cost per c.y. $\frac{\$4,680}{1,800 \text{ c.y.}}$ = $2.60/c.y.

3.6 Explosives and accessories cost

Powder factor	1.8 lb/c.y.
Cost per c.y.	1.8 x $1.00 = $1.80/c.y.

3.7 Total benching cost

3.3	Drilling	$ 0.70/c.y.
3.4	Mucking and hauling	3.00
3.5	Labour	2.60
3.6	Explosives	1.80
	Total Cost	$ 8.10/c.y.

4.0 Cost of services

4.1 Cost of air compressors:

Air requirements	cfm	Hours	Total cfx10^6
Top Heading - 10 drills x 400 cfm	= 4000	x 3300 x 60	= 800
Benching - 8 drills x 500 cfm	= 4000	x 6000 x 60	= 1500
Miscellaneous	= 2000	x 1500 x 60	= 200
Total	10,000		2,500

Compressors required:

10,000 cfm x 80% = 8 - 1,000 cfm electrical compressors

Number of hours used:

$\frac{2,500 \times 10^6 \text{ cfm} + 10\% \text{ capacity margin}}{1,000 \text{ cfm} \times 60 \text{ min}}$ = 45,800 hours

say: 46,000 hours

Cost of compressed air supply:

Air compressor purchase 8 x $40,000	=	$320,000
Maintenance 46,000 hrs @ $3.00	=	138,000
Power 46,000 hrs x 200kW x $0.015	=	138,000
Compressor operators - 2 man/shift x 220 days/yr. x 24 hrs/ 3 shifts x 1.5 yrs. x $15	=	237,600
Air pipes & fittings (estimate)	=	100,000
Miscellaneous materials (estimate)	=	100,000
Total compressed air supply		$1,033,600
	allow	1,050,000

4.2 Ventilation

Air required:

7,000 HP, 75 cfm/HP @ 80% = 420,000 cfm

Number of fans required

4 - 125 HP

Total fan hours:

4 fans x 3 shifts x 6 hrs/day x 220 days/yr
x 1.5 yrs = 24,000 hrs

Ventilation pipe:

48" dia. duct 10,000 lin. ft.

Power required 24,000 hrs x 90 kW = 2,200,000 kWh

Doors - 2 doors/face = 2 doors

Cost of ventilation:

Fans 4 x $15,000	$ 60,000
Duct 10,000 lin. ft. @ $10.00	100,000
Power 2 x 2 10^6 kWh @ $0.015	33,000
System maintenance (estimate)	50,000
Doors 2 x $5,000	10,000
Total ventilation	$253,000

4.3 Miscellaneous power requirements

Heading, benching	100 kW
Lighting	150 kW
Exterior lighting	200 kW

Power tools	100 kW
Pumps	500 kW
Total	1,000 kW

Net power required 1,000 kW x 60% 600 kW

Electrical material for 20,000 feet

Cost of power:

$600 \times 24 \times 250 \times 1.5 \times 80\% = 4.32 \times 10^6$ kWh

$4.32 \times 10^6 \times \$0.015$	\$ 65,000
Material 20,000 ft. x \$20.00	400,000
Maintenance materials (est.)	200,000
Emergency power (estimate)	100,000
Total miscellaneous power	\$ 765,000

4.4 Water supply and dewatering-allow \$1,000,000

4.5 Telephone - allow \$ 200,000

4.6 Service crew

2 foreman
2 electricians
2 electrician's helpers
2 pipefitters
2 pipefitter helpers
3 pumpmen
6 labourers
2 service truck drivers

Total 21 men

Service crew cost:

21 men x 30 hrs x 250 days x
1.5 years x \$15.00 = \$3,550,000

4.7 Miscellaneous service crew
maintenance material (15% of labour) 550,000

4.8 Total Services Cost

4.1	Compressed air	$ 1,050,000
4.2	Ventilation	253,000
4.3	Miscellaneous power	765,000
4.4	Water supply & dewatering	1,000,000
4.5	Telephone	200,000
4.6	Service crew	3,500,000
4.7	Misc. maintenance material	550,000
Total service cost		$ 7,318,000
	allow	$ 7,320,000

Cost per c.y. excavation

$$\frac{\$7,320,000}{2,055,000 \text{ c.y.}} = \$3.56/\text{c.y.}$$

5.0 Summary of Underground Reservoir Excavation Cost

2.23	Top heading	297,000 c.y. @	$ 21.07	= $ 6,258,000
3.7	Benching	1,760,000 c.y. @	8.10	= 14,256,000
4.8	Services	2,055,000 c.y. @	3.56	= 7,315,000

Total direct cost of excavating	$27,829,000
Delays and costs of opening face and establishing ramps 20% of above	5,500,000
Consolidation, including rock bolts, grouting, supports and shotcreting 20%	6,600,000
Total cost of excavating	$39,571,000

$$\text{Cost per c.y.} = \frac{\$39,571,000}{2,055,000 \text{ c.y.}} = \$19.26/\text{c.y.}$$

TRANSPORTATION - ALTERNATIVE A - VERTICAL HOISTING AND TRUCKING

1.0 Shaft construction

1.1 Shaft sinking - 2,000 ft. shaft x 30 ft. dia.
= 26 c.y. per foot
Excavation direct cost
2000 x 26 x $50.00 = $ 2,600,000

1.2 Construct concrete collar
50 ft and sheet piling
$2000 per foot = 100,000

1.3 Shotcrete material and equipment
2000 lin.ft. @ $250.00 per ft. = 500,000

2.0 Shaft equipment

2.1	1,000 ton/hr double skip hoist 20 tons	1,500,000
2.2	man hoist	1,250,000
2.3	service hoist	750,000
2.4	install 4 hoistways @ $500,000	2,000,000
2.5	headframe and bin	1,000,000
2.6	feeders (2), measuring pockets (2)	750,000

3.0 Power

3.1 6,000 HP x 0.75 = 4,500 kW
@ $0.015/kWh = $68/hr
Cost: $\frac{2,055,000 \text{ c.y. x 2.2 tons/c.y.}}{1000 \text{ tons/hr}}$
= 4,500 hrs @ $68.00 310,000

4.0 Operation and maintenance

4.1 Hoist maintenance, including ropes
4,500 hrs @ $200.00 900,000

4.2 Labour - operate and monitor hoists
Total operating hours: 4,500

Crew:

3 hoist operators

2 riggers

2 mechanics

1 bin operator

1 skipman

1 foreman

Total 10 men

Cost 10 x 4,500 x $15.00 675,000

Total cost of hoisting $12,335,000

Cost per c.y. $= \dfrac{\$12,335,000}{2,055,000 \text{ c.y.}} = \$6.00$

5.0 Hoist for heavy powerhouse equipment

To be installed after excavation is completed

5.1 200 ton capacity hoist including headframe, hoistway etc. 8,000,000

5.2 Operation and maintenance, power (estimate) 1,000,000

$9,000,000

6.0 Additional transportation - trucking from shaft to disposal area

Distance: 25,000 ft.

Volume: 2,055,000 c.y. (lower reservoir) + 52,000 c.y. vertical shaft) = 2,107,000 c.y. Using 25-ton highway trucks.

Speed: 9 mph = 9 x 5,280 / 60 = 792 ft/min.

Cycle time: $\dfrac{25,000 \text{ ft.}}{792 \text{ ft/min}} \times 2 = 63.13$ min

Trips/50 min. hour: 50/63.13 = 0.79 trips/hr.

Truck hours: $\dfrac{2,107,000 \text{ c.y.} \times 2.2 \text{ ton/c.y.}}{25 \text{ tons} \times 0.79} = 234,700$ hrs

Trucking cost:

234,700 hrs @ $30.00/hr. = $7,041,000

Cost c.y. $= \dfrac{\$7,041,000}{2,107,000 \text{ c.y.}} = \$3.34$/c.y.

TRANSPORTATION - ALTERNATIVE B - 35% (18°) INCLINED SHAFT,
CONVEYOR AND TRUCKING

1.0 Construction of inclined shaft

6,500 ft. x 32 ft. x 18 ft.

22 c.y./ft

1.1 Shaft excavation

Direct cost

= 1.8 x underground heading cost (2.23)

= $21.07 x 1.8 = $37.93

Direct cost of shaft excavation

6,500 ft. x 22 c.y. x $37.93		$5,424,000

2.0 Conveyors

2.1 Conveyor purchase and installation:

Purchase 1 conveyor

Belt $50/ft. x 2,080 ft.		104,000
Pulleys and drives		15,000
Idlers		53,000
Frame, hoppers, hoods		32,000
Motors and starters (650 HP each)		13,000
Wiring and controls		7,000
Lubrication piping		13,000
Cost/conveyor		$237,000
Cost of 6 conveyors		1,420,000
Installation - 6 conveyors		500,000
2.2 Maintenance		
1 belt	105,000	
Lubrication		
@ $50,000/yr x 1.5	75,000	
Repair materials	100,000	$280,000

2.3 Power

4,000 HP x 0.76 kW/HP = 3,000 kW x $0.015/kWh = $45./hr.

Cost

$$\frac{2{,}055{,}000 \text{ c.y. x } 2.2 \text{ ton/c.y.}}{1{,}000 \text{ tons/hr}} =$$

4,500 hours x $45/hr	$205,000

	2.4 Labour		
		1 millwright	
		2 oilers	
		1 operator	
		1 foreman	
Total		5 men x 4,500 hrs x $15.00/hr.	340,000

3.0 Primary crusher for 10% oversize
= 10% of 1,000 tons per hour
= 100 tons per hour

3.1	Use 48 x 40 crusher	250,000
3.2	Maintenance	
	4,500 hours @ $5.00	22,500
3.3	Power	
	500 HP x 0.75 kW/HP x $0.015/kWh x 4,500 hrs.	25,300
3.4	Operation	
	2 operators x 4,500 hrs x $15.00	135,000

4.0 Feeders and Hoppers

4.1	Feeder and hoppers (2) purchase	320,000
4.2	Installation	30,000
4.3	Maintenance - feeder and hoppers	
	4,500 hrs x $3.00	13,500

5.0 Man hoist and track

5.1	Maintenance 4,500 hrs. x $10.00	45,000
5.2	Operator 4,500 hrs. x $15.00	67,500

6.0 Equipment and material hoisting

6.1	Purchase Hoist	500,000
6.2	Operation and maintenance 4,500 x $15.00	67,500
	Total cost of Conveyor Transportation	$10,200,000

Cost per c.y.

$$\frac{\$\,10,200,000}{2,055,000\text{ c.y.}} = \$4.96/\text{c.y.}$$

7.0 Additional transportation - trucking from shaft to disposal area

Distance: 20,000 ft.

Volume: 2,055,000 c.y. (lower reservoir) + 143,000 c.y. (inclined shaft) = 2,198,000 c.y. Using 25 ton highway trucks.

Speed: 9 mph = 9 x 5,280/60 = 792 ft/min

Cycle time: $\frac{20,000 \text{ ft}}{792 \text{ ft/min}}$ = 25.25 min

Trips/50 min. hour: 50/25.25 = 1.98 trips/hr.

Truck hours: $\frac{2,198,000 \text{ c.y.} \times 2.2 \text{ ton/c.y.}}{25 \text{ tons} \times 1.98}$

= 97,700 hrs.

Trucking cost:

97,700 hrs @ $30.00/hr = $ 2,931,000

Cost/c.y. = $\frac{\$\ 2,931,000}{2,198,000 \text{ c.y.}}$ = $ 1.33/c.y.

TRANSPORTATION - ALTERNATIVE C - 7% ACCESS TUNNEL AND TRUCKING

1.0 Excavate access tunnel

Tunnel dimensions: 40 ft. x 25 ft* = 37 c.y./ft.

Grade 7%

Maximum depth: 2000 ft.

Length of tunnel: $\frac{2000}{0.07}$ = 28,500 feet

Total volume: 28,500 ft x 37 c.y./ft

= 1,054,5500 c.y. + 10% for cutouts (for electrical installation, vehicles and equipment etc)

= 1,160,000 c.y.

1.1 Cost of access tunnel excavation

Use top heading cost determined under 2.23 ($21.07)

1,160,000 c.y. x $21.07 $ 24,441,000

1.2 Truck hauling

Length of tunnel: 28,500 ft.

average hauling dist. 14,250 ft.

Volume: 1,160,000 c.y. using 25 ton highway trucks

Speed: 9 mph = 9 x 5,280 / 60 = 792 ft/min

Cycle time: $\frac{14,250 \text{ ft.}}{792 \text{ ft/min}}$ x 2 = 36 min

Trips/50 min. hour: 50/36 = 1.39 trips/hr.

Truck hours: $\frac{1,160,000 \text{ c.y. x } 2.2 \text{ ton/c.y.}}{25 \text{ tons x } 1.39}$ = 73,440

Trucking cost:

73,440 hrs @ $30.00/hr = $ 2,203,200

Cost/c.y. = $\frac{\$2,203,200}{1,160,000 \text{ c.y.}}$ = $ 1.90/c.y.

* Determined by the size of heavy equipment to be installed in the powerhouse (turbine scroll cases, transformers and the transporting vehicle dimensions).

Cost per c.y. - Excavation and Transport

$21.07 + $1.90 = $22.97

1.3 Excavate lower reservoir

Use excavation cost determined under 5.0 ($19.26).

2,055,000 c.y. x $19.26 = $39,580,000

1.4 Truck hauling

Length of tunnel: 28,500 feet

Volume: 2,055,000 c.y. using 25 ton highway trucks

Speed 9 mph = 9 x 5,280 / 60 = 792 ft/min

Cycle time: $\frac{28{,}500 \text{ ft.}}{792 \text{ ft/min}}$ x 2 = 72 min.

Trips/50 min. 50/72 = 0.69 trips/hr

Truck hours: $\frac{2{,}055{,}000 \text{ c.y. x } 2.2 \text{ tons/c.y.}}{25 \text{ tons x } 0.69}$

= 262,100 hrs.

Trucking cost:

262,100 hrs @ $30.00/hr. = $ 7,863,000

Cost c.y. = $\frac{\$\ 7{,}863{,}000}{2{,}055{,}000 \text{ c.y.}}$ = $3.83/c.y.

Cost per c.y. Excavation and Transport

$19.26 + $ 3.83 = $ 23.09

APPENDIX B

PENSTOCK EXCAVATION WITH THE ALIMAK RAISE CLIMBER

Introduction

Vertical shaft excavations in general and penstock excavations in particular require a special degree of expertise to achieve the high production rates which are usually imposed by the construction schedule. In addition, the method employed must maintain safe working conditions in the hazardous climate created with the great heights involved. In Canada, the Alimak Raise Climber was successfully involved in the excavation of penstocks associated with the Churchill Falls Hydroelectric Project, in Labrador, as well as the LG-2 Project of the La Grande Complex.

Alimak Raise Climber [20]

This system of shaft excavation was developed by Linden-Alimak of Skelleftea, Sweden. The system is designed for the driving of vertical and inclined raises of practically any shape.

The main elements of the system are (see also Figure 1):

1. Work platform, safety netting and safety roof.
2. Support beam and frame
3. Drive unit, operated by air or by electricity

4. Cage for operators of equipment (used during ascent or descent)

5. Air and water supply system.

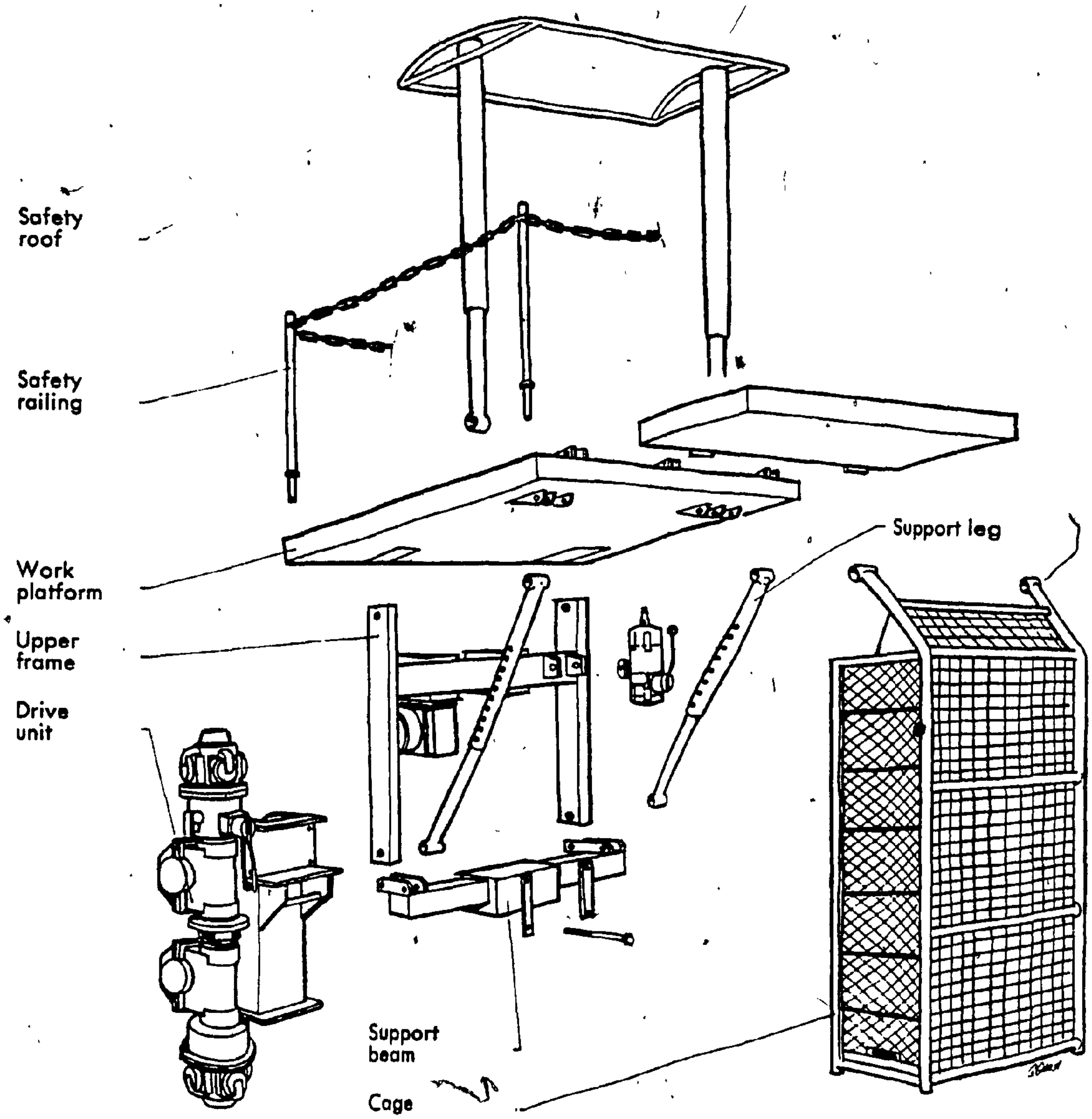
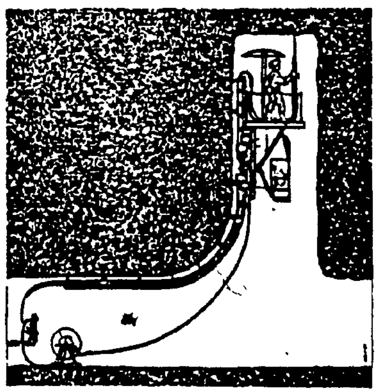


Fig. 1 - Main Elements of the Alimak Raise Climb System

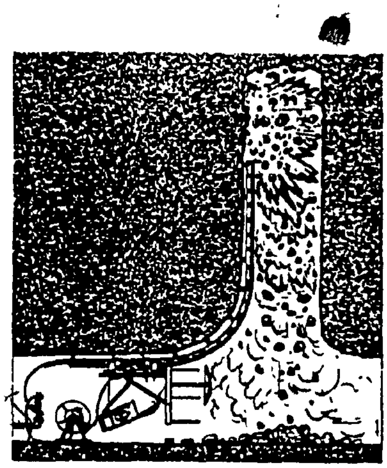
The electrically driven raise climber is used in long shafts where the loss of air pressure would not permit the use of the air operated drive unit. Electricity also offers the advantage of higher upward travelling speed of 60 ft./min. and downward speed of 80-100 ft./min.

The Raise Climber climbs along the rack bolted to the guide rail. The guide rail also carries the air and water pipes and is easily extended as the drilling progresses. The guide rail and rack are fixed to the rock wall by expansion bolts.

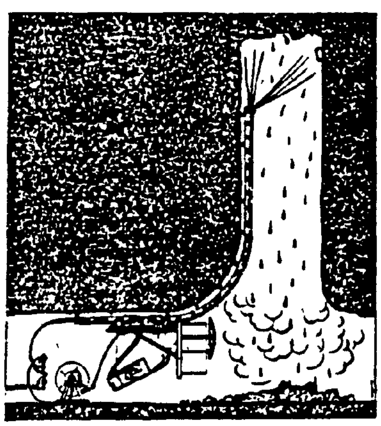
Figure 2 shows the steps involved in starting the driving of a vertical shaft.



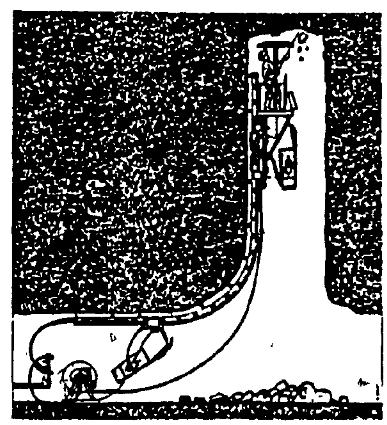
1. Drilling and loading are done from the platform, under a heavy safety roof of steel. Air and water are available through the pipes of the guide rail.



2. After drilling and loading the Raise Climber is driven down to the bottom of the raise so that during blasting the machine is well protected.



3. After blasting, the raise is cleared of fumes with an air and water spray. The top of the guide rail is well protected by a heavy steel top now functioning as jets for the ventilation.



4. Scaling of the face and walls can be done from under a safety roof, offering the miners good protection.

Fig. 2 - The Alimak Method of Raise Driving using Curved Guide Rails

The minimum dimensions of station cut out required for the installation of a standard Raise Climber with a platform of 5'3" x 5'3" when mucking is done in the direction of the guide rail or at 90° to the guide rail track is shown in Figure 3 and Figure 4.

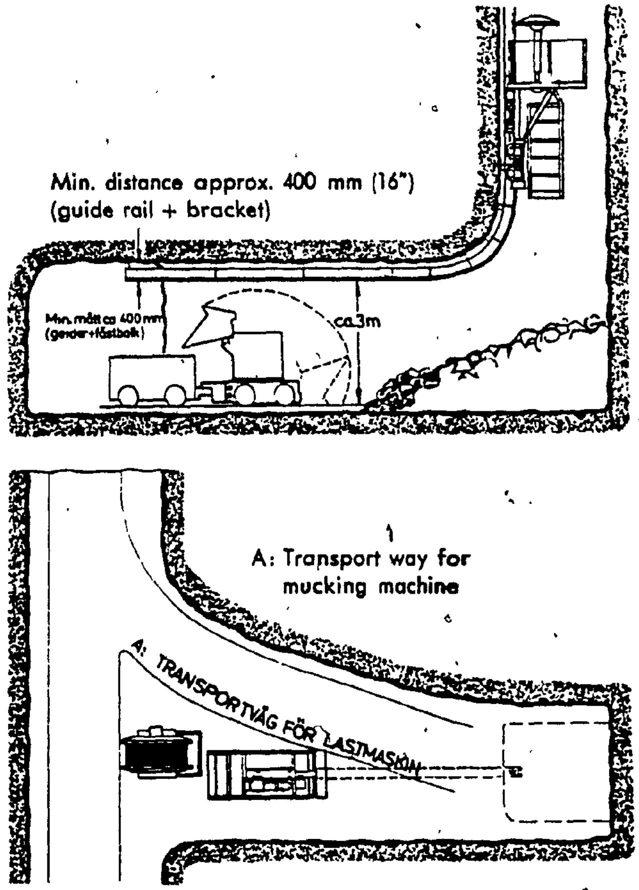


Fig. 3

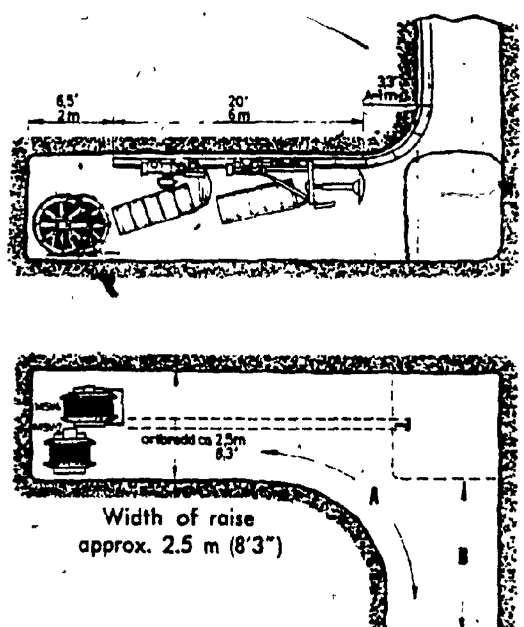


Fig. 4

Figure 5 shows the arrangement when mucking is carried out at lower level and Figure 6 depicts the arrangement in the case of a high station cut out.

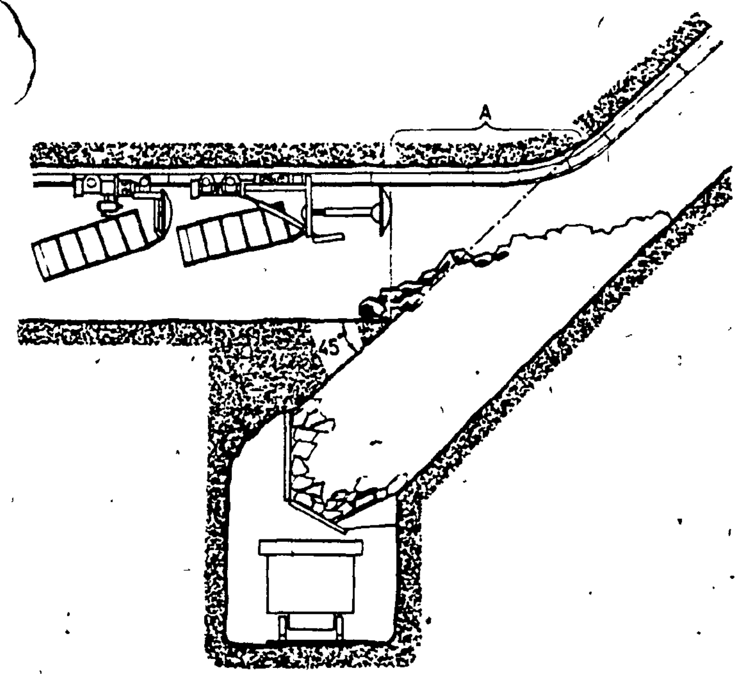


Fig. 5 - Mucking at lower level

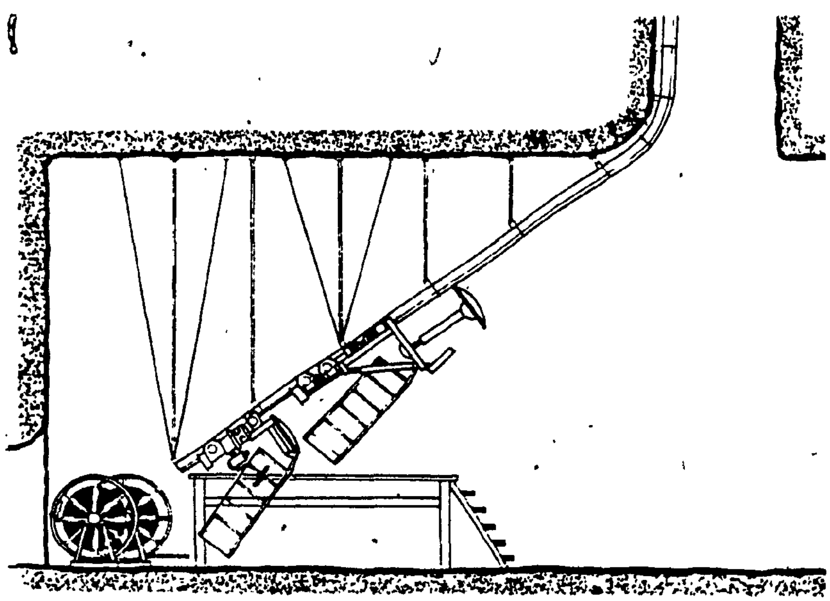


Fig. 6 - High Station Cut out

The dimensioning of the horizontal cut out for the installation of the Raise Climber in case of an inclined shaft is shown in Figure 7 and in case of a vertical shaft, in Figure 8.

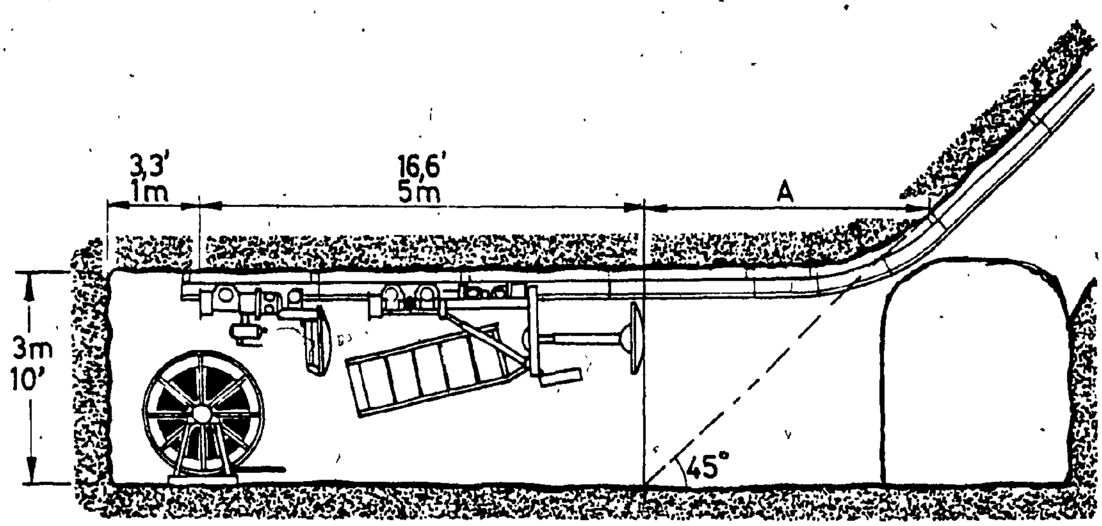


Fig. 7 - Dimensioning of Horizontal Cut out for an Inclined Shaft

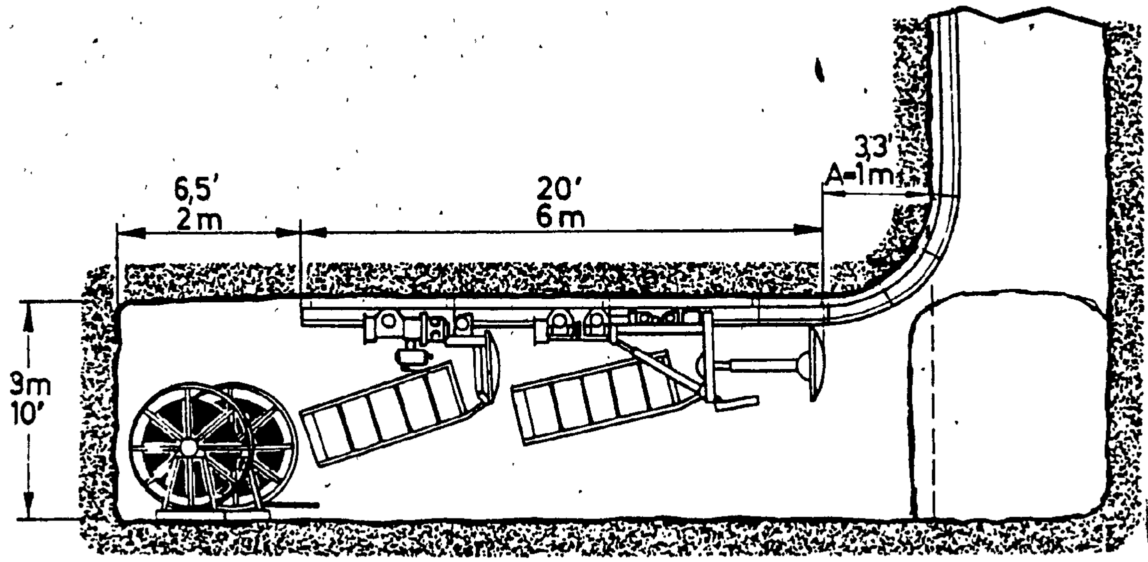


Fig. 8 - Dimensioning of Horizontal Cut out for a Vertical Shaft

The installation of a 90° guide rail curve (8°, 25°, 25°, 25°, 8°, radius 7'-7") requires a minimum space of 8'2½" safety distance between guide rail and face of raise or 11.3' total distance as shown on Figure 9. However, to facilitate the work, the first excavation should be 16.7' as this will make it possible to fit one or more straight guide rail sections so that the work platform of the Raise Climber may be horizontal.

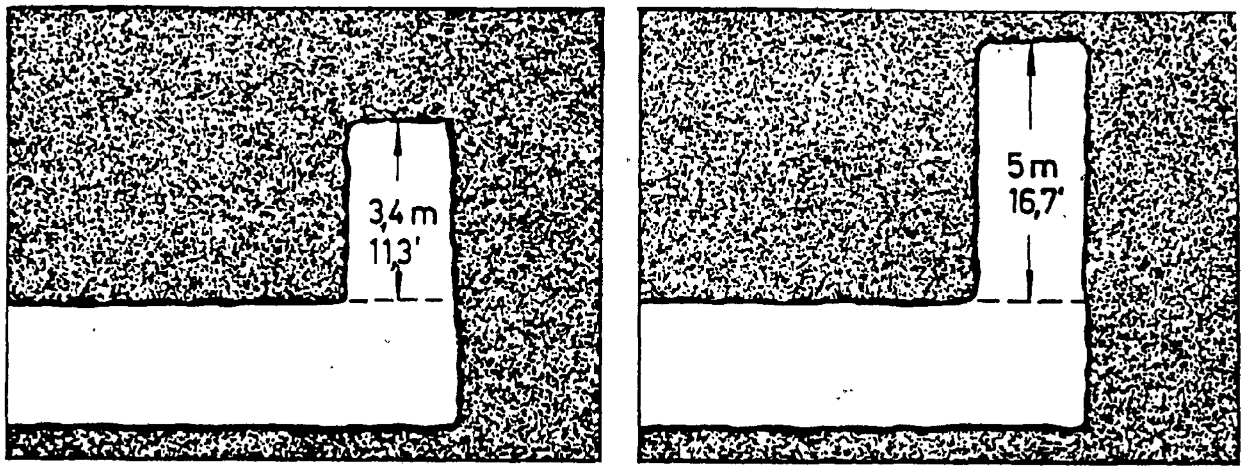


Fig. 9

To install the curve, the brow is slashed at a 45^{0} angle (see Figure 10) which corresponds to approximately 3.3' from the corner as per Figure 11. The location of the rail is then marked on the rock and the rail curve is installed. (Figure 12)

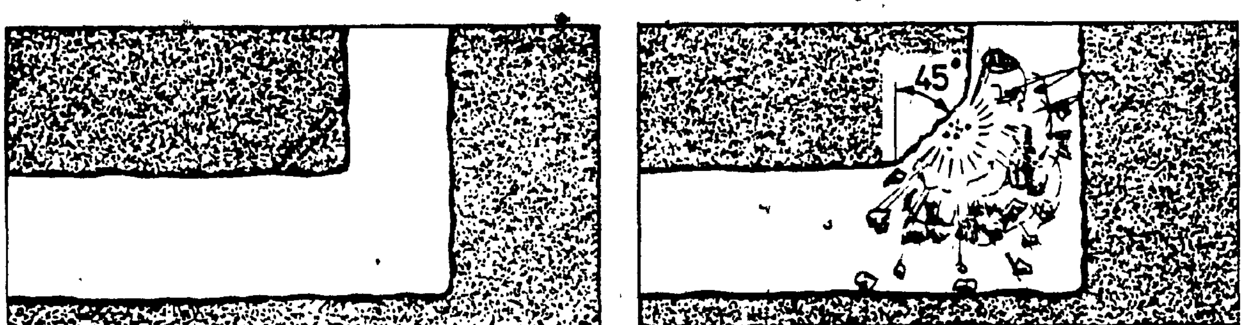


Fig. 10

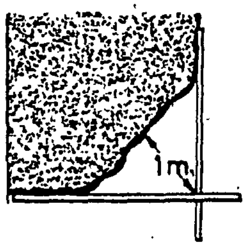


Fig. 11

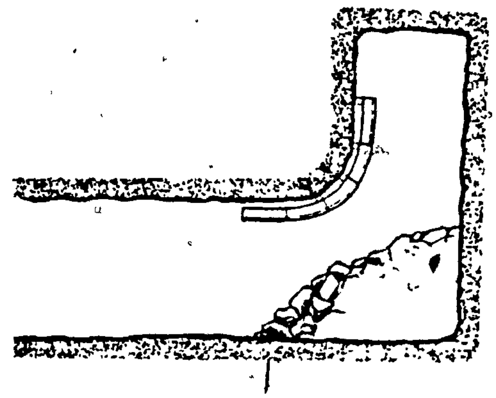
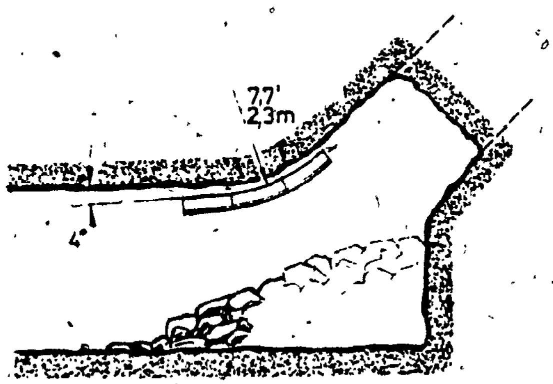


Fig. 12

The slashing for a 45° guide rail curve together with the installation of the rail section is shown in Figures 13 and 14.



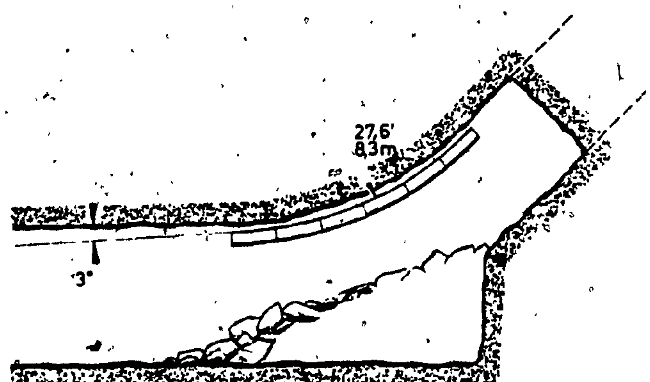
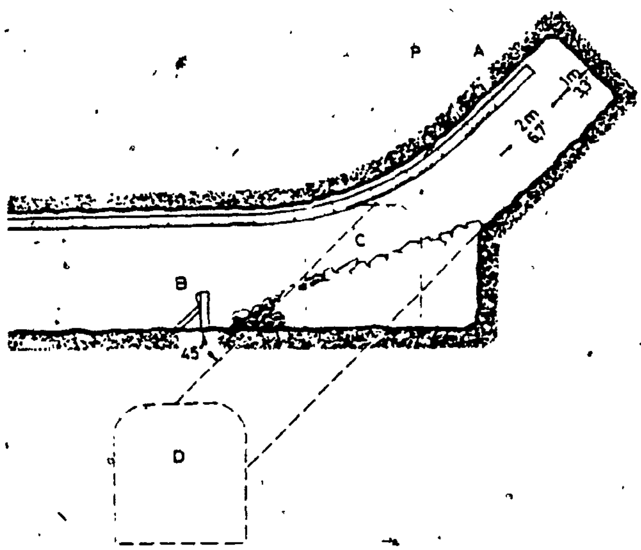


Fig. 13



A = 2 m guide rail
B = Shield
C = Muck drift, alt. 1
D = Muck drift, alt. 2

Fig. 14

The guide rail sections are installed as follows:

- standing on the rock, pin holes are drilled and a platform is installed
- at a minimum height of 9'-10" above the horizontal cut out a pulley is installed (P 1 in Figure 15) and the rail sections are pulled up and installed on anchor bolts driven into the rock.

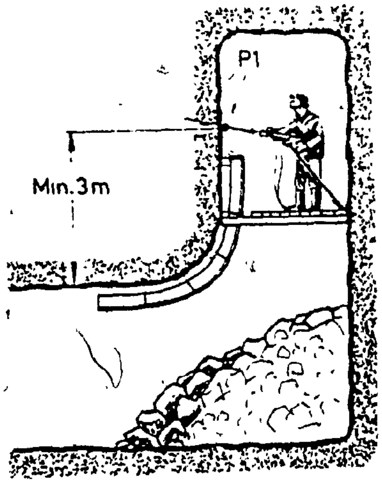


Fig. 15

- in inclined shafts the pulley might have to be installed quite far up in the shaft requiring the construction of platforms (Figure 16).

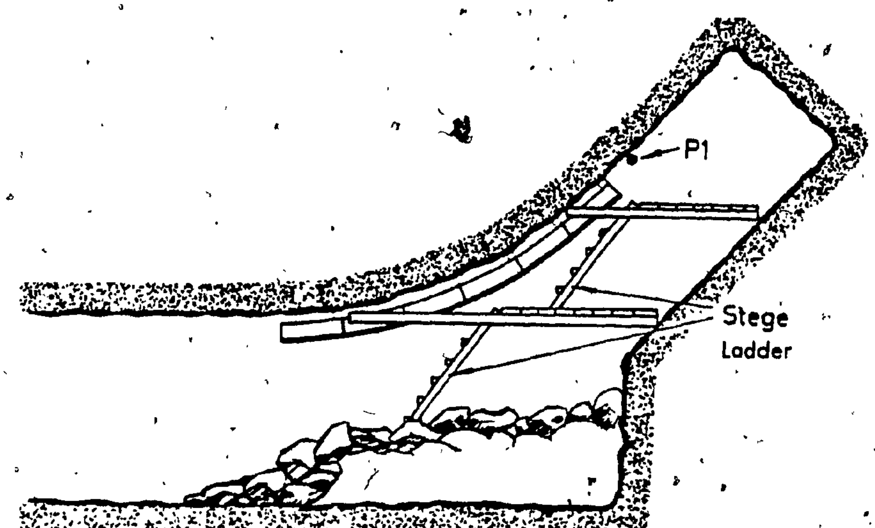


Fig. 16

The Raise Climber is then installed by:

- connecting an air hose to one of the air motors to enable the driving of the Raise Climber along the guide rail during erection

- installing the drive unit (Figure 17)

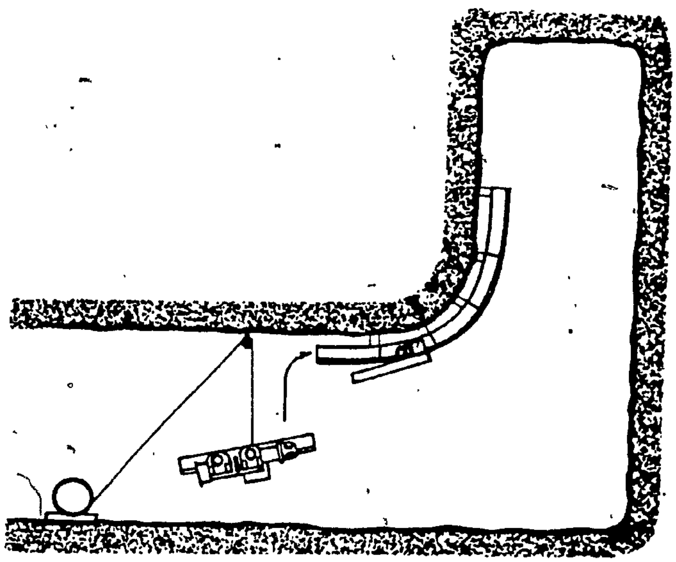


Fig. 17

- attaching cage, platform, etc. (Figure 18)

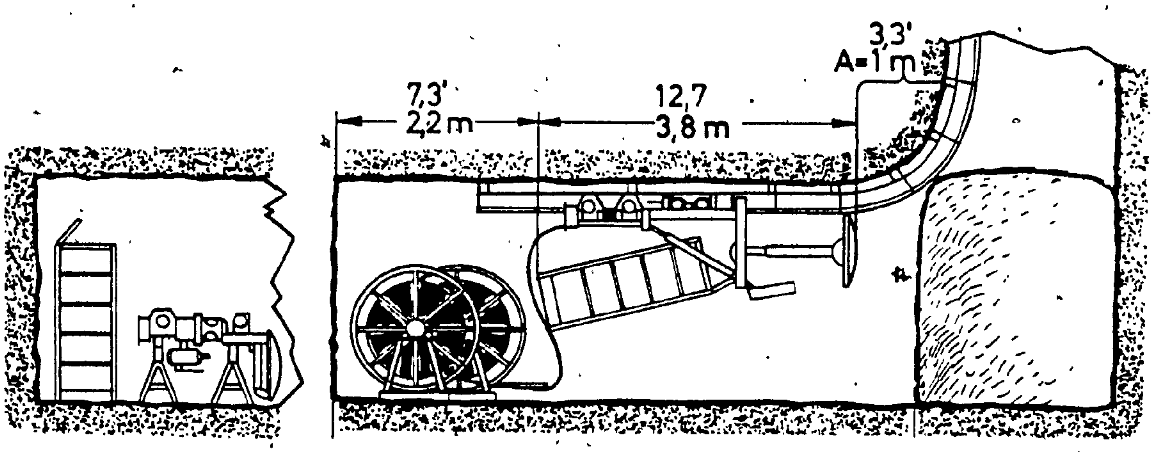


Fig. 18

The hose reel shall be installed behind the hoist in a location which will provide protection against falling rocks (Figure 19).

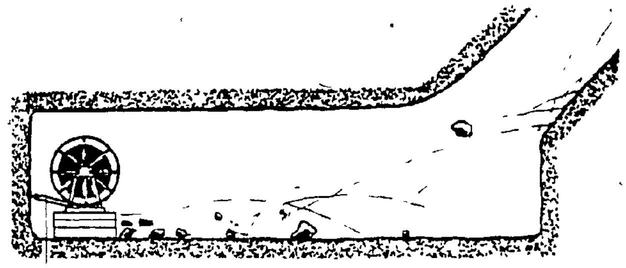


Fig. 19 - Hose Reel protected against falling stones

After this the automatic air/water center will be installed in the station cut out (Figure 20). The center is connected to the guide rail by three 1" air hoses and one 1" water hose

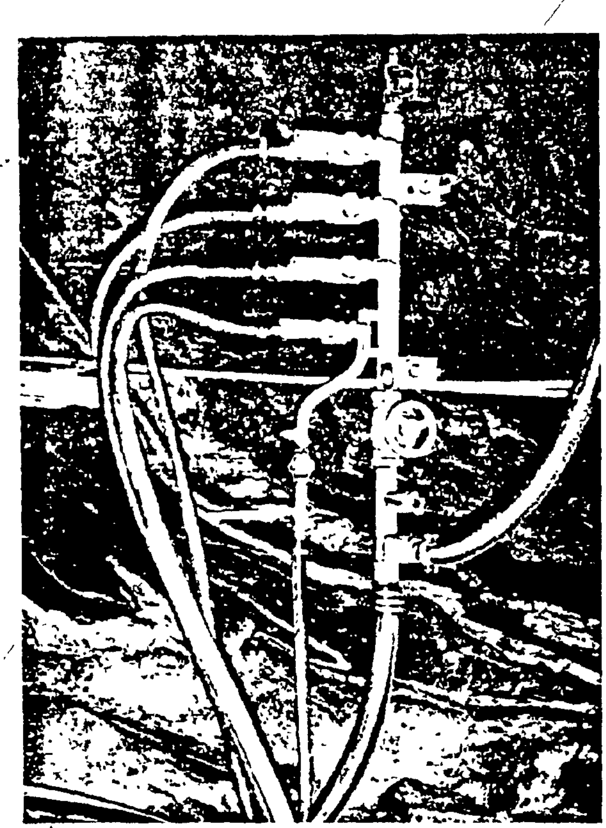
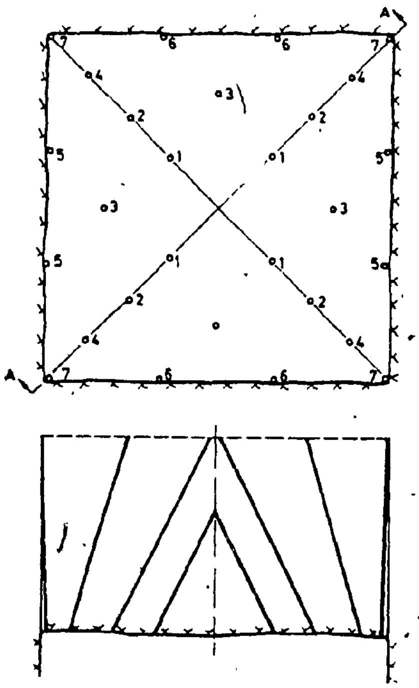


Fig. 20 - Automatic air/water center

Fig. 21

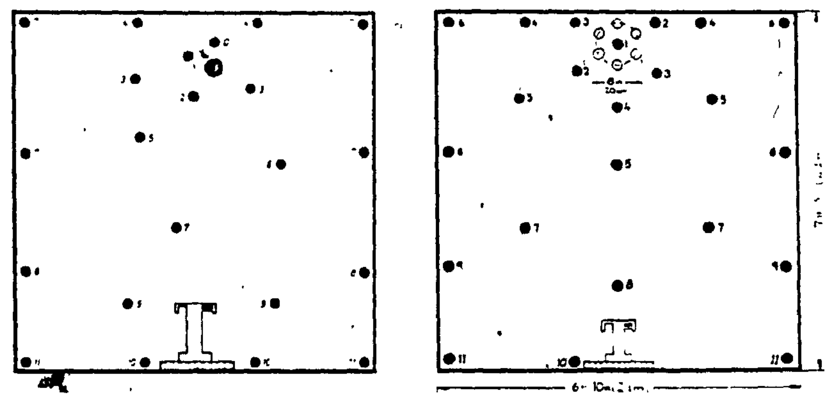
When all systems are installed drilling can commence. Drilling is done from the work platform (Figure 21).

Some of the more common drill patterns are shown in Figure 22. There is no universal pattern as conditions vary from site to site.



A - A

Round type pyramid
Raise 3×3 m (9'10"×9'10")



Blasting agents

Dynamite	25- 165 mm (1" - 6½") 26-1150 mm (1" - 45¼")
Gurit	17×500

The numbers of the holes indicate sequence of ignition.
El. blasting caps: 0,5 sec.

Dia. of hole	32 mm (1¼")
No. of holes	28
Average depth of hole	2.2 m (3'11")
Drill metre	61.6 m (202')
Advance	2.1 m (3'6")
Drill metre m^3 solid rock extracted	3.26 m (10'8")
Kg dynamite round	20-30 kg (44-46 lbs)

Area	4 m^2 (43 sq.ft)	4 m^2
No. of holes	22+1	29
Depth of round	2,4 m (7'11")	2.4 m
Side dimension	2 m (6'7")	2 m
Drill metre	52.8 m (172')	69.5 m (228')
El. ignition	½ sec.	½ sec.
Kind of rock	Leptite	Leptite

Fig. 22

Drilling in vertical raise is done using a stoper machine (Figure 23) under the safety roof. In inclined shafts the safety roof is not essential as the hanging wall provides sufficient protection. A jack hammer with air leg is used (Figure 24).

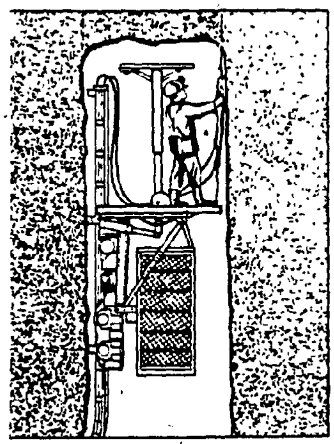


Fig. 23

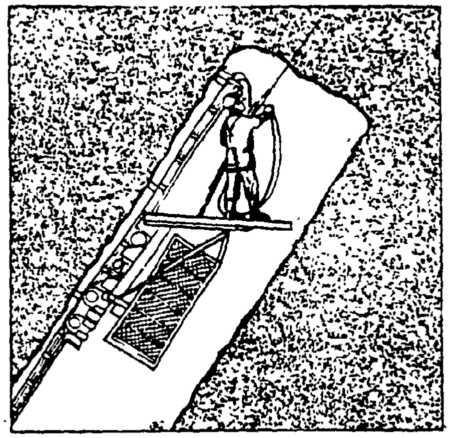


Fig. 24

After the drilling is finished the holes are loaded with dynamite or other blasting agent and blasted with suitable electric caps. After the round is fired, water and air is discharged through the guide rail to clean the face. The time required for this operation depends on the excavation facilities in the horizontal shaft. To facilitate the evacuation a fan may be installed. After ventilation, the Raise Climber ascends to the top of the guide rail. The face is then scaled so that another section of guide rail may be installed.

The final scaling of face and walls must be done under the safety roof.

Large diameter raises may be done with special stepped platforms in the case of inclined shafts (Figure 25) or by using additional platform sections and drive units (Figure 26).

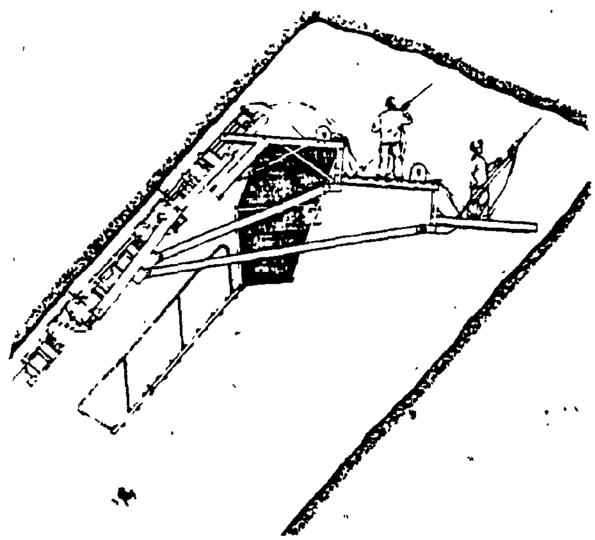


Fig. 25

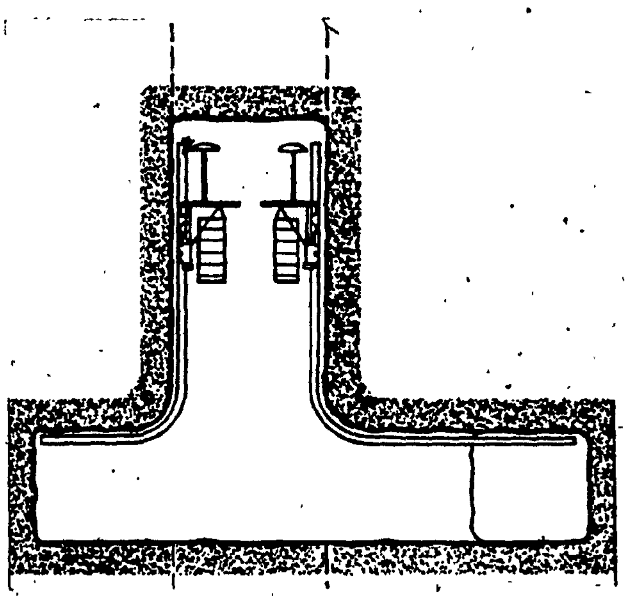


Fig. 26

To drive a large diameter raise, the Raise Climber may be used to make a pilot raise, at the center of the final raise planned (Figures 27 and 28). Slashing to the full area will then be done. Personnel and materials are transported in the Raise Climber through the pilot raise from above.

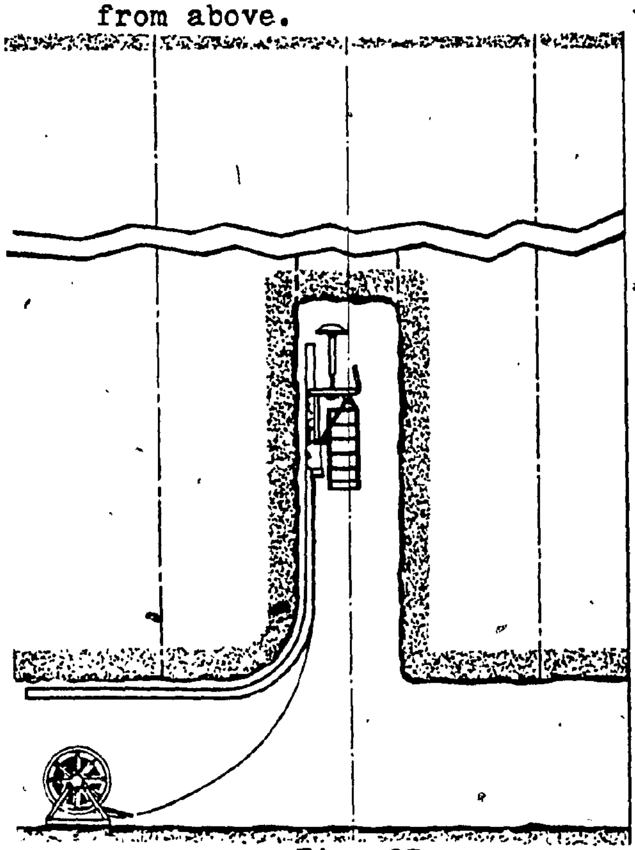


Fig. 27

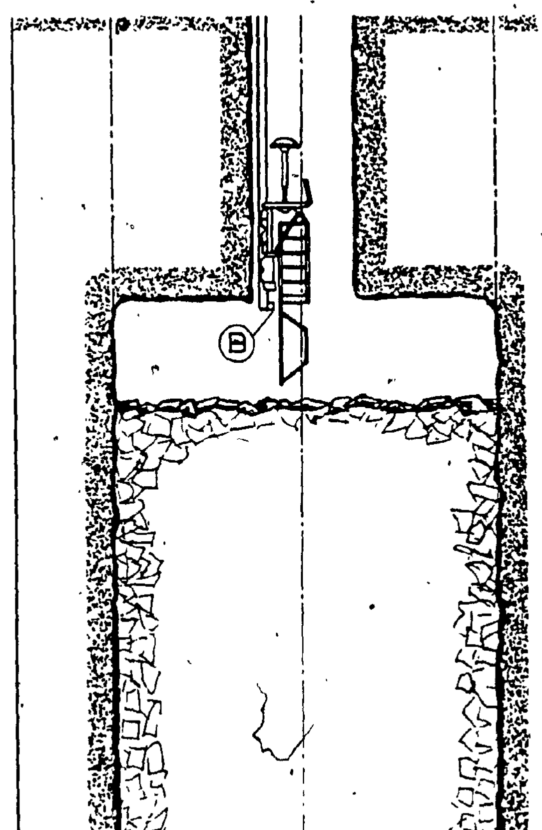


Fig. 28

The men drill and load standing on the rock pile. Before blasting, the lowest guide rail sections are removed and transported in a special basket attached to the cage of the Raise Climber. An extra bottom stop (B) must be fitted under the Raise Climber before removing the lower guide rail sections, otherwise the Climber may be driven off the rail.

Stoping with a pilot raise is shown in Figure 29(a). Figure 29(b) shows the equipment required for stoping in a fairly large raise and Figure 29(c) shows the equipment in a very large raise in three steps.

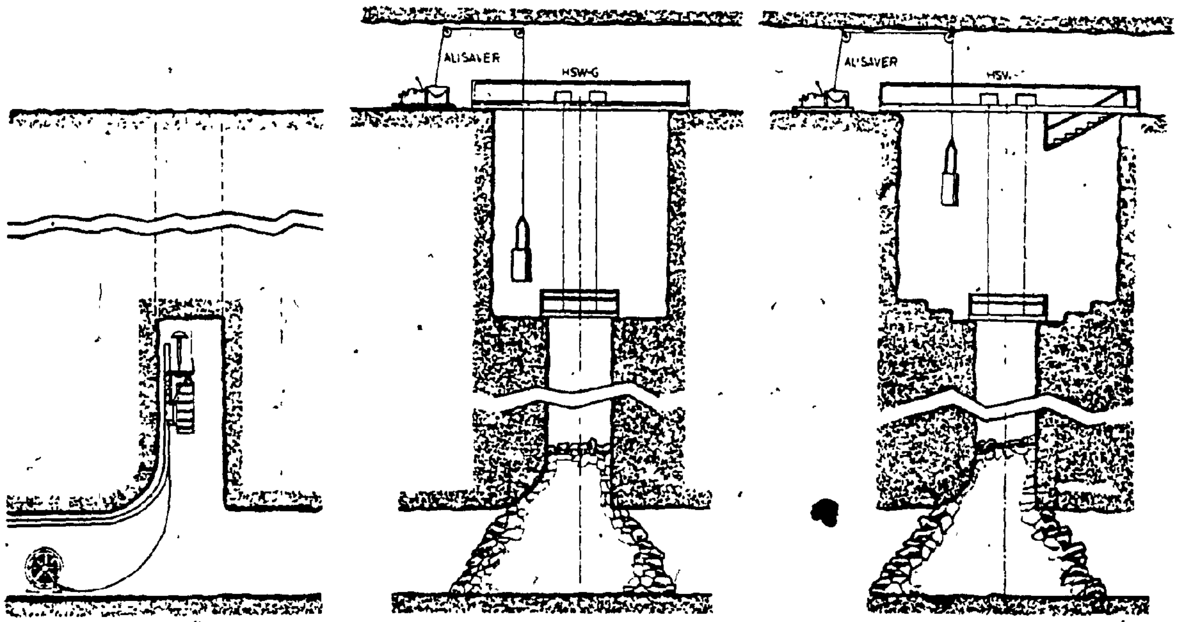


Fig. 29(a) Fig. 29(b) Fig. 29(c)

For large raises the platform is built in two steps. The upper platform covers the whole area and protects the men during drilling and loading. The lower platform covers the pilot raise.

During blasting the whole platform is driven up into a safe position above the stoping level.

Penstock Excavation with Alimak Raise Climber Cost Estimate

Description	Cost $/c.y.
Upper elbow	30
Vertical portion	80
Lower elbow	90
Horizontal portion	65
Reducer	65
Average direct cost of excavation	66
Indirect cost 40% of direct cost: 0.4 x 66	26
Average cost of Penstock Excavation per c.y.	92

Penstock Concreting Cost Estimate

Upper elbow	270
Vertical portion	277
Lower elbow	505
Horizontal portion	264
Steel lined portion	114
Reducer	470
Average direct cost of concreting	317
Indirect cost 40% of direct cost: 0.4 x 317	127
Average cost of Penstock Concreting per c.y.	444

Penstock Steel Liner Cost Estimate

	Cost $/lb.
Horizontal section	1.10
Reducer	1.50

Source: Programmation et Contrôle des Coûts (PCC)
Société d'Energie de la Baie James (SEBJ)
Montreal, Quebec

PENSTOCK EXCAVATION WITH ALIMAK RAISE CLIMBER
CHURCHILL FALLS PROJECT

The 1200 ft. long penstocks of the Churchill Falls Project are inclined at 58 degrees to the horizontal and range in excavated diameter from 22 ft. at the intake elbow, to 26 ft. near the bottom, before tapering to 20 ft. at the lower transition elbow (Figure 30).

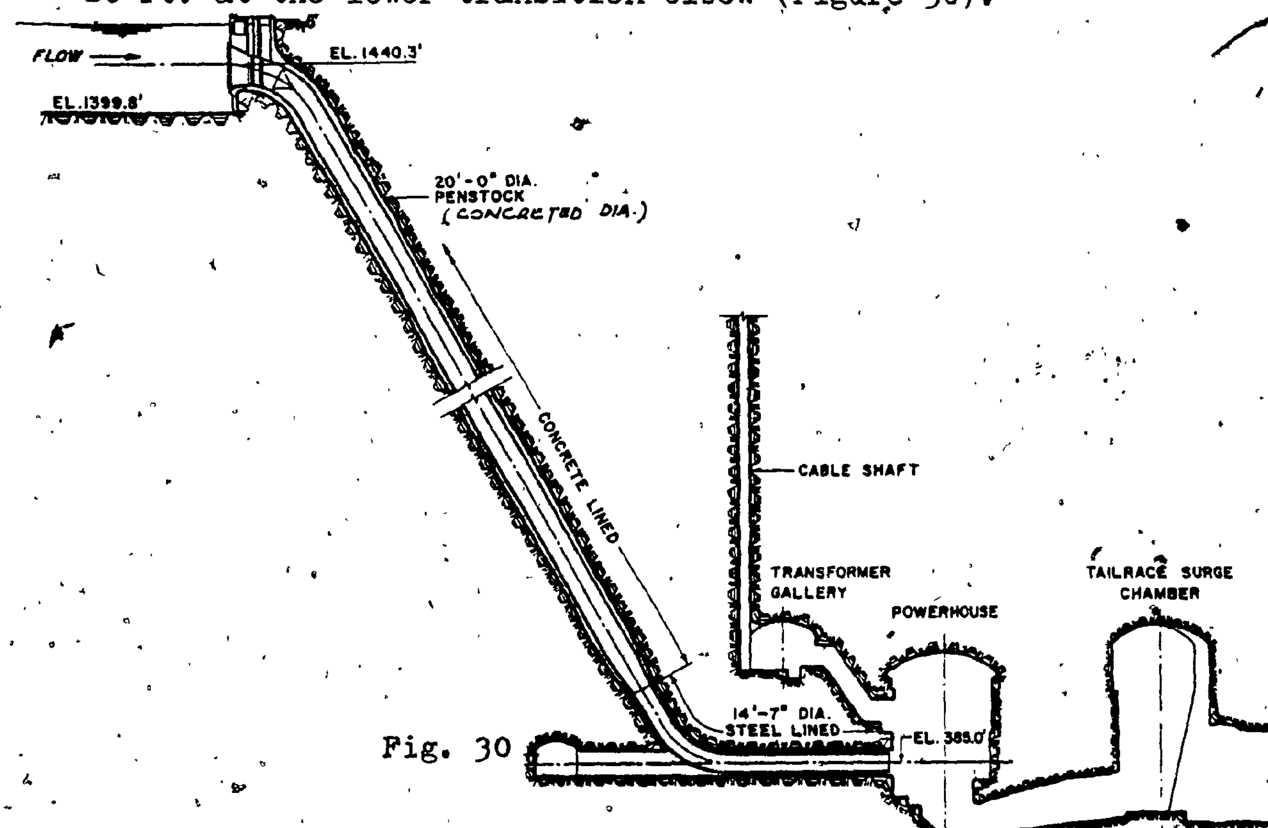


Fig. 30

Viewed in plan, the penstocks fan out from the central No. 6 penstock, so that at the intake elbow they are 60 ft. on centers, and at the lower transition elbow 72 ft. on centers.

Excavation

The initial excavation of the penstocks was made using Alimak Electric Raise Climbers to drive an 8 ft. by 10 ft. pilot raise on the penstock foot wall.

The main slashing operation to full penstock diameter was carried out using two 30-ton rail mounted drill jumbos, each equipped with six drills mounted on hydraulic booms and used in conjunction with a sliding plate assembly.

Before using either jumbo in a penstock raise, an initial 110 feet had to be slashed to full diameter using conventional air track equipment. This gave sufficient room for the jumbo to be positioned and retracted for the initial drilling and blasting. The jumbo and the plate assembly were both positioned and retracted by means of separate cables from the hoist in the intake area.

There were seven stages involved in the slashing operation, as shown on Figure 31:

1. Round was drilled and loaded
2. Pilot raise safety bulkhead was raised and the jumbo retracted to the back of plate (approximately 30 ft.). Platform outriggers were then raised.

3. Sliding plate assembly was retracted about 14 ft.

4. Jumbo was retracted about 14 ft. and blast took place.

5. Jumbo was moved to the front of the plate assembly (approximately 28 ft.)

6. Plate was moved forward to the new face and the outriggers were put down.

7. Jumbo was moved to the face and the pilot raise safety bulkhead was put in position. Scaling and mucking were performed as necessary; the face was marked and drilled while 14 ft. of rail was installed behind.

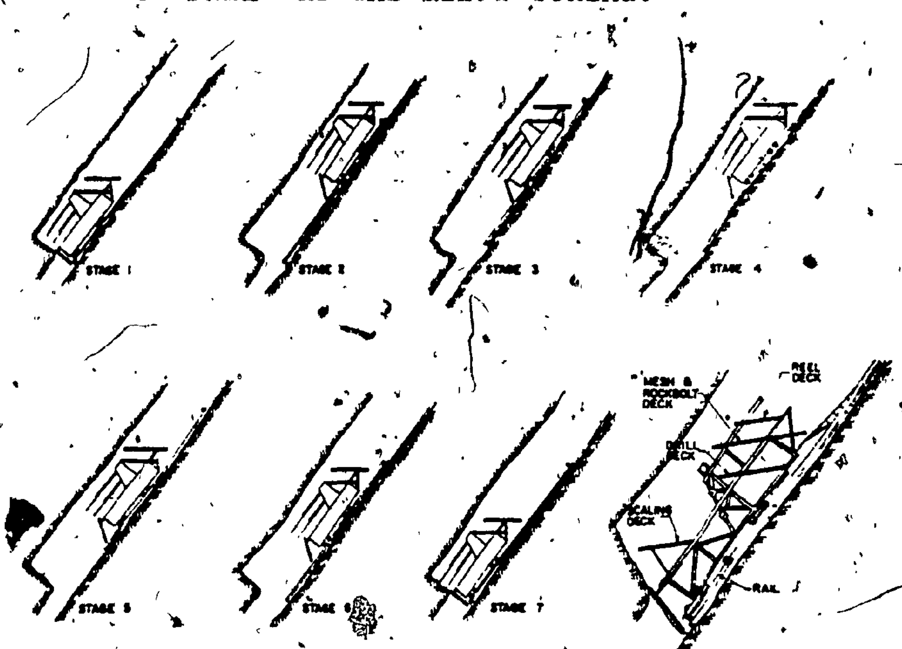


Fig. 31 - Penstock excavation sequences - Stages 1 to 7

Muck from each slashing round dropped down the pilot raise on the penstock footwall to the penstock access drift, where it was loaded and taken out on trucks to the disposal area. Rockbolting, wire mesh, and granite were applied when required as the work progressed.

Concreting

A steel section - type barrel form, with a hinged lower section used to permit collapse of the hinged wall panels for freeing from concrete encasement, provided the full 20-foot inside diameter lining.

Top and bottom sections were specially inclined to produce a slope for concrete compaction that would not require a solid bulkhead. The initial form installation used in penstock No. 1 consisted of a self-climbing needle beam/barrel form arrangement. However, this method of using a 50 ft. barrel required a 120 ft. long needle beam and was found to be awkward and potentially hazardous when handling the 80 tons of structural form. All subsequent penstocks were poured using a 40 ft. form supported on a carrier beam, as shown in Figure 32. Movement of the form between each pour was accomplished by either a double drum hoist and ten-part line or a rope grip with hydraulic rams. Each hoist was carefully monitored to ensure safe movements. Concrete placement achieved rates as high as one complete cycle every 24 hours for sustained periods.

The concrete set up consisted, essentially, of an 8 cubic yard hopper positioned over a pumpcrete remix unit; a 6 inch diameter Schedule 40 slick line in 20 ft. lengths coupled together with Victaulic couplings; a bridge section to carry the slick line from the footwall to a position on the top of the form just under the hanging wall; a specially built valve and $3\frac{1}{2}$ ft. lengths of 6 inch diameter elephant's trunk coupled together with chain links to carry the concrete behind the form . (Fig. 32)

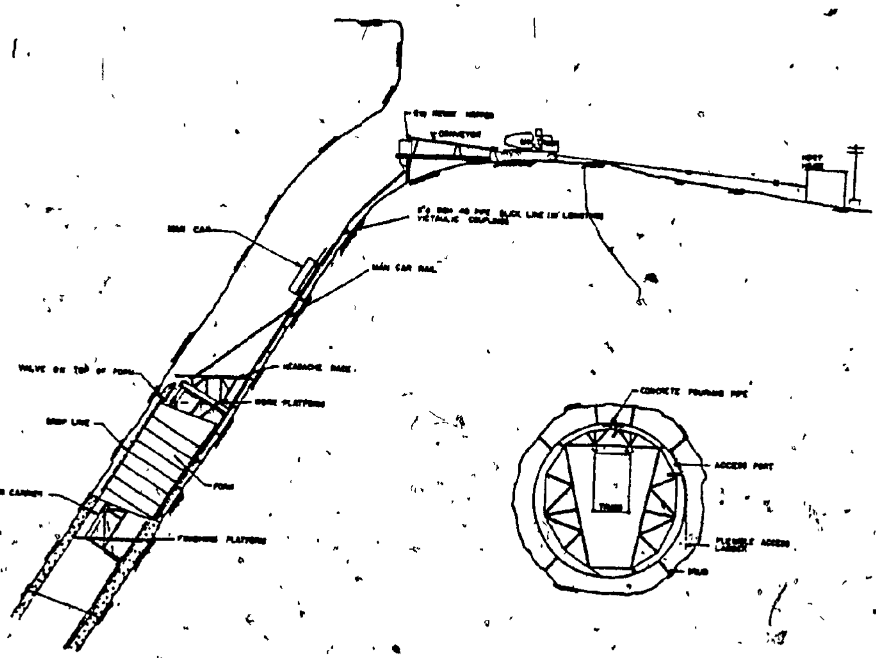


Fig. 32: General arrangement of penstock concreting operation.