REVIEW OF ADVANCEMENT IN PUMPED STORAGE HYDRO DEVELOPMENT

A DISSERTATION
submitted in partial fulfilment
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in
WATER RESOURCES DEVELOPMENT

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C E R T I F I C A T E

Certified that the dissertation entitled "Review of advancement in pumped storage hydro development" which is being submitted by Shri A.G.Chittaranjan Das in partial fulfilment of the requirement for the award of the Degree of Master of Engineering in Water Resources Development of the University of Roorkee is a record of the candidate's own work, carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period exceeding nine months in connection with the preparation of this dissertation.

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SYNOPSIS

1. In the first chapter, what is a pumped storage scheme and how it is important for the system to solve its peaking problem is explained with a typical daily load curve. Further how the system reliability is improved in comparison with other types of generation and intergrid system has been explained.

2. In the second chapter the historical developments of pumped storage plant from its humble beginning in 1882 as a pumping station with reciprocating pump to the latest planning of 2000 M.W. pumped storage plants with reversible machines has been traced. Further the two basic types of pumped storage developments, viz; i) pure pumped storage and ii) mixed type pumped storages has been explained. How the economy of power house construction effected by three machine unit and two machine unit with reference to vertical and horizontal shaft setting has been discussed. The necessity of going in for underground power house construction and its advantages over the other types of power house layouts in case of pumped storage due to the deeper setting required for modern large capacity units have also been explained in this chapter.

3. In the third chapter, the current development trends in the pumped storage technology, starting from the development of large stations with large unit capacity, large underground power house cavern, the latest concept of cluster layout and the development of equipments particularly the Isogyre turbine and hone turbine have been discussed. Other developments

leading to improvements in the pumped storage operation like

i) back pressure operation for Pelton wheel to reduce the shaft length

ii) wicket gate operation

iii) improving the thrust bearing and seal arrangement

iv) direct water cooling for generator motor for better performance and reduction in size of the machine, and

v) by employing pole changing synchronous machine to increase the speed of the pump by 20% so that the overall efficiency is improved

are discussed in detail.

In addition, the various types of starting method adopted for pumping mode in reversible turbine with their advantages are described.

4. In the fourth chapter, the pumped storage development in some of the advanced countries, like

i) U.S.A., ii) West Germany, iii) Japan

iv) Italy v) U.K., vi) U.S.S.R

and other countries has been described.

5. In the fifth chapter an overall summary of the pumped storage development with reference to improving the overall grid stability and the economy of the system due to its high flexibility is discussed.

The future prospectus in the development of pumped storage generation like

i) establishing regional grids and super grids

ii) using of tidal power in conjunction with pumped storages

iii) using the large condenser cooling water storages

for pumped storages

iv) locating underground reservoir and power houses with the upper reservoir in a depression in the ground level or sea, and

v) using of sea water as lower storage and creating an upper reservoir on a mountain top near the sea shore

are also described.

6. In the sixth chapter the economics of the pumped storage plant with reference to some of the pumped storage plant now under operation is explained. The economics of Kadamparai pumped storage plant in Tamilnadu (India), recently (1973) sanctioned by Planning Commission, is worked out.

7. In the last chapter the importance of such developments and how future pumped storage plants are planned in India is discussed. As an example the need for such development in Tamilnadu is explained with a daily load curve.

REVIEW OF ADVANCEMENT IN PUMPED STORAGE HYDRO DEVELOPMENT

CHAPTER I

INTRODUCTORY

WHAT IS PUMPED STORAGE POWER DEVELOPMENT AND WHY IT IS NECESSARY?

1. Basically pumped storage is a sort of storing surplus energy available in a power system. During slack demand period the surplus energy which will have no tariff value is utilised to pump water from a lower basin into an upper reservoir where it is retained as hydro power potential and is utilised for power generation during peak demand period and thus to supplement the peaking capacity of the system without any additional source of energy. Also the energy so generated during peak demand period will carry high tariff value.

2. It will be apparent from the above that there will be some loss of energy while pumping water from lower to upper reservoir and then again when the power is generated with the pumped water and so the process will involve losses twice and overall efficiency in terms of energy may be of the order of 65% to 75% only. However, the surplus energy available in the system during slack demand period has no tariff value. In case surplus energy is available from the hydro sources, the water from the sources will have to be flown down and utilization of such surplus energy will involve no additional cost. In the case of nuclear and thermal plants also though they can be shut down, the boilers will have to be maintained on bank fire even during absolute closure and, therefore, the saving of fuel

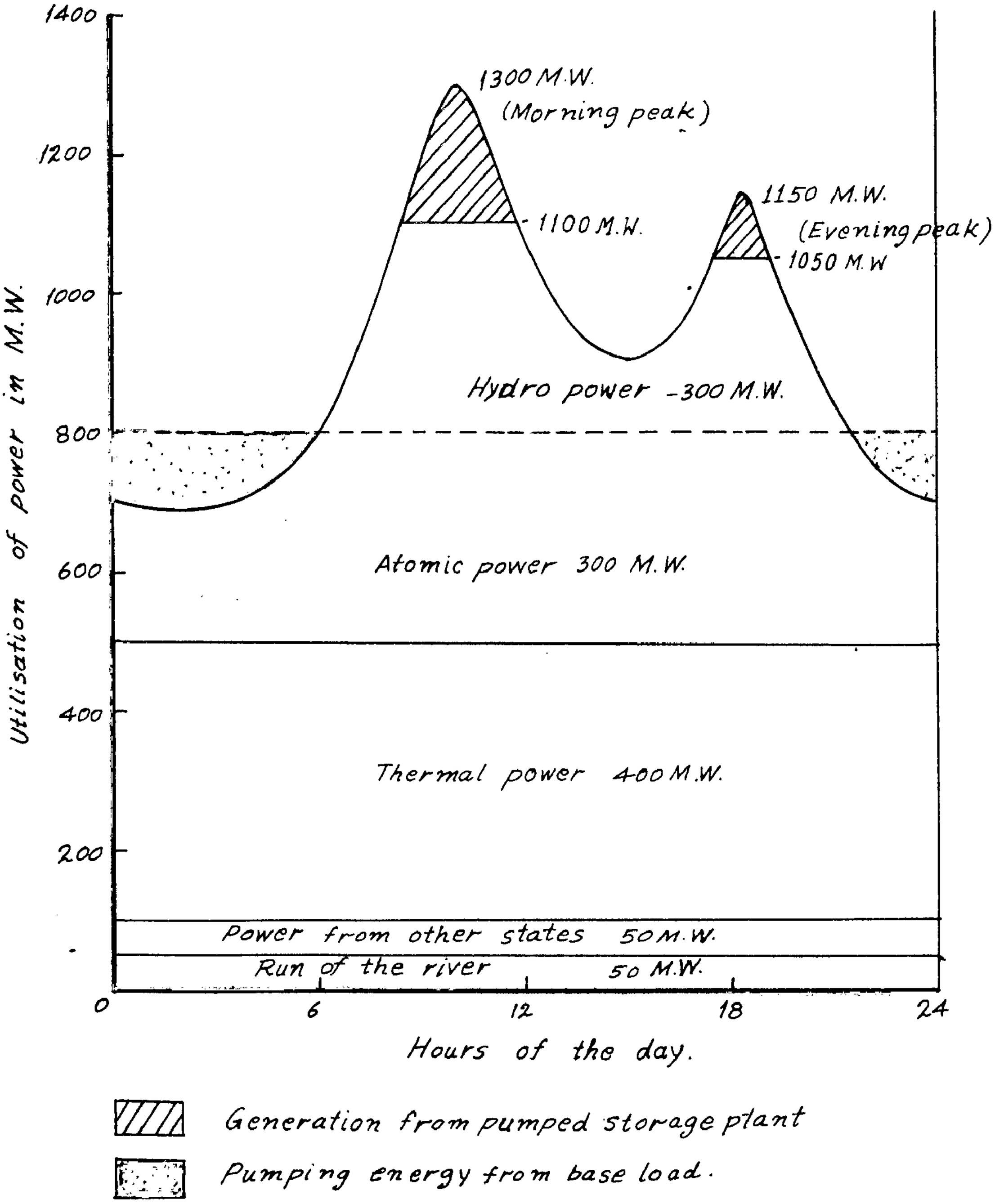


FIG. 1-TYPICAL DAILY LOAD CURVE

would be only partial. Utilisation of surplus generating capacity in the system will involve only the extra cost of some fuel and some lubricants etc. which will be small as compared to the tariff value of the power generated from the pumped water during peak demand period. Thus inspite of low efficiency by consideration of energy, economy of pumped storage development should be quite favourable in all cases where surplus generating capacity may be available in the system during slack demand period.

3. To make the planning of a pumped storage scheme more clear let us consider a typical daily load demand of a system. However, it is stressed here that a pumped storage plant can be designed as a weekly or seasonal basis also. Let the power demand increase from 6 A.M. and reach the peak demand at 10.00 A.M. After this let it fall to a certain level and again by 4 P.M. let the demand rise in the evening and reach the peak say at about 6.30 P.M. and again slowly it drops to the original level at about midnight. Fig.(1) shows the graphical representation of the above rise and fall of the power demand by means of a curve termed as daily demand curve or daily load curve.

Let this system comprise of the following:

i)	Run of the river generation	...	50 M.W.
ii)	Power from neighbouring states	..	50 M.W.
iii)	Thermal power	...	400 M.W.
iv)	Atomic power	...	300 M.W.
v)	Some hydro power	...	300 M.W.
	Total system capacity	...	1100 M.W.

As the power from item (i),(ii),(iii) and (iv) has to be utilised continuously they are marked as base load.

The total base load capacity is therefore equal to 50+50 +400 + 300 = 800 M.W.

It may be seen from the curve,(i) the power demand or utilisation is less than the available power upto 6 A.M. Similarly after 10 P.M. in the evening also demand is less than the power available (marked in dotted). Thus this power becomes surplus to the system, since they form the base load stations. As already explained in the previous para letting down the run-of the river water without generating power is wasting of energy even though we may not require at that time. Similarly closing down the thermal plant to save some fuel during that time will not permit saving corresponding to the power cutout.

(ii) Let us now consider the demand between 6 A.M. in the morning to 10 P.M. in the evening. It is found from the curve the demand is more than our base load capacity. It is assumed that in this system there are some hydro stations of 300 M.W. capacity with high head and storages. Due to the limitation of the run-off and storages let the power generated by these hydro may be taken as 'X' K.W. hours, and shown shaded in the curve. Let the peak demand be 1300 M.W. in the morning and 1150 M.W. in the evening. It may be seen that the total capacity of the system is less by 200 M.W. (1300-1100) during morning peak and less by 100 M.W. in the evening peak demand period (hatched portion). Hence the system is having peak deficit in installed capacity assuming the system has adequate energy.

This can be fulfilled in three ways:

(a) By having hydro stations. This means we require new water resources.

(b) By having thermal stations. This means we require more fuel.

(c) By pumped storage plant of say 200 M.W.capacity. This does not require any new water resources. But will use the surplus power available (in the morning and night) during the slack demand period described earlier. Let us say energy required in the peak demand period is 75% of the energy available as surplus power. Then it is now found the 25% extra available as surplus will take care of the pumping and generating losses.

Thus it is clear, how the adequate capacity of pumped storage plant with reference to the available surplus energy in thé slack period is put to make good deficit in the peak demand. In case the surplus power is less than peak deficit we may require some energy schemes in addition to the pumped storage scheme which will reduce the capacity of the new energy scheme to the extent it can utilise the surplus off peak power, thus reducing the cost and regular maintenance of new scheme.

Hence it is shown that pumped storage scheme is a valuable asset to the system to make best use of the energy available, which otherwise will go waste.

4. Besides this, the improvement of load factor of thermal plants due to the presence of pumped storage scheme and of

overall efficiency of the supply system is in itself a decisive advantage.

5. In a system comprising several large thermal plants for example, addition of a pumped storage scheme to meet expanding demands, not only saves the provision of additional thermal plant but also saves the fuel such new plants would consume.

6. The importance as instantaneous reserve may also be underlined. On the one hand starting time for pump turbines are very short i.e. about 70 seconds and for change over from pumping to turbining some 150 seconds. On the other hand, pumped storage project are operated most of the time at 80% of the full capacity so that in the case of system break down or other incidents their output can be increased from 80% to 100% within a few seconds. In an interconnected system pumped storage therefore constitutes an important reserve which cannot be equalled by any other type of power plant.

7. Further as system demand continues to increase at a rapid rate in a developed or heavily industrialised country, two major aspects have to be considered:

(i) Provision of peaking power at the lowest cost.

(ii) Maintenance of system reliability.

Both are independent. This can be ensured by number of methods as described below:

a) Intergrid connections

b) Additional base load steam plant or peaking steam plants.

c) Additional gas turbine peaking units.

d) Additional capacity at the existing hydro stations

e) Construction of pumped storage plants.

a) Taking an example in U.S.A. 95% of all generating capacity is now interconnected at a common frequency. A national reliability council is established for improving the system reliability with the help of twelve regional coordination groups and with interconnecting transmission network[54]. But all this requires a high level of reliance and cooperation between the members. Further, it is costlier and during emergencies or system disturbances one system may be isolated from the other within few minutes. Such things have happened in past, for example in New York in 1965 when a major power station broke, thereby reducing the system frequency very badly, which in turn isolated other systems to protect their equipment and with the disastrous result of plunging New York city in utter darkness. When frequency falls intentional separation is also possible. Such things have happendd in summer 1972 in Tamilnadu Grid also. Hence this may not solve the problem entirely.

b) The time taken for a thermal unit with a steam turbine to go on line at full load is about 1½ to 2 hours. This is alright for an anticipated peak, but for an emergency this is too long a period, in which undue damage will occur in the system. Even the most modern machine will take 30 to 45 minutes.

c) Even for the gas turbine the time taken to go on full load is about 20 minutes. In addition due to low thermal efficiency and higher fuel cost per unit its use is limited.

d) The hydro station can handle such emergency peaks within a few minutes but only drawback is the water that is used for

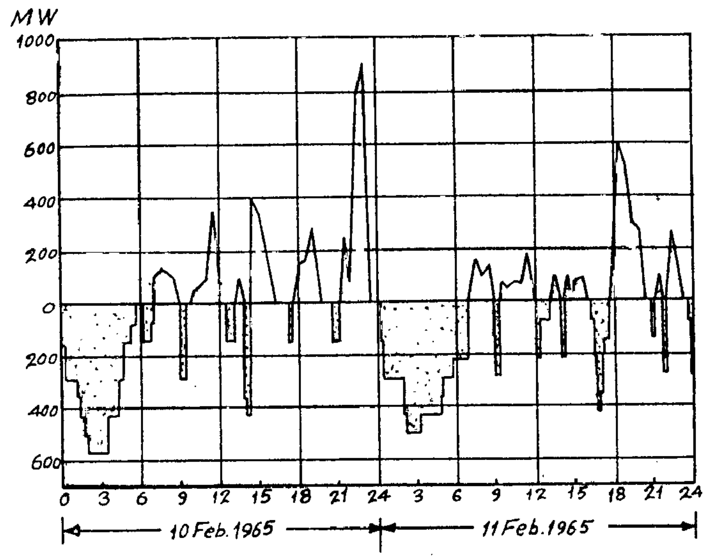


FIG. 2. - TYPICAL SCHEDULE CURVE FOR THE VIANDEN PUMPED-STORAGE PLANT WITH A NIGHT TIME PEAK FOR TELEVISION ON FEBRUARY 10, 1965. LUXOMBOURG.

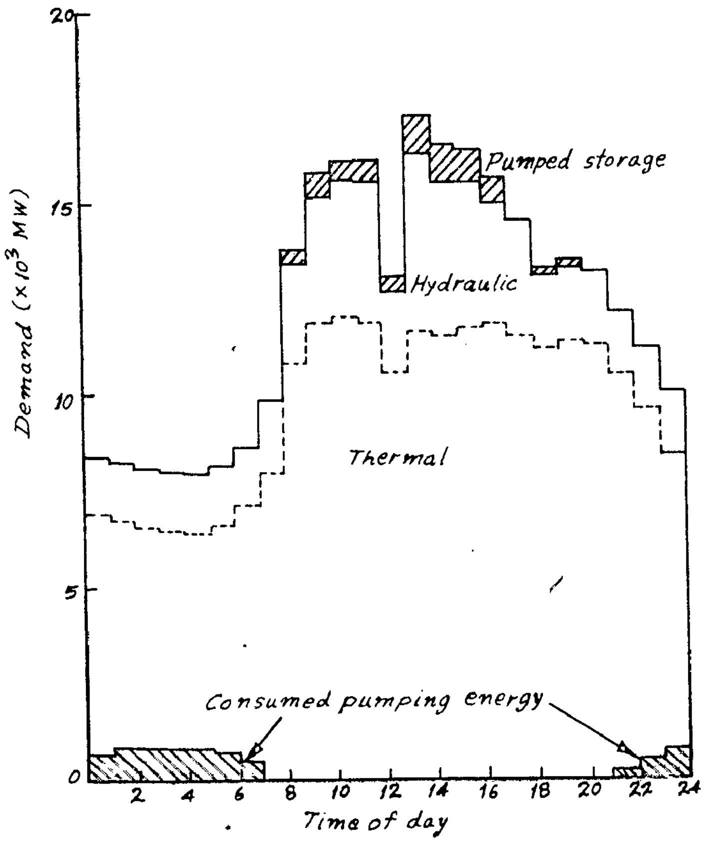


FIG. 3. - AN EXAMPLE OF THE DAILY LOAD CURVE IN THE TOKYO AREA DURING SUMMER (JULY 22, 1970.) THE SUMMER PEAK IS GREATER THAN THE MAXIMUM DEMAND DURING WINTER. JAPAN

power generation is lost for ever for the particular hydro power stations.

e) A pumped storage plant has got all the advantages of a hydro-electric station in addition to the water used for generation can be reused for generation by pumping back to the original storage after the emergency is over. Further, compared to thermal unit it takes only about 70 to 90 seconds from standstill to full load and from full pumping mode to full generating mode about 2½ minutes.

8. In the industrially developed countries the problem of levelling out diurnal fluctuations in thd electric load is becoming increasingly urgent due to irregular utilisation of electricity at various periods during the year, week or day. The difference between the night and morning load already amounts to thousands of Megawatts. under present day conditions in large power systems with a very sharp load fluctuations. This problem is particularly acute for countries with predominantly thermal power stations which are ill-equipped for such variable conditions of operation.

The pumped storage plant simultaneously resolves the two basic problems in levelling out the power system load curves (as shown in para 3) in which power stations of all types must participate at the same time meeting the peak demands and filling the night time troughs in the curve. Fig. 2 and Fig.3 show some of the typical daily load curves of developed countries with large load fluctuations and how the operation of pumped storage has been helpful to them.

9. In short the advantages as well as the necessity of having a pumped storage plant in a system is as follows:

i) There is no fear of exhausting the source of power generation, there is practically no limit for fixing the capacity of pumped storage plant. The way in which large unit capacity and large pumped storage plants have progressed so far in the last 10 years have promised a bright future in the coming years and have brought out the above fact clearly.

ii) In any system where such a large reserve is available at a short notice will make the system reliable to the users of electricity.

iii) It assures an adequate standby in the time of breakdown.

iv) It can take care of variations in frequency which is very important now-a-days. As fall in frequency of supply means large scale damage to sophisticated modern equipment and breaking away of neighbouring system to protect their equipments and thereby making the situation more critical.

v) Above all as stated in earlier paragraphs its energy is available practically at little cost to take care of the sharp peak demand in the system with no appreciable loss in its water resources.

CHAPTER II

HISTORICAL REVIEW

1. The idea of pumping water into high level reservoirs in order to store energy is not new. The first pump for this purpose of which records are available was installed at Zurich in 1882. This was a reciprocating pump. The first centrifugal pump was installed at Luino in Italy in 1894. It had 75 h.p. capacity, pumping against a head of 210 ft. to an artificial reservoir, and was used by a spinning mill. Between that date and 1925 the size of units increased slowly but steadily upto about 50,000 h.p., but no large capacity pumps were installed until the Niederwartha station near Dresden was put into operation in 1928 with two, later four 27,000 h.p. pumps and 30,000 h.p., turbines. These units were the fore-runners of a number of large capacity pumping sets built in Europe during the subsequent five years, of which the largest in capacity at that time were the four 36,000 h.p., pumps at Herdecke station in the Ruhr. More recently a pump of 62,000 h.p., was put into operation at Providenza in Italy, and units of 85,000 h.p., have been completed at Limberg in Austria. Upto 1951 the development of pumped storage schemes has been largely confined to Europe and of a total of about 850,000 h.p., of pump capacity installed throughout the world, some 600,000 h.p., was to be found in Germany alone. For the most part the remainder was divided in order of aggregate capacity between Italy, Switzerland, France, Austria and the United States. Isolated schemes exist in Sweden, Spain and Chile. In U.K. one small installation of

230 h.p. built in 1918 on the river Tweed, was the only example of pumped storage until the North of Scotland H.E.Board put in hand a scheme at Sron Mor near Inverary. This comprises a 5000kw horizontal francis turbine generator to which a storage pump is coupled. The tail pond of the Sron Mor station is also the regulating head pond of a peak load station, Clachan situated at a lower level. The function of the pump is to transfer to the main reservoir above Sron Mor the natural inflow into the tail pond which otherwise would be wasted when Clachan is not working. Only by 1963, the first large scale pumped storage development in U.K., i.e. Ffestinoig pumped storage plant in Wales with a capacity of 4 x 75 MW (300 M.W) has been made.

2. In U.S.A. the earliest pumped storage plant in operation from 1929 is at Rocky River, Connecticut, of capacity 7000 kilowatt. The next highest plant capacity was installed only in 1950 at Buchann, Texas of capacity 12,000 kw. In 1956 at Hiwassee, North Carolina, the capacity installed was 59,000 kw(27). However, this figure rose to 240,000 kw by the addition of Lewiston, Niagara pumped storage scheme in New York system. In 1967, the pump generating plant capacity in U.S.A. rose to 800 M.W. by the construction of Muddy Run at Pensinsylvania. Now there are schemes like Cornwall of 2000 M.W. installed capacity under construction in U.S.A.

3. In U.S.S.R. until 1970 there was no development, the first pumped storage is Kiev pumped storage plant with a capacity of (6 x 34.6 MW) 200 M.W.commissioned in 1970. There has

been a great awakening now and large scale planning in thousands of Megawatts capacity is going ahead in U.S.S.R.

4. To-day the planning and the construction of a number of large capacity pumped storage station is a characteristic of expanding modern electrical power supply systems. As an example experts in the U.S.A. who in 1958, were hardly prepared to think of possible pumped storage schemes have now at the design stage more than 19000 M.W. to be commissioned by 1980 in the areas of New York, New Jersey, Peninsylvania and so on.

5. Historically there are two main basic types of pumped storage development. In the first the water is pumped from a low level reservoir 'A' into a high level storage 'B' against a head 'H'. This water is later used to generate energy when flowing in the reverse direction from B to A, over the same gross head 'H'. Because of the friction losses the pumping head will on the average be greater than the generating head; level variations in the two reservoirs have also to be considered. This type of pumped storage development is often called pure pumped storage schemes.(35) Such schemes usually have the power house and lower reservoir in the existing river or lake. For the upper storage nearest hill top is chosen which gives the shortest water conductor system. Hill top reservoirs are usually constructed by choping up the hill top and constructing a ring bund or embankment to store the adequate water necessary for the pumped storage operation eg. Taum Sauk P.S.P., Ludington P.S.P. of U.S.A., Vianden I and II of

Luxembourg, Ronkhausen P.S.P. of West Germany, Revin P.S.P. of France, Turlough Hill P.S.P. of Ireland and Camlough P.S.P of U.K. etc.

In the second type of pumped storage either head available for power generation or the quantity of water available for power generation are larger than the pumping head or pumped water to offset the losses in the pumping cycle then it is called Mixed Pumped Storage Scheme. Earlier versions are mostly of this type i.e. water from a water course having lot of flow is pumped to a high level reservoir with or without its natural catchment and for power generation the water is drawn from the high level reservoir to a power station located suitably at a far low level than the pumping stations level to gain more head for power generation. Earlier types of this are found in most of the countries. Even in India e.g. in Kundah Hydro Electric Project in Tamilnadu copious water from a stream below upper Bhawani reservoir is pumped into it and power is generated in four powerhouses located on the other side of the mountain utilising a head of more than 5000 ft. But such schemes are generally called as pumping schemes.

6. In a pumped storage version, though separate pump and turbine with separate motor and generator are used, the water for pumping and generation is drawn through the same conduit. As the technology advanced three machine arrangement developed in place of the four machine arrangement, mentioned above. Single generator-motor replaced separate generator and separate motor. Therefore, the most usual layout of pumped

storage plant comprises a turbine with a generator and a pump coupled together on one shaft, the generator operating as a synchronous motor also for driving the pump. Generally the shaft is horizontal but vertical shaft arrangements were also adopted where there were considerable fluctuations in tailrace level, in order to avoid excessive suction head on the pump. With vertical shaft units the pump is always on the bottom with the turbine in the middle and generator above it. In the horizontal arrangement generator motor may be between the turbine and the pump just like any other hydro electric plant, the turbine adopted is Francis turbine for head upto 350 metres and above that pelton wheel. As the turbine technology progressed, Francis turbines limiting head gradually improved and now even for a head of 700 meters Francis turbine is being thought of. For example, the highest head upto which it has been used is 672 m at Rosshag P.S.S. in Austria. However, above this pelton wheel alone is adopted.

In the meanwhile there were developments going on to combine turbine and pump also into one unit with a view to improve the economy of pump storage development. Such machines are intended to generate power when driven in one direction and to pump in an another direction, hence it is also called Reversible turbine. A saving in cost of about 11% was possible over separate pump and separate turbine. An overall saving of 26% was possible as shown below (based on an estimated cost of units working in Poland):[58]

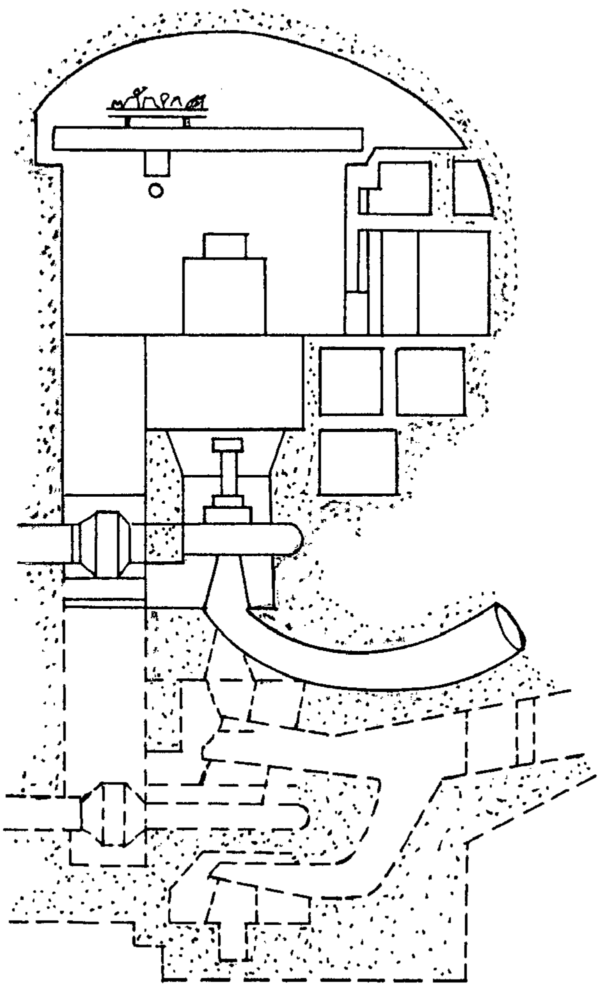


FIG. 4 - SECTION THROUGH A PUMPED-STORAGE PLANT SHOWING (IN DOTTED LINES) THE EXTRA PLANT & INCREASED CIVIL WORKS THAT WOULD HAVE BEEN NEEDED IF SEPARATE PUMPS HAD BEENINSTALLED TWO & THREE MACHINE ARRANGEMENT.

Sl. No.	Equipment and works.	Units	
		Reversible	Three machine type.
1.	Mechanical plant.	69%	90%
2.	Electrical Power plant.	22%	24%
3.	Constructional works	9%	12%
	Total	100%	126%

Figure 4 brings out the extraplant and civil works that would have been needed if separate pump and turbine had been installed.

First reversible hydraulic machine was said to be installed at the Baldencyree power station in Germany in 1931. The machine which has given trouble-free service for more than 40 years was designed and manufactured by the Swiss firm Escher-Wyss. The machine has the following characteristics. As turbine it developed 1500 H.P. under a head of 9 metre at a discharge of 15 cum. per second with an efficiency of 90%. As a pump it is capable of delivering 8 cu.m/sec against a head of almost 9 m. at an efficiency of 78% and at an input power of 1800 h.p[20]. These were followed by two larger reversible turbine pumps installed in Brazil manufactured by J.M.Voith (A German firm) and was placed in service in 1939, the other was of American Manufacturer - Allis Chalmers and was placed in service in 1940[27]. Subsequent extensive research and development work on this type of turbine by American hydraulic turbine industry have produced designs of economical machines having good performance characteristics. The development of the reversible pump

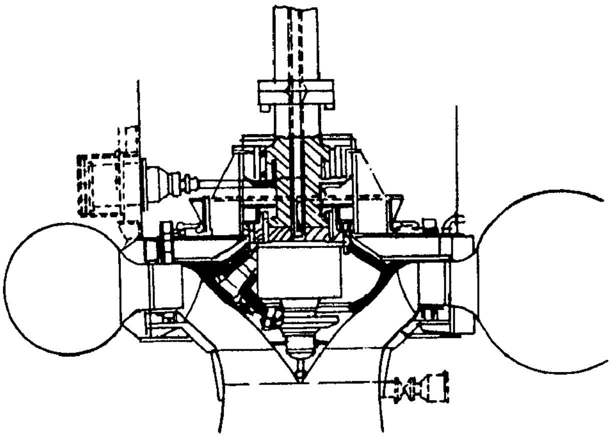


FIG. 5.- REVERSIBLE PUMP TURBINES FOR VALDECANAS, SPAIN
TURBINE OUTPUT 110,000 B.H.P. HEAD 240 FT. PUMP
INPUT 82,000 TO 100,000 B.H.P. HEAD 164 TO 238 FT.
150 R.P.M.

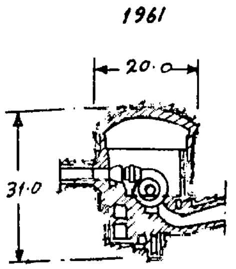
DERIAZ TYPE REVERSIBLE PUMP TURBINES WITH
CONVENTIONAL SPIRAL CASING FOR VALDECANAS,
SPAIN. COURTESY: ENGLISH ELECTRIC CO.)

turbine has greatly extended the field of economic development of pumped storage projects because of the substantial saving in the cost of hydraulic machinery etc. Later in 1950, M/S Allis Chalmers put out an efficient type of reversible unit and some of those units were installed in Flat Iron P.S.P., Colorado; Hiwassee in South Carolina. The recent tests performed by Japanese engineers have provéd the capabilities of these reversible machines as 500 metres. Table I gives some of the important Francis and reversible turbines in the world.

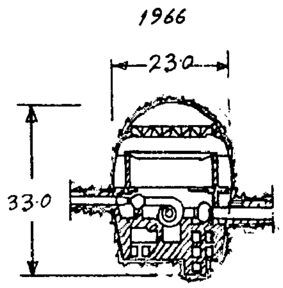
7. The pump turbine technology has further developed and for lower heads the "Deriaz Reversible pump turbine"(Fig.5) installed at the Sir Adam Beck pumped storage stations at Niagara Falls is capable of working under partial loads (i.e. partial head and partial discharge). Further they can be started as pump direct on line. Friction losses for Deriaz runners when spinning are very small as the runner blades overlap each other.[34, 35, 40]

8. However, for higher heads the main disadvantage with reversible machine is that it will run in one direction as turbine and in another opposite direction as pump. Hence constant research is being carried out to design an uni-directional reversible machine. Some of the developments in this direction are Isogyre pump turbine (Fig.9) and Hone turbine (Fig.10). They are described in the next chapter in detail.

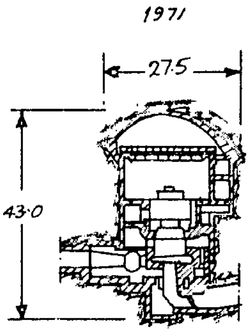
9. Alongwith the advacement in equipment for pumped storage development, the power house arran ement are also changing



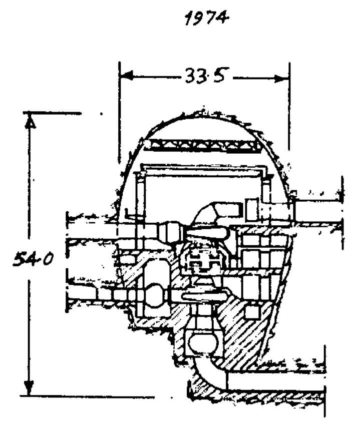
(a) Vianden I-IX Luxombourg
area = 450 m²
9 × 100 MW (F.S.) hor. 278 m.



(b) Sackingen W. germany
area = 670 m²
4 × 90 MW (F.S.) hor 400 m.



(c) Coo-Trois points Belgium
area = 760 m²
6 × 144 MW (R.T.) Ver. 270 m.



(d) Weldeck II W. Germany
area = 1390 m²
2 × 220 MW (F.S.) Ver. 329 m.

FIG. **6** - EXAMPLES OF RECENT PUMPED STORAGE CAVERNS SHOWING THE STEADILY INCREASING SPANS BEING ACHIEVED radically. From surface power station it has grown to shaft type power house. The developments are also mostly influenced by the vertical shaft settings for the two and three machine arrangement as against the conventional horizontal shaft setting adopted in the past. Each has got its own advantages and disadvantages, but as the head increases the pump requires deeper setting and that means deeper excavation and the vertical arrangement enables the lower setting of the pump machineries without much difficulty. This has favoured the development of shaft type and underground type construction for pumped storage plants. Table II gives the setting depth adopted for some of the pumped storage plant.

As there is limitation of depth even for a shaft type of arrangement the option for underground power house location gradually increased alongwith the increase in the operating head. Due to the development in the mining technology it is now easy to construct an underground pumped storage station of greater spans. Fig. 6 shows the growth of underground power house caverns adopted for pumped storage plants. Further it has the following advantages.[49]

i) The greatest flexibility in locating the power house so that the water conductor system is the shortest.

ii) Underground locations exclude disturbance of slope stability which is probable when running penstocks along the ground particularly on steep slopes and bad geologic condition if prevailing.

iii) Reduces costly conduit installations to a minimum when operating at a high head. Such underground conduit system to the underground power house improves the operating conditions of the pumped storage station by reducing the hydraulic losses and providing better conditions for machine regulation. Further such arrangement saves a large amount of steel required for penstock and tunnel lining and thereby lowers the capital investment.

iv) On account of difficult operating conditions of unit in turbine mode vibrations may occur in the penstocks which cannot be foreseen. The underground version completely excludes such vibrations.

v) Construction of the underground station is independent of climatic conditions and can proceed at the same rate throughout the year, which shortens the construction time particularly in a region with a severe climate.

10. By 1990, in all those highly developed countries like U.S.A., Japan, U.K., and West Germany about 20% of all generating capacities will consist of flexible electrical plants. These creates conditions for reliable and economical development of power systems.

Table III gives some of the important pumped storage stations in the world.

CHAPTER III

CURRENT DEVELOPMENT TRENDS

1. Fast increasing development of electrical energy from conventional fuels or nuclear sources has greatly widened the scope of hydro-electric power potential by pumped storage for supplementation of generation during peak period even in those regions where there are practically no hydro power sources.

Nuclear units in common with larger conventional thermal units can be used most efficiently under conditions of continuous operation. Off-peak power from such units can be used to operate pump-turbines as described earlier and the hydro power derived from the same units in the reversible operation becomes available for use during periods of peak demand. Examples of such stations are given below.

U.K. i) The 300 M.W. Foyers pumped storage station operates in conjunction with 1200 M.W.Hunterstan 'B' nuclear power station.(25)

ii) The 360 M.W. Ffestinoig pumped storage station built in conjunction with nearby Trawsfynydd nuclear station.(24)

U.S.A. The Keowee Toxaway power system brings together hydro-electric, reversible pumped storage and nuclear thermal systems in a unique combination. It has the world's largest nuclear station i.e. Oconee nuclear station of capacity 2658 M.W. for supplying base load.(38)

2. The above trend of operating pumped storage stations with the development of larger thermal and nuclear units and fapid growth in the interconnection of utility system has resulted in the installation of larger capacity for pumped storage stations and consequent lower costs per kilowatt. In Germany, the recently constructed pumped storage plants with high capacity and larger units prove that good results for solving the peaking problem at the lowest cost per kilowatt and highest efficiency is possible. Therefore the planning for pumped storage project development for the solution of future power problems should be imaginative by undertaking large capacity units in conjunction with large capacity thermal and nuclear units, as they offer better prospects technically and economically.[29] The trends towards larger capacity pumped storage development is borne out by the following statements[82];

In 1950, the largest pumped storage installation was 45 M.W. but by 1960 the largest pumped storage installation was 225 M.W. and by 1970 the largest pumped storage installation was 1000 M.W. in operation and 3000 M.W. being planned.

Some of the large pumped storage plants now under construction throughout the world is listed below. Most of them are of reversible type.[41]

Sl. No.	Name of the station.	Country.	Station capacity (M.W)
1.	Northfield P.S.P.	U.S.A.	1000
2.	Blenheim P.S.P.	U.S.A.	1000
3.	Lago Delio P.S.P.	Italy	1040
4.	Sintoyone P.S.P.	Japan	1150
5.	Tumut- II P.S.P.	Australia	1500
6.	Castaic P.S.P.	U.S.A.	1500
7.	Ludington P.S.P.	U.S.A.	2000

Capacity of individual unit is also increasing and some instances are listed below:

Sl. No.	Name of the station.	Country	Head utilised (m)	Unit capacity of each machine(M.W)
1.	Taum Sauk P.S.P.	U.S.A.	263	204
2.	Numappara P.S.P.	Japan	478	230
3.	Kisenyama P.S.P.	Japan	220	240
4.	Ludington P.S.P.	U.S.A.	110	343
5.	Racoon Mountain P.S.P.	U.S.A.	317	382

All of them are of reversible turbine type.

has pointed out that though the pumping efficiency increases with specific speed upto a certain limit ie.,2750, the purpose of reduction in cost will not be achieved as higher speed will effect the cavitation factor 'σ' (sigma) which will increase exponentially with "Ns", and also may necessitate stronger members for guide and stay vanes.

4. Owing to the demand for larger machine sets with the highest possible speed, power houses have been arranged lower and lower below the water level of the lower reservoir in order to give high intake pressures. In the case of Erzhausen pumped storage plant, west Germany, this led to the design of a closed frame work structure which was given an earthfill to improve the stability. Hence it can be classified as an underground power plant constructed in an open pit. At Ronkhausen the new shaft type of construction was employed. Here the two machines are accommodated in a circular shaft of 30 m. diameter. Other examples are Vianden II, Luxambourg, Foyers pumped storage plant in U.K.

5. However underground layout significantly mitigates the problem of deeper setting accompanying the high specific speeds. A better understanding of rock mechanics now permits the excavation of large cavities in relatively inadequate rocks. The provision of suitable anchoring allows the rock itself to be used as a supporting arch e.g. one of the largest underground electric plant in the U.S.A. as well as the world's largest pure pumped storage plant is 1000 M.W. - Northfield Mountain

3. In view of such large capacity units the cost of machine as well as powerhouse and other civil works increases. The size and cost of the rotating machinery and the powerhouse can be reduced by increasing the specific speed. Improvement in cavitation performance is considered to be the key to achieve further increase in rotational speed. Hence the recent trends have been towards high specific speed for a given application to take advantage of cost reduction associated with reduced machine size.

One method of describing the relationship between rated heads and specific speeds for hydraulic machine is a factor 'K' called $K = NsH^{0.5}$. This factor has been used for sometime in the hydraulic turbine industry with 'Ns' defined as turbine specific speed.[61]

In 1950's the francis turbines for projects in U.S.A. were being built with a 'K' value of about 1330 (metric units) as general practice. This number resulted from an emphorical tabulation of units in operation that had shown little tendency to cavitate. The current design practice is to select francis turbine and pump turbine speed between 'K' values of 1680 and 2530, depending on the project characteristics. In these cases additional submergence of the units is necessary. In this connection a paper entitled "Selection of Reversible Pump Turbine specific speeds" by W.G.Whippen (Allis Chalmers,U.S.A) presented in the I.A.H.R. Sixth Symposium held in Rome in September 1972 is worth noting[1]. In this paper the author has pointed out that though the pumping efficiency increases with specific speed upto a certain limit ie.,2750, the purpose of reduction in cost will not be achieved as higher speed will effect the cavitation factor 'σ' (sigma) which will increase exponentially with "Ns", and also may necessitate stronger members for guide and stay vanes.

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unit recently constructed in Massachusetts. The underground powerhouse is of size 100 m x 21 m x 47 m high and is unlined with merely shortcrete on a wire mesh for the roof arch(63).

In addition to the freedom of selection of hydraulic machines and the possibility of obtaining the necessary depth relative to the lowest level in the lower pool an underground power house has lot of other advantages as described earlier.

Some of the large underground pumped storage plants in the world under operation, under construction and under planning are listed below.

Sl No.	Name of station and head developed.	Country	Station capacity (M.W)	Size of the cavern (m)	Remarks
1.	Vianden-I(278 m)	Luxembourg	9x100 = 900	330x17x30	1964
2.	Shintoyne(230 m)	Japan	5x230 = 1150	140x2[illegible]x46	1973
3.	Lago Delio(732m)	Italy	8x125 = 1000	196x21x58	1972
4.	Northfield (250 m)	U.S.A.	4x250 = 1000	100x21x47	1972
5.	Bear Swamp (235 m)	U.S.A.	2x300 = 600	69x25x47	Under construction.
6.	Racoon Mountain (317 m)	U.S.A.	4x382 = 1528		"
7.	Cornwall(354 m)	U.S.A.	8x250 = 2000		"

If the statement is closely studied it will be found that the size of cavern is not increasing or decreasing with reference to generating capacity. The reason is this, in the first example for the Vianden I, as it was constructed in 1964 when the confidence in reversible machine was not much, three machine unit with conventional horizontal setting was adopted. Therefore for nine units and the three machine arrangement has made the cavern unduly long though the height and the width is reduced. For lago Delio P.S.S. since vertical arrangement was adopted the cavern length is reduced to two thirds. The depth is however, more because it is a high head three machine unit with vertical arrangement. However, by having large capacity unit, which also reduces the number of units for the same installed capacity, with vertical, two machine arrangement the size of the cavern will reduce considerably. For example Northfield pumped storage plant with 4x250 M.W. (1000 MW) has only one third of the length for the Vianden I power house. Hence the latest trend is to adopt larger capacity reversible units in vertical arrangement to reduce the overall cost of the pumped storage plant as well as to have the minimum cubic capacity per kilowatt of installed capacity.

6. It follows from the previous paras that the increased cost of a surface power house because of deep submergence tends to swing the economic choice between above and below ground installations towards the underground type.

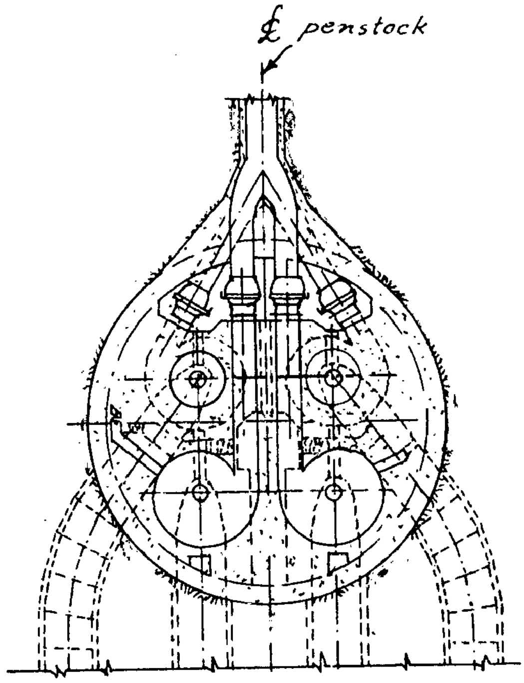


FIG.7 - PLAN AT THE CENTRELINE OF THE DISTRIBUTORS
CLUSTER LAYOUT

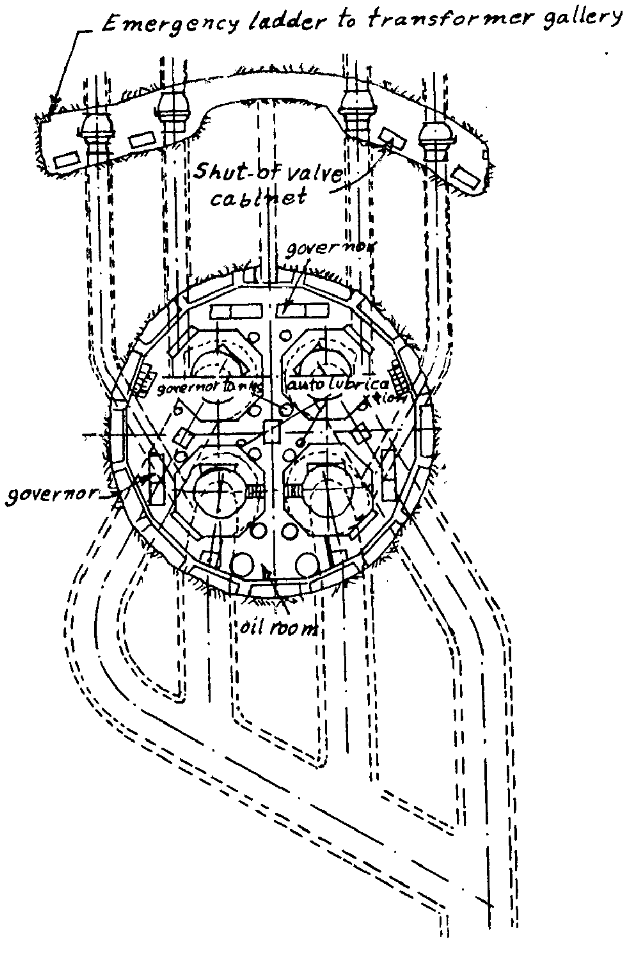


FIG. 8 - CLUSTER LAYOUT ALTERNATIVE

However where geological conditions are not favourable for an underground powerhouse, a pumped storage project is encumbered with the high cost of a surface type powerhouse. Under the above circumstances a new concept in the power house layout named as "The cluster layout" described by Mr. J.G. Patrick in an article entitled "The cluster Layout - a new concept for pumped storage", is worth studying.

The cluster layout is based on grouping the units together rather than placing them in line as in the conventional power station arrangement. The grouping of units permits a new approach to the design of a power house structure.(80)

a) Surface Application

The installation of a generating unit in a shaft or pit is already explainedin the case of Vianden and Ronkhausen plant in Europe. However, in this layout installation of a number of units in a single circular shaft described in the article offers significant advantages over conventional layouts. The Fig. 7 shows the plan of a cluster type power house, housing four reversible units with a total generating capacity of 1000 M.W. at 1000 ft. head.

The power house structure itself is formed by a circular excavation, which is concrete lined and provided with floors to house the required electrical and mechanical equipments. So the entire structure is below ground level near the shore line of the lower reservoir, the visual impact of the power house on the landscape is substantially less than that of a conventional surface type powerhouse. The only features visible are the top deck, the gantry crane and the transformers.

Further advantages of the concrete shell construction for this type of layout are:

1) Minimum cracking and hence practically no leakage
2) has smaller volume and consequently less uplift
3) can be located further into the hill side thereby reducing the power tunnel length.

A feasibflity study madd by the author showed that a specific construction cost saving of approximately $ 4.75 million (This comprises $ 2.85 Million saving in power house cost plus $ 1.9 million reduction in the cost of steel lined power tunnel), could be achieved by the adoption of cluster layout instead of a surface power house of same capacity i.e. 1000 M.W. and 1000 ft head.

b) <u>Underground Application</u>

The apparent structural and economic advantages of the cluster type surface power house (i.e. in a deep shaft) has led to the consideration of the concept in an underground location against the conventional underground powerhouse of a long, straight sided chamber with an arch roof.

An underground cluster power house (fig. 8) containing four units would be a cylinderical shaped chamber with a domed roof, an inherently more efficient shape for an underground cavity from the stand point of space utilisation and structural strength. In effect the cluster arrangement minimises the size of the cavity and results in a shape better adopted to withstand the rock stress. The orientation of the cluster concept with its circular cavity and domed roof is influenced less by rock jointing thereby always permitting an in line arrangement of the water conduits and consequently minimum total conduit length.

A comparison was made of the rock stresses which could be expected to occur around the excavated chamber for the conventional power house and the cluster power house. For the case of equal vertical and horizontal initial stress in the rock, for the conventional power house the maximum compression was computed to be 16,800 lbs/sq.in. and for the cluster power house it was10,600 lbs/sq.in. The magnitude of stress along the walls and around the roof is also substantially less for the cluster layout.

7. Development of Pump-turbine machineries

Development of reversible turbine-pump units has been responsible for the current fillip in pumped storage development since it has greatly improved the economics of such development. Present day development is mostly confined to the range of such units. Therefore attention throughout the world is concentrated on more and more advancement in this type of equipment with a view to cover greater range both in respect of head and unit capacity and also to improve efficiency to the maximum.

Tests are being successfully performed in Japan on a 230 M.W. unit with a head of 500 m employing a single stage pump.

Theoretical investigations have already been carried out into pumped storage at higher heads. In order to reduce the submergence it becomes necessary at high heads to employ multi-stage pump turbines with fixed or adjustable guide vanes. As per the article in Escher Wyss news(36), it is found that two stage pumpe turbine with adjustable guide vane is advantageous, since in a pump turbine with fixed guide vane it can be operated at one point at a particular head, whilst a machine with adjustable guide vane in both stages can operate over a wide range at good efficiencies.

In addition to the limitation of head for francis as well as reversible turbine (which no doubt will improve in coming years) they have certain other problems also. For example the point of maximum efficiency for turbine and for pump do not coincide but occur at different speeds or alternatively at given speed different runners are required for the same maximum efficiency for pump and turbine. This alternative was achieved in "Tominaga Pumped Storage Scheme" (Japan) runner by use of an auxiliary runner housed within the body of the main runner and carrying extensions to the runner blades. For pump running the auxiliary runner is moved downwards by an oil servomotor so that the extension register with the main blades, this being equivalent to increasing the diameter of the runner. For turbine operation the auxiliary runner is raised so that the blade extensions are withdrawn.(68)

Another problem with reversible pump turbine is the change over from pumping to turbine operation means a change in the direction of rotation. This does not, however, result in serious delays since the stream of water changes its direction of flow very quickly when pump is shut down and then drives the machine set. For Rodund II (Austria) pumped storage scheme to be commissioned in 1975 as per the designs and tests carried out the reversible unit picks up full load generation from full load pumping in 80 seconds.

The process of reversing is more complicated for change-over turbine operation to pumping. For this it is necessary to brake the machine set to stand still and re-start it. The total change over time is approximately 500 seconds i.e. 8 minutes a condition which means the load cannot be taken instantaneously. However, for some unit at Austria the changeover time from full turbine load to full pump load is only 250 seconds i.e. 4 minutes.

To overcome this problem a new type of pump turbine called Isogyre pump turbine has been developed by Charmilles, Swiss [33]. Currently one set of 10 M.W. has been erected and is under operation in Robiei pumped storage plant Switzerland. It uses a head of 400 m, and the cost is only slightly higher than a reversible unit. They have also another order for 55 M.W. for 475 m head, speed 1000 R.P.M. for Handeck III power station, Switzerland. Hone turbine is also being developed for solving the same problem.

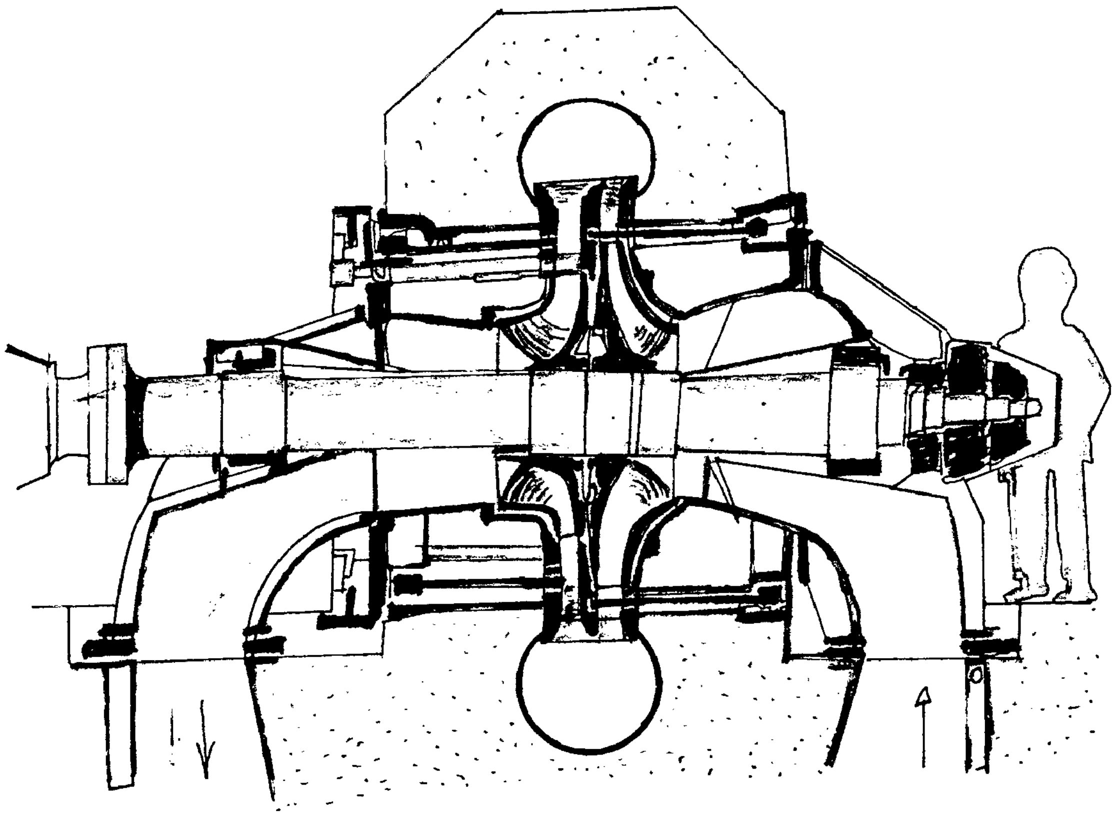


FIG. 9.- SECTION THROUGH CHARMILLES ISOGYRE PUMP TURBINE

a) Isogyre Pump Turbine (Fig.9)

The isogyre pump turbine has this in common with the conentional reversible pump turbine that it fulfills both purposes i.e. the same operates both as pump and as turbine, but apart from this it has very little else in common with the reversible pump turbine.(33)

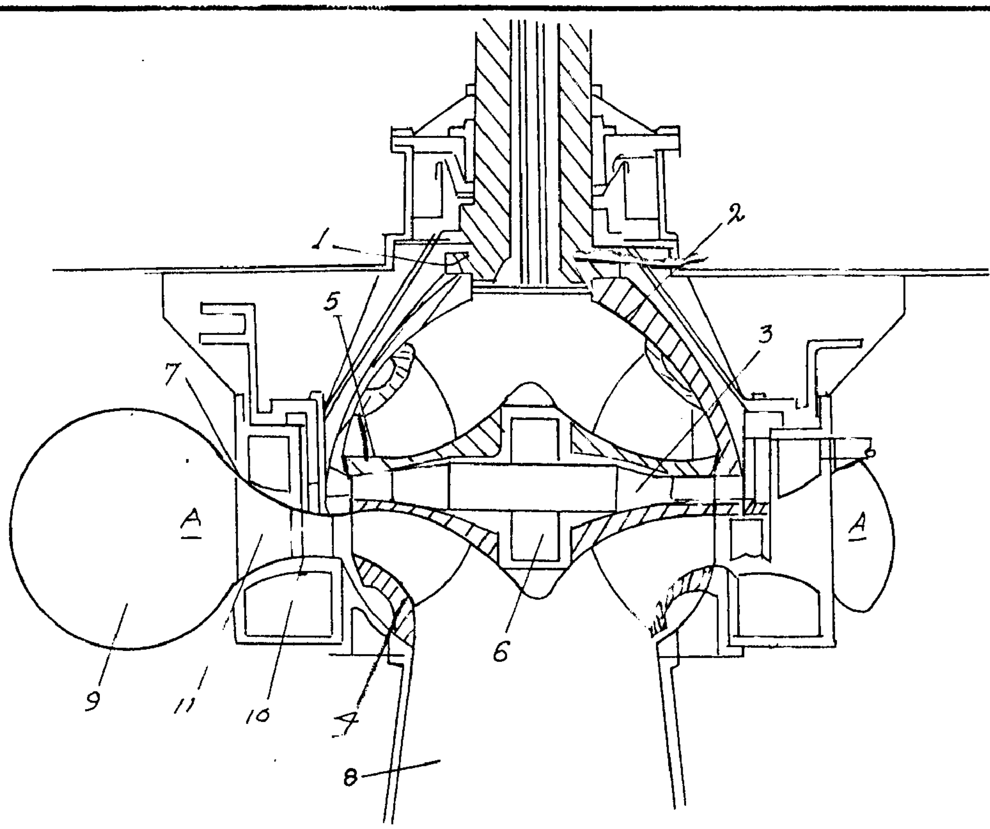
An outstanding feature of the isogyre pump turbine is that the direction of rotation of the machine remains the same whether it operates as a pump or as a turbine hence the name isogyre. The switch over from the pump operation to turbine operation and vice versa is consequently obtained with the maximum ease, and in the minimum of time. On a working model of this tested in Charmilles Laboratory, Geneva, it takes approximately 30 seconds to changeover from full load turbine operation to full load pump operation and vice versa. And it is felt even in regular machine it should not take more than between one and three minutes. Another important feature of the Isogyre pump turbine is that no special provision need be made to start up the unit as a pump since the machine is invariably run upto speed as a turbine and synchornised with the supply system and then changed over to pump operation.

The isogyre pump turbine comprises basically an independent turbine runner, an independent pump impeller arranged side by side on the same shaft in the centre of a spiral casing common to both runner and impeller. Around the turbine runner is arranged a conventional movable guide vanes, distributor and a stay ring, whereas around the pump impeller is arranged a conventional diffuser (guide wheel) with stationary vanes. The machine is moreover provided with two sleeve valves one of which is located on the turbine end between the runner and the spiral casing and the other on the pump end between the impeller and the spiral casing. These valves operate independently of each other and serve to isolate and unwater the impeller when the machine operates as a turbine or inversely to isolate and unwater the runner when the machine operates as a pump.[33]

These design peculiarities conduce to the following distinctive features:

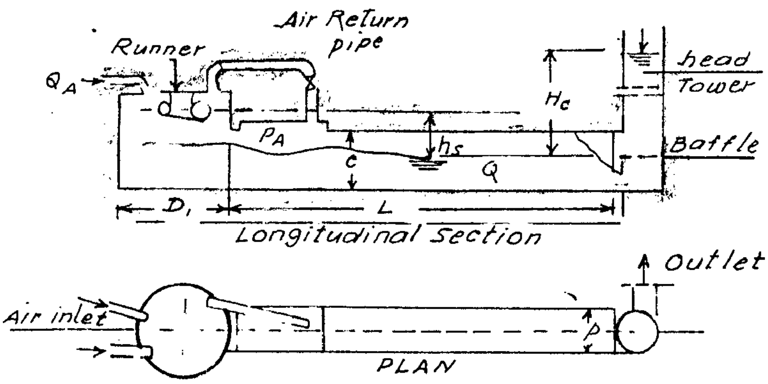
i) Since the turbine runner is completely independent of the pump impeller each is designed to comply exactly with the conditions required of it, not only as regards the operating heads (which are generally not the same on account of friction losses in the pipe lines) but also as regards the output end and the rate of flow; there is no necessity to compromise between pump efficiency and turbine efficiency, as in the case of reversible machine with a single runner and therefore maximum efficiency is obtainable for both the modes of operation.

ii) The fact that the turbine discharge is not bound to the pump discharge can improve considerably the overall economy of a scheme, especially when the pumping periods are longer than the generating periods as is frequently the case.



1. Main Shaft 2. Driving Chamber 3. Shaft
4. Runner 5. Impeller 6. Rotating Servomotor
7. Speed Ring 8. Draft Tube 9. Spiral casing
10. Guide vanes 11. Blades

FIG. 10 - HONE TYPE REVERSIBLE TURBINE.



BACK PRESSURE ORERATION OF PELTON TURBINE
EXPERIMENTAL ARRANGEMENT OUTLINE.

FIG. 11.

iii) As the turbine end is provided with a conventional adjustable guide vane apparatus, automatic load, speed and load regulation is obtainable as with any conventional turbine while the unit is generating power, whence improved efficiency at partial load and a reduction of the wear of the runner due to cavitation are secured. On the pump end the diffuser is provided with stationary vanes and the danger of excessive vibration during pump operation is thereby obviated.

b) Hone Turbine (Fig.10)

In the I.A.H.R. sixth symposium held at Rome in September 1972[1] the development of Hone turbine which were results of researches carried out by the renowned turbine designers Prof. Miroslav Nechleba and Ing.V.Hosnedle (Hosnedle Nechleba Patent) was discussed. An experimental Hone type pump turbine unit will be installed by 1977, in the pumped storage power station at Porazska Pothradi in Czechoslovakia for a head of 150 m and an output of 30 M.W.[1]

The development of this turbine was also same as that of Isogyre turbines to overcome the problem of two directions in the reversible turbine mentioned earlier.

The Hone turbine has its main shaft flange connected to a semi-spherical driving chamber having a conjoint runner and impeller mounted on a shaft passing across the driving chamber. The runner and impeller set can be rotated about the shaft by a servo motor to bring either the runner or impeller opposite

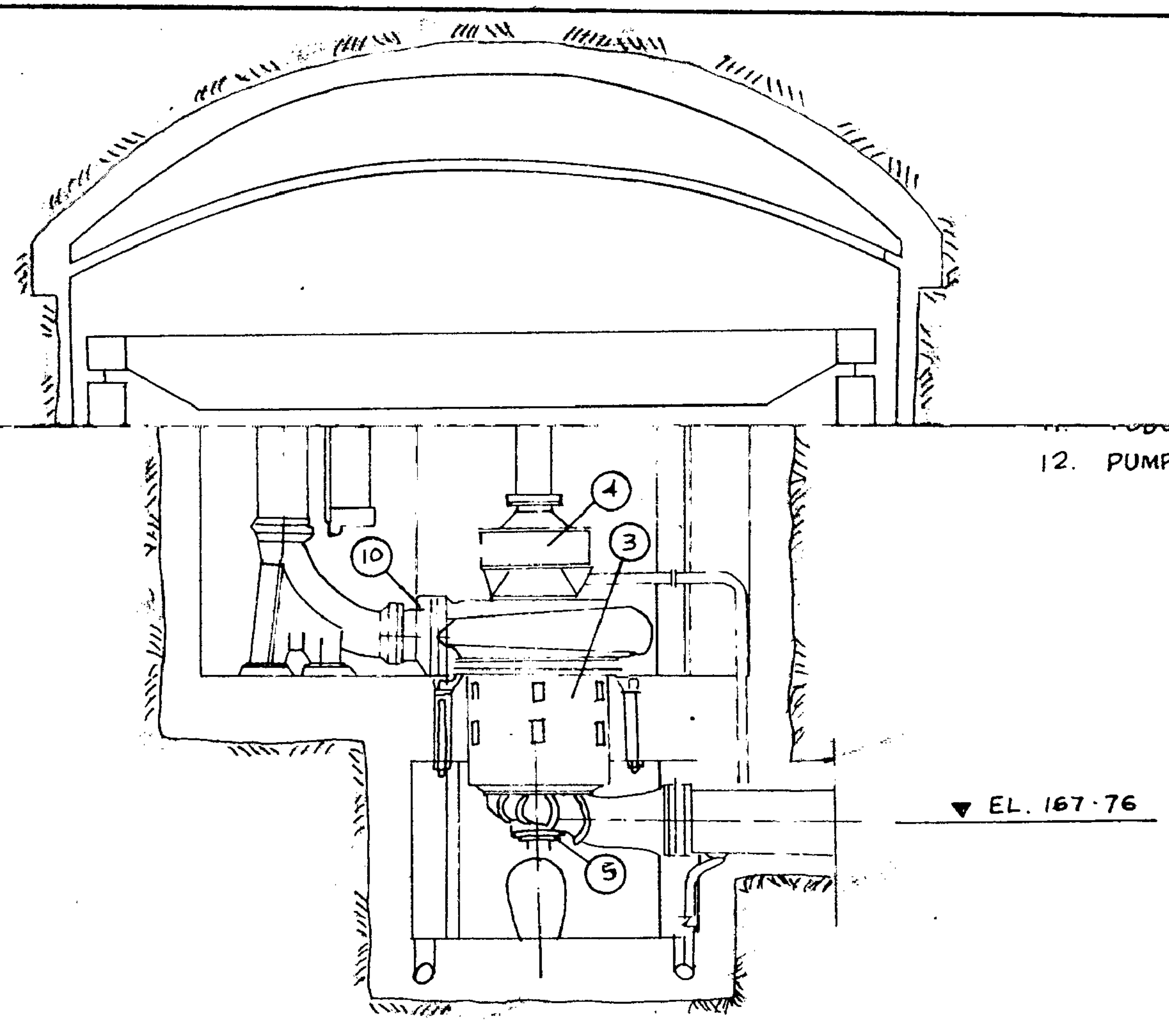
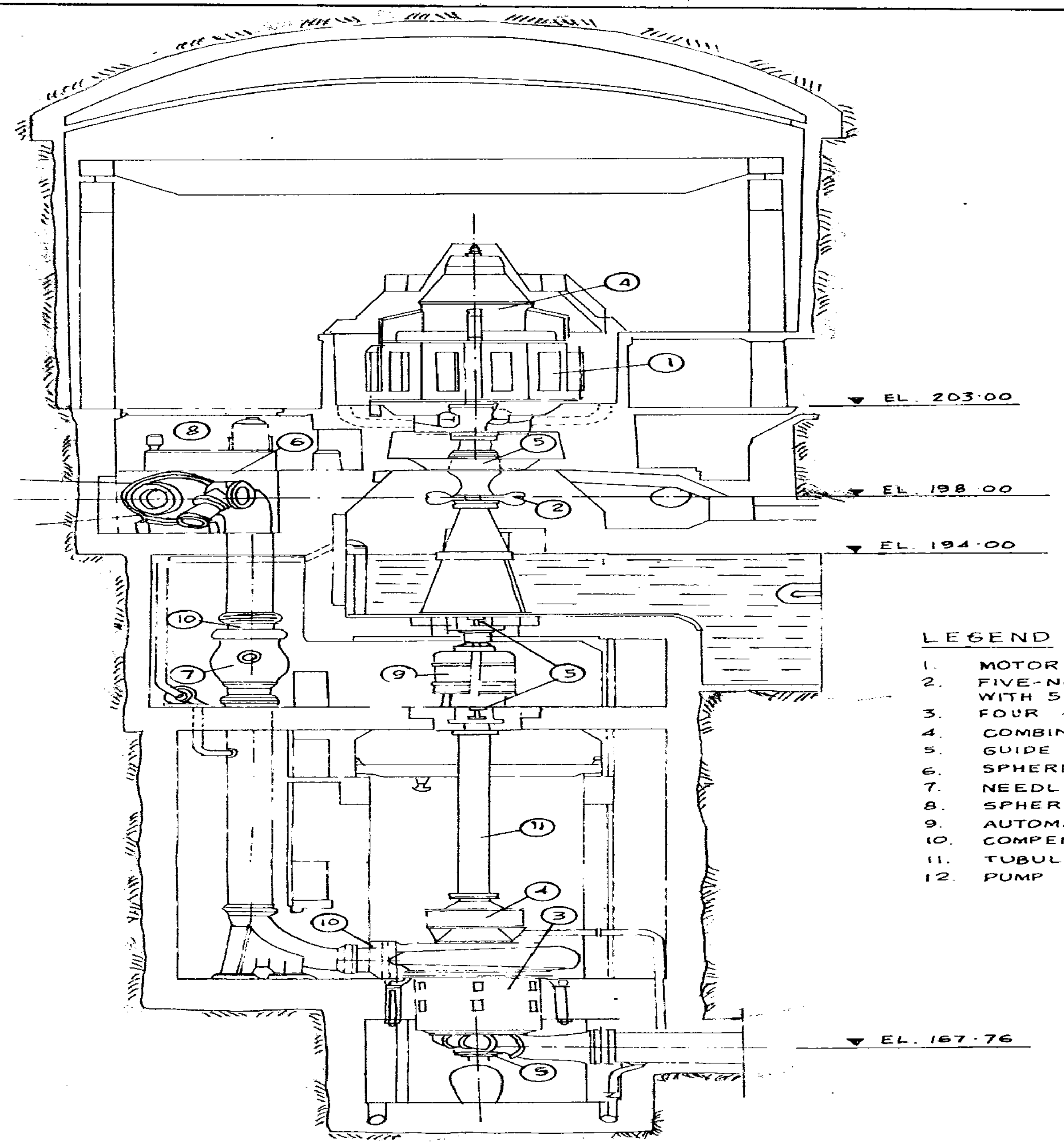


FIG. 12.- VERTICAL CROSS-SECTION LAGO DELIO PUMPED STORAGE POWER STATION



LEGEND

1. MOTOR GENERATOR
2. FIVE-NOZZLE PELTON TURBINE WITH 5 BREAKING JETS.
3. FOUR -STAGE PUMP
4. COMBINED THRUST & GUIDE BEARING
5. GUIDE BEARING.
6. SPHERICAL VALVE, 1400 MM Ø.
7. NEEDLE VALVE, 1200 MM Ø
8. SPHERICAL VALVE, 1200 MM Ø.
9. AUTOMATIC TOOTH COUPLING.
10. COMPENSATION JOINT.
11. TUBULAR SHAFT.
12. PUMP SERVICE CRANE.

FIG. 12.- VERTICAL CROSS-SECTION LAGO DELIO PUMPED STORAGE POWER STATION

to the distributor, while the other is hidden in the driving chamber. Guide vanes a e of the swing through types. All other parts of the machine, the speed ring with its reinforcing blades, draft tube, spiral casing are of standard design and perform the same function as with the conventional machines.

c) Improvement for the high head operation of pumped storage plant

It is well known in the case of vertical pumped storage units using separate pelton turbine and multi-stage pumps (Terinary units) for very high heads exceeding 500 m, the overall length of combined turbine and pump shafts is generally very large. This is due to the fact that while the Pelton runner has to be installed above the maximum tailwater level, the pump impellers have to be installed much below the minimum tail water level for safety against cavitation. For example the shaft length of the ternary units at Lago Delio(Fig.12) and St.Fiorino, Italy have lengths of the order of 40-50 metres. With a view to avoid the excessive shaft lengths with consequent increases in cost of machinery and civil works as well as accompanying operational difficulties like vibrations etc and extra maintenance, "Back Pressure Operation for Pelton Turbine" (Fig. 11), has been experimented for enabling the Pelton wheel to be installed below the tailwater level with a reduced shaft length. Compressed air in the runner housing depresses the water level low enough so that it will not disturb the turbine efficiency.

A few straight generation plants of this type have been in existence, working under back pressure in exceptional conditions of level in the downstream of Lago Delio and St. Fiorano for brief periods under relatively small tailwater depth. In a paper presented in the I.A.H.R. symposium held at Rome in 1972 by Mr. Oresto Ceravolo of "ASGEN-F-TOSI" Italy and others it was concluded from the experimental studies carried out by him that the possibility of safe and trouble-free operation of ternary units under back pressure was realisable without any significant effect on efficiency. The value of air consumption obtained from model tests are stepped upto the prototype keeping in view the uncertainty of scale effect in the air water flow. One problem is of designing the runner housing structure to withstand high internal pressure especially during transients. It is expected that back pressure operation of ternary units will help to eliminate long shaft lengths required otherwise, in the future high head installations.

8. Further modifications and minor improvements

A. Pump-turbine

a) In a paper presented by Mr. P.Schipitales (Austria) in the Rome Symposium he has concluded from certain studies made by him that efficiency of reversible machine can be improved substantially by a slight change in the shape of the leading and trailing edges of the runner blades.

b) Advances in mechanical design features towards maximising unit reliability are best typified by the changes in wicket gate linkage reflected in the most recent pump turbines being designed for installations in the U.S.A.[61]

Fourteen pump turbines currently in design provides for individual gate servo motor instead of the traditional gate lever /shear pin link design with a massive gate operating ring and two large motors. Advantages are

i) Individual gate control is possible

ii) Eccentric pins or adjusting links are not required

iii) Since each servo motor is designed for a pre-determined force there is no risk of gate mechanism being over loaded in the event of gate becoming jammed.

c) As it is becoming increasingly difficult to obtain sound castings of large weights at reasonable prices and within the desired delivery time, the technique now adopted for the manufacture of turbine components by forgings and plate steel instead of steel castings as it is now possible through automated and very efficient welding process.[61]

d) In reversible machines, the thrust and guide bearings have to be designed for both directions of rotation particularly during pumping, to reduce the starting load on the motor, the thrust bearing is jacked with high pressure oil to reduce the surface friction.

From the tests conducted in the laboratory and subsequently in the site, the phenomenon of oil film formation, mechanical and thermal distortions of the pads, and temperatures during starting, steady operation and stopping were observed and measured. Tests confirmed the critical conditions of the lubrications occuring during the starting and stopping.

And to withstand the conditions during the starting and stopping oil injection system on the thrust bearings were recommended.

e) High head and high speed francis type reversible pump turbines have brought new and severe conditions of seal service, requiring in addition capacity to withstand and retain high air pressure during spinning or pump starting (in the draft tube depressed condition).[1]

Seal operation difficulty particularly air loss was experienced in the Cruchan Pumped storage plant machines in Scotland. Complete failure was reported after 8000 hours of operation.

Mr. T.R.Millar (U.K.) in his paper presented in the Rome symposium has reported the development of a new axial design seal using continuous, unbroken angled faces with face load adjusting springs relative to hydraulic force, which overcomes these problems of circumferential seals and has proved superior to the conventional design. The improved seals are expected to prove satisfactory on the Cruchan power house units and an optimistic estimate of the life of seal before a replacement is as high as 24,000 hours.

f) The development of machineries for a head of 900 m have confirmed that the use of multi-stage reversible turbine pumps reduces the cost considerably. Alternative suggestions discussed in the Rome symposium was to use one reversible machine in series with a single stage pumps. In turbine operation only the reversible machine will function while pumping operation will be performed by both machine in series.[1]

It was also decided in the symposium that while evaluating the operation of hydraulic machines in transient regimes special attention is to be given to resonant phenomenon in pressure conduits which if not taken into account can result in a considerable under estimation of the design loads.

B. Generator-Motor

a) For generator-motor a system study performed by the T.V.A. determined that a unit with a lower then normal inertia constant and with a suitable reactance could be used. Cost studies based on these parameters led to the selection of a unit with direct water cooling in the stator coils and in the rotor winding.[61]

When a study was made for a particular machine with direct water cooling versus air cooled unit it was found efficiency is increased considerably and the direct cooling,has resulted in a considerably lower and more uniform temperature distribution in the machine parts less thermal expansion of the stator winding resulting in larger insulation life and most importantly a reduction in size and weight. The direct cooling method is adopted for Racoon Mountain's 382 M.W. generator-motor and this has resulted in a considerably smaller size machine with resultant economy alround.

Obviously the reliability of the cooling water system is of particular importance and therefore all circulating pumps and heat exchangers are duplicated.

b) Because of reversible features of the pumped storage units, the ventilations must be positive in either direction of rotation. Instead of radial fans which were used formerly were not sufficient at present separate blowers are being considered not only to provide positive ventilation but also to reduce windage loss of the machine. This is adopted for the Fairfield pumped storage plant (496 M.W.) of U.S.A.(61)

c) In pumped storage scheme using reversible machines optimum hydraulic efficiency is obtained when for the same head, the speed of the pump is made about 20% higher than that of the turbine. This is possible if suitable pole changing synchronous machine is employed. Compared with that of a machine having only one speed pole changing synchronous machine are very interesting in the event that the pump or turbine head is liable to vary, apart from the fact that the full pressure head range can often not be utilised with a single speed for hydraulic reasons.(cavitation) It is possible with two speeds to achieve an increase of 2.6% in the hydraulic efficiency.(2) At Ova Spin pumped storage station-Switzerland (where the variation in head is between 205 m to 70 m) this type has been in use since 1968. Such types of machines are ordered for the following pumped storage plants also:

i) Jukla Pumped storage scheme - Norway (40 MW)

ii) Malta Oberstuffe-Austria (variation in head 198 m to 63 m)

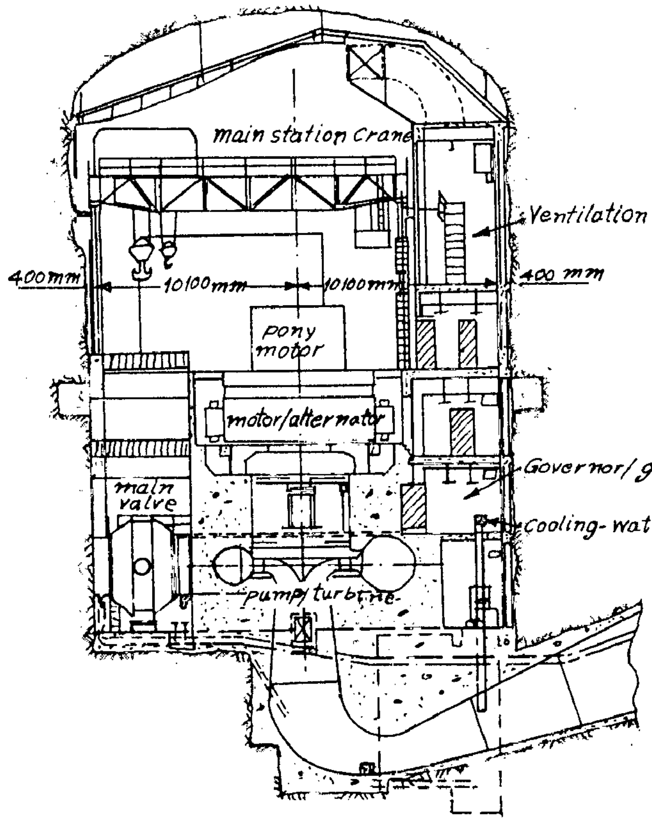


FIG. 13 - A CROSS SECTION THROUGH ONE OF THE REVERSIBLE SETS IN THE POWERHOUSE VERTICAL ARRANGEMENT WITH PONY MOTOR

CAMLOUGH P. S. S. (U. K.)

9. Recent Trends in the Different starting Methods of pump-turbine machineries

Different starting methods in vogue are as follows:

i) Starting with a pony motor

ii) Starting with an auxiliary turbine

iii) Back to back starting by another set

iv) Asyncronous starting with reduced or full voltage[2]

The first two methods were adopted in the earlier version of reversible machines. The pony motor starting is used to reduce the opposing torque when the machine is started in the pumping mode with water blown down by compressed air. The capacity of the pony motor is about 5 to 10% of main machine. For Cruchan pumped storage plant, U.K[77] the pony motor is a 3.3 KV slip ring induction machine wound for a synchronous speed of 600 R.P.M. and is controlled by a liquid starter. It can bring the 100 M.W. set upto speed in less than 5 minutes. To start a set for generating it takes 2 minutes, whereas for the pumping mode it takes about 8½ minutes as it involves additional operations like blowing down the water in the pump turbine, starting the pony motor, priming the turbine, opening and locking the guide vanes etc. The 230 M.W.(i.e. 2 x 115) Camlough pumped storage scheme, U.K. now under construction has been designed for pony motor starting only. Fig. 18 shows the Camlough underground power station with pony motor arrangement. Though this method of starting is now considered outmoded still it is being used in some countries because of its simplicity. However, in U.S.A., Germany this method is now not adopted as it involves additional cost for the pony motor and also will not be able to cope up the emergencies, particularly for the larger capacity machines now under development and operation. For the same reason the second method of starting is not generally adopted.

The current trend is to adopt the back to back starting, asynchronous starting and static frequency convertor method of starting.

iii) Back to back starting

This is possible when there are more than one unit in the pumped storage plant as one will drive the other and then that unit which drives will also work. In Ludington pumped storage plant, U.S.A. (6 x 312 MW) there are six units[19]. In this the above method of starting is adopted. Unit No.1 and 6 will serve as driving units. Unit I will start unit 2 and 3 and unit 6 will start unit 4 and 5 for pumping mode as 1 and 6 will generate power for rotating the others as pumps. After that 1 and 6 will start pumping by means of the pony motor equipped on the top of them. Estimated time to get all the six units to pumping mode from standstill is 43 minutes.

This method is also adopted for Kadamparai pumped storage scheme, Tamilnadu,India (4 x 100 MW), however instead of pony motors it will have static frequency convertor for starting the driving unit.

iv) Asynchronous starting

The recently commissioned Vianden II pumped storage plant of Luxembourg with a capacity of 1x230 MVA (reversible unit) is at present one of the largest units to be started asynchronously.[2] The outstanding advantage of this type of starting is not only its simplicity but also its economy, particularly very suitable for when fast starting is required. The starting energy which during asynchronous acceleration is converted into heat in the rotor is considerably less with partial frequency starting than with normal asynchronous starting. Consequently the problem of thermal stress on the rotor is vertually eliminated.

Static Frequency Starting

The use of static starting system for multiple pumped storage unit is a new application. The first such systems is adopted for the Racoon Mountain pumped storage plant (4x382 MW) U.S.A.[61], where it will be used to start individually the four generator motors. The static device will also be used to brake the units to zero speed on shutdown.

For Kadamparai pumped storage in Tamilnadu the static frequency starting will be used as a second mode of starting the pump in addition to the back to back starting. The equipment is being manufactured by Brown Boveri, Switzerland.

With the increased acceptance of pump starting methods other than pony motor starting and the use of static excitation systems instead of the traditional rotating exciters, a much more compact unit design has now been developed.

Further the needfor the upper guide bearings on pumped turbines was frequently dictated by pony motors mounted above the generator motors, [illegible] above the starting motor, and the permanent magnet generators located on the top. All these will increase the size and cost of the machine.[61]

The advance to-date in pump-turbine and generator motor arrangement is perhaps best typified by a comparison between the 220 M.W. units that have been in operation at Taum Sauk, U.S.A, since 1964 and the 400 M.W.units currently being installed at Racoon Mountain in 1975. Though the hydraulic machines appear very similar, the generator-motor assemblies differ significantly.[61]

In future it is expected that public utilities will adopt very close coupled pump turbine and generator motor with the thrust bearing supported on the head cover. Thus by bringing the electrical machine as close to the hydraulic machine as possible through the use of one piece shaft has been found more economical than using traditional arrangement.

Thus after a review of pumped storage technology for the past 20 years it can be said with assurance that there is no longer significant differences in the efficiencies between separate pump and turbine design and reversible pump turbines.[61]

CHAPTER IV

PUMPED STORAGE DEVELOPMENT IN SOME ADVANCED COUNTRIES

1. A brief study of the pumped storage development in some advanced countries will be quite informative as to how this type of energy development has figured in their progress.

1) U.S.A.

2. It is well known that amongst the highly industrialised countries in the world, U.S.A., stands foremost. Technological and industrial development has been simply phenomenol. Its rapid load growth has given impetus to the expansion of system generation through large steam electric installations as they provide relatively low cost energy when operating at high plant factors to supply base load. Meanwhile because of its reliability, availability at short notice and its ability to regulate for system load control its hydro capacity has shifted its position in the daily load curve from serving as a major resource to providing peaking capacity. To match this trend of complementing large thermal units by hydro peaking, the size of its plants are no longer limited by the hydrology of a stream as related to normal load curve of system, but rather by the peaking capabilities which can be developed in coordination with the other purposes of the project. While considering future hydro power development, great potential of pumped storage development as an ideal source of peaking power to supplement the rapid growth in thermal generation has been realised.

As already pointed out in U.S.A., the first application of pumped storage power development was in 1928 with a capacity of 7 M.W. Till 1950 its total installed capacity was only 30 M.W. However, after the announcement of an efficient type of reversible machine to function both as a pump and turbine by M/S Allis Chalmers in 1950 there was a spurt in the growth of the pumped storage plants. By 1972 its total installed capacity of pumped storage plant grew to 4400 M.W. And now with the projects under construction, by 1977 another 10,000 M.W. will be added by pumped storage installation, all with reversible turbines only. According to latest U.S.Federal Power Commission Surveys installed pumped storage capacity in the U.S.A. is projected to be 70,000 M.W. by 1990 compared with 4400 M.W. at the end of 1972.[61] In all its pumped storage development U.S.A. has been adopting only reversible machines as they are more economical.

3. In U.S.A. most of its earlier pumped storage plants are either semi outdoor or outdoor type so as to reduce the cost as well as time for construction e.g. Lewiston pumped storage plant, Smithmountain pump~~p~~ed storage plant, and Taum Sauk pumped storage plant.

The Ludington pumped storage plant of 6 x 312 M.W. now under operation is also of semi outdoor type only. The latest trend is to locate the pumped storage plant in underground cavern as discussed earlier due to various reasons particularly for environmental reasons. Cornwall pumped storage plant of 2000 M.W. has to be located semi underground and the Bear Swamp project of 2 x 300 M.W. is to be located underground only for the above reason.

4. Some of the latest pumped storage plants under operation and construction are briefly described below:

i) Ludington pumped storage plant - 6 x 312 M.W. (Largest pure pumped storage plant)

ii) Bear Swamp Pumped storage plant - 2 x 300 M.W. (Underground pumped storage project)

iii) Hyatt-Therm-alito pumped storage plant - (Tandem operation of two pumped storage plants)

i) <u>Ludington pumped storage project (U.S.A.)</u> (6x312 M.W)

The Ludington pumped storage plant has an installed capacity of 1872 M.W. The upper reservoir with 53,000 acre ft. is formed by a 6 mile long earthfill dam with a sandwich type asphalt facing. The six penstocks are encased in concrete, under the embankment, and buried in silty sand on the slope. At the intake structure the gates are suspended by hoists which allow for fast emergency closure. A prestressed, precast concrete baffle wall serves as vortex suppressor and ice barrier. The intake apron with splitter walls is an energy dissipator for the pumped water energy. The power house constructed on clay is protected by a break water and two jetties because lake Michigan, one of the five great lakes, serves as the lower reservoir.

Major consideration has been given to the project appearance for it is located in a recreational area. The power house is the semi outdoor type and is conventional in design except that it is bearing entirely on clay and therefore it requires a heavily reinforced substructure. Its size is 160 m x 52 m x 32.0 m ht. The maximum generating capacity is 1072 M.W. The six Nos 312 M.W. reversible turbines operating under a head of about 120 m (400 ft). is remotely operated and are started in pumping mode by the synchronous back to back method and pony motor. Special consideration has been given to the pump turbines and the generator motors being the largest yet built, both in their capacity and their size. Hitchi, Japan is manufacturing the pump turbines.

The station will operate on a weekly cycle.(19)

ii) Bear Swamp Pumped storage project (2 x 300 M.W.)

In this, the environment was considered an integral part of the overall project not only from the very inception of conceptual design, but also to the final delineation of the individual features and detailed designs, including guidelines for the implementation of construction.

Some of the attractive aspects of this particular location for the project was :

1) proximity to an existing transmission system.
2) availability of a natural depression above the seer field river valley for locating the upper storage.

The main power house with an installed capacity of 600 M.W is currently under construction and will be located underground on a direct line between the upper and lower reservoirs. The size of the cavern is 69 m x 25 m x 48 m height. It will have two reversible units of 300 M.W. each operating under a maximum head of about 235 m. The station is capable of generating 600 M.W. for 5 hours and requires 6.5 hours of pumping to replenish the upper reservoir.[8]

iii) Hyatt-Thermalito Power Complex

The Hyatt-Thermalito Power complex, a facility of the California Water Project has a combined dependable capacity of 725 M.W. for the two power plants. Hyatt power plant is an underground plant of Oraville dam with three conventional units and three reversible units of total generating capacity equal to 678 M.W. The water from the units are let into the lower storage formed by Thermalito Diversion dam downstream. From the diversion dam the water is drawn into another forebay by a (2.5 mile) 4 km. long power channel. The Thermalito pumped storage plant located below the forebay is a surface type power station with a total installed capacity of 115 M.W. at a head of 28.5 m (95 ft). It will have three reversible units and the water is let down into an after bay.

The special tests conducted to verffy the operation of the two power plants working in tandem for the generating and pumping mode under every condition of overload were found to be satisfactory. (J.of P.D.of ASCE Nov.'73 p. 405).

5. Multipurpose power development bringing together H.E. reversible pumped storage and nuclear thermal system has also been adopted in some of its projects e.g. Keowee-Toxaway power system.[38]

(ii) WEST GERMANY

6. In West Germany, the generations and distribution of electric supply is vested with private utilities. Hence to be more remunerative they had located their hydro as well as coal based thermal plants nearest to the energy source. Meanwhile they realised the advantages of pumped storage development which can be constructed for langer capacity without any fear of exhausting the resources. Hence they started the pioneer development in pumped storage power generation. By 1930, their Herdecke pumped storage plant started functioning with 132 M.W of installed capacity utilising a head of 155 m. By 1943 installed capacity in pumped storage plant rose to 650 M.W., and by 1968 it became 2000 M.W. Ronkhausen with 2 x 70 M.W. in 1969 was the first pumped storage plant to have reversible turbines. Before 1969, all the other stations had separate pumps, generators and turbines of the horizontal or vertical type. Unlike in U.S.A. and Japan reversible turbine has not made much progress here.

Most of the pumped storage schemes are of pure pumped storage type where natural flow is not needed. Hence out of its 19 pumped storage stations, 14 have hill top, artificial upper storages with mostly ring shaped enclosures. Its upper storages are kept as large as possible for allowing pumping operations during weak-end also.

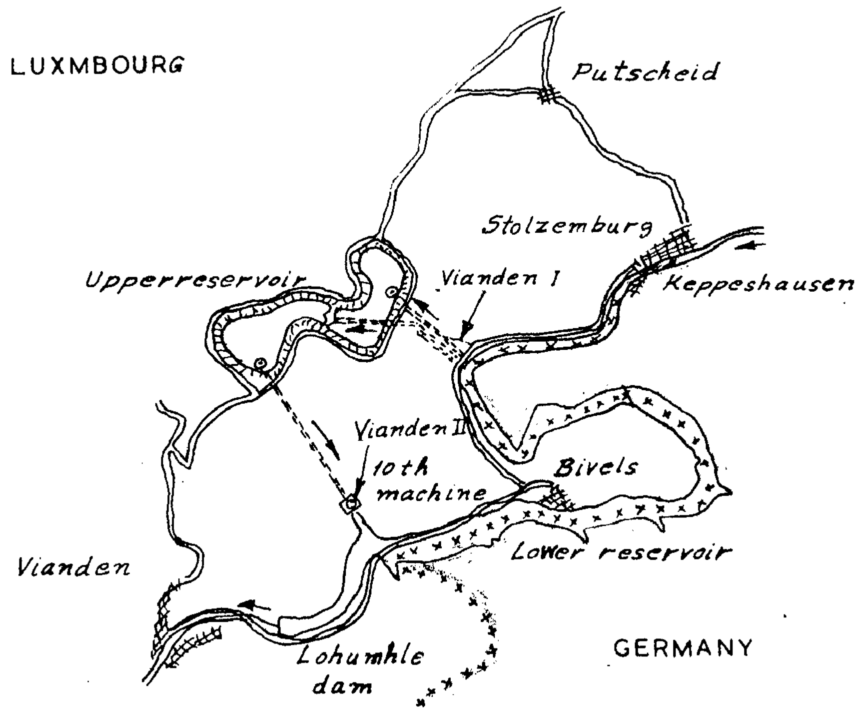


FIG. 14.- A PLAN OF THE AREA SHOWING THE RELATIVE POSITIONS OF THE VIANDEN I STATION AND THE TENTH MACHINE

7. Such reservoirs have been useful for later expansion of pumped storage generation also e.g.

i) Vianden II (1 x 200 M.W.) constructed in 1973 in Luxambourg near Vianden I of 1964

ii) Waldeck II (2 x 220 M.W.) constructed in 1974 near Waldeck I of 1933.

A brief description of the above two pumped storage plants are given below:

1) Vianden II

Vianden I was constructed in the years 1959 to 1964. Since the upper reservoir has no natural water inflow the installation operates as a pure pumped storage station with operation on daily reversing closed cycle. At Vianden I, there are nine conventional pumped storage sets with horizontal shafts, the unit capacity of which is 100 M.W. in generator operation and 70 M.W. in pumping operation. The machine hall was constructed under ground at a position where the distance from the two reservoirs is shortest.

Since the time the Vianden I was planned the peak demand increased considerably especially due to increase in the number of television sets and thus reducing the pumping hours. Hence an extension of the installation by adding a tenth machine was considered. Since no extension in the underground was possible, the erection of a separate power station was planned. Fig.14 shows the relative locations of both the power houses and the upper reservoir. As against conventional horizontal machine adopted in Vianden I, it has one unit of vertical reversible

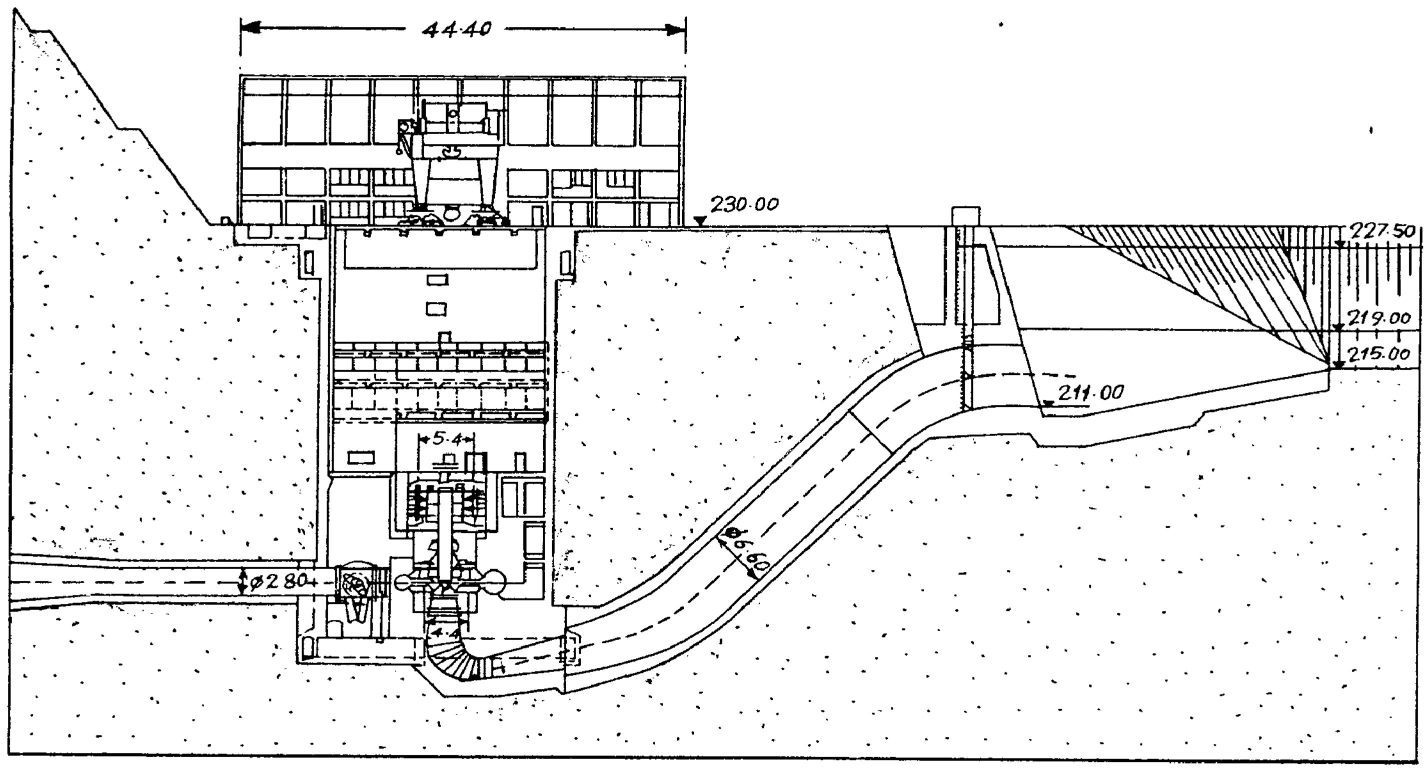


FIG. 15. - THE CROSS SECTION AND PLAN THROUGH THE CIRCULAR POWERHOUSE STRUCTUR DESIGNED FOR THE VIANDEN DEVELOPMENT'S TENTH SET.

pump turbine set of 200 M.W. using a head of 291 m when operating as generator and 215 M.W. as a pump. The new pump turbine with its auxiliaries will be located in a cylindrical shaft 22.20 internal diameter and 50 m deep, right beside the lower reservoir (Fig. 15).

The shaft type of construction was preferred mainly for economic reasons. Important advantages are improved accessibility and favourable hydraulic conditions by shortening of the tailrace tunnel.

When Vianden I was constructed in 1963, the European manufacturers had insufficient experience with reversible machine and hence they adopted conventional units with separate pump and turbine due to the shorter starting and reversing time which was very much needed in its case as Vianden is primarily a peak load and frequency regulating plant for the German Grid. However, by 1973, with the advancement in pump-turbine technology and by adopting the asynchronous method of starting for Vianden II with 200 M.W. Generating capacity a switch over time of 4½ minutes from turbine operation to pumping operation is possible as against 2 to 3 minutes for 100 M.W. units of Vianden I[71]. Thus a higher capacity reversible unit was installed at an economical cost practically without any loss in its operational efficiency.

ii) Waldeck II

Similar expansion of existing pumped storage utility has been carried out for Waldeck I built between 1929 and 1932.

The main advantage of the location was that it offered development of a 330 m head between a suitable site for the upper reservoir and the Waldeck I lower reservoir which could be easily enlarged to serve Waldeck II. The reservoirs were only 1.4 km apart. Waldeck I is a surface power house with four conventional horizontal units of total capacity equal to 140 M.W. The Waldeck II now nearing completion will have two vertical units of three machine type of total capacity equal to 440 M.W (2 x 220 MW). The machines will be located inside an underground cavern of size 106 m x 34 m x 54 m height. As a deep setting of 50 m below tail water were required for such large units of 220 M.W., the power house has to be located in an underground cavern with vertical axis units. Unlike Vianden II it will have three machine arran ement with turbine on the top to reduce the height with generator-motor in the middle and pump at the bottom. Fig. 6(d). There is also a future proposal to construct Waldeck III pumped storage plant with another 2 x 220 M.W. capacity. Now itself a separate upper storage for Waldeck II and III has been constructed, however for lower reservoir as already stated the existing reservoir will be enlarged for Waldeck II and III.(74)

The expansion of existing pumped storage plants with further units near about has increased the operational efficiency of the pumped storage generation with maximum economy.

(iii) JAPAN

8. The first pumped storage power station in Japan was constructed in 1933 when a multistage pump directly coupled

to a motor (with a capacity of 3.75 M.W. and a pumping head of 668 m) was addded to Oguchigawa No.3 power plant so as to store the surplus energy produced by hydraulic power plants in the rich water season. This station and the Ikojirigawa scheme were the only plants constructed until 1951, when Numazaoanuma , a modern type of Station with an installed capacity of 43.6 M.W. was commissioned. This plant is equipped with two sets of horizontal tandem type machines i.e. horizontal shaft generator motor coupled to two stage pumps and francis turbines.

The first reversible pump turbine was erected in 1959 at Omorigawa (1 x 12 M.W.). Thereafter in all their new pumped storage plants in operation as well as in construction they have been adopting only reversible units. Till 1959 its total pumped storage capacity was only 67 M.W. Once the advantage of reversible units was realised, the development in its pumped storage generation grew from paltry 67 M.W. to 3500 M.W. by 1970 and with the schemes under construction it will become 10,000 M.W. by 1978 (83, 54). Just as in U.S.A. here also the trend is for constructing larger plants with larger reversible units. The largest reversible unit now under erection is 3 units of 310 M.W. of Okutataragi pumped storage plant(44) and 4 units of 320 M.W. for Shintakasegawa pumped storage plant. Most of its pumped storage stations operate in conjunction with downstream hydro electric stations(48).

Along with the world trend, Japan has also contributed towards the developments in pumped storage plant. They have

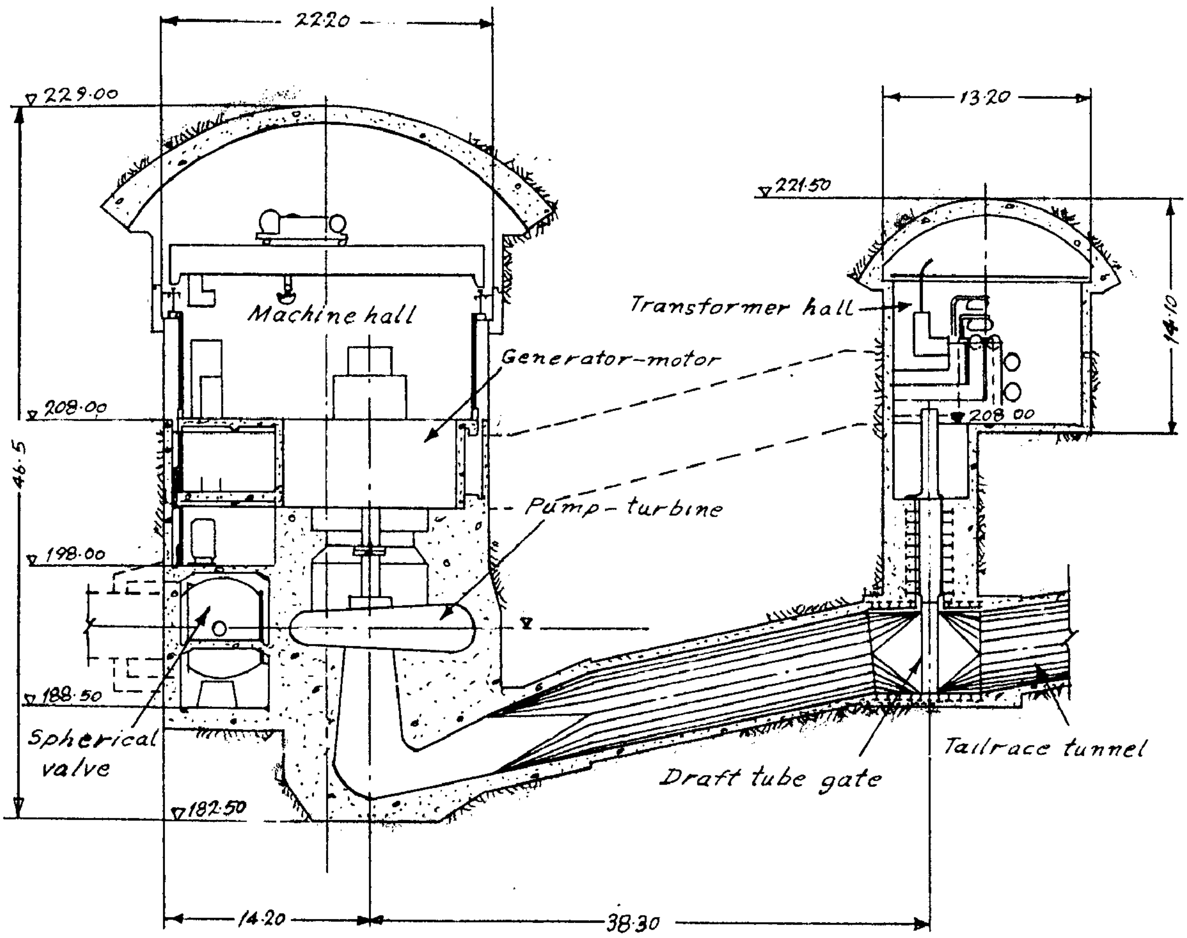


FIG. 16 - A CROSS-SECTION THROUGH THE 22 M-WIDE, 46 M-HIGH MACHINE HALL AND THE TRANSFORMER HALL FOR THE SHINTOYONE SCHEME JAPAN

been cont-inously trying to increase the operating head for reversible turbine. For Numappara pumped storage of Japan they have successfully tested the 230 M.W.unit for an operating head of 500 m, Now they are designing a reversible turbine of 315 M.W. capacity for a head of 621 m for a Yugoslavian pumped storage plant (W.P.July 1975). They have manufactured and supplied the large capacity reversible unit of 312 M.W. for Ludigton pumped storage plant, U.S.A.

9. Underground pumped storage plants are widely adopted in Japan for the main reason that it can be located in any convenient position in the hydraulic circuit. A large negative suction head can be provided in pumped storage station. As in Japan the islands are in volcanic zone the rock is weak and hence the underground chamber is almost invariably to be concrete walled and roofed.

An example of large underground pumped storage plant now nearing completion is Shitoyne pumped storage plant of 1150 M.W. capacity. Its five vertical reversible units of each 230 M.W. will be operating under a maximum head of 240 m and are located inside a cavern of size 140 m x 22 m x 46 m height. Transformers are located in a separate cavern. Fig. 16 shows the cross section through the underground machine hall and the transformer gallery. For starting in pumping mode, two of the units will be started by synchronous method and the rest of the three by pony motors of 20 M.W. capacity.[53,83]

iv) ITALY

10. The first pumped storage plant of 30 M.W. conventional unit with separate impulse turbine and pump came into operation in 1940. Till 1963 its total pumped storage capacity was only 532 M.W. As its load demand grew with large fluctuations between maximum and minimum demand to the tune of 4000 M.W. (as in 1963), Italy has decided to go in for pumped storage plants in a big way to satisfy its peak demand as technical or economic means adopted for load levelling and peak reduction were not quite effective. By 1975, with the schemes under construction it will increase its pumped storage capacity by 3500 M.W.

As most of its pumped storage plants are of high head type, they have to install only three machine type i.e. generator motor, separate impulse turbine and separate multistage pumps. As the impulse wheel has to be kept above maximum water level and the pump has to be kept at a low level the length of shaft is of the order of 40 - 50 m. With a view to avoid excessive shaft lengths now they are experimenting with "Back Pressure operation for Pelton wheel "as described already in Chapter III.

11. The largest underground pumped storage plant of 1000 M.W. capacity now under construction in Italy is Lago Delio pumped storage plant. It has the most ideal conditions for a pumped storage development. One thing for its upper and lower storages it has got two big natural lakes viz Lago Delio and Lago Maggiora. Secondly for the 730 m head available the length

LAGO DELO PUMPED STORAGE POWER STATION
GENERAL LAYOUT. ITALY

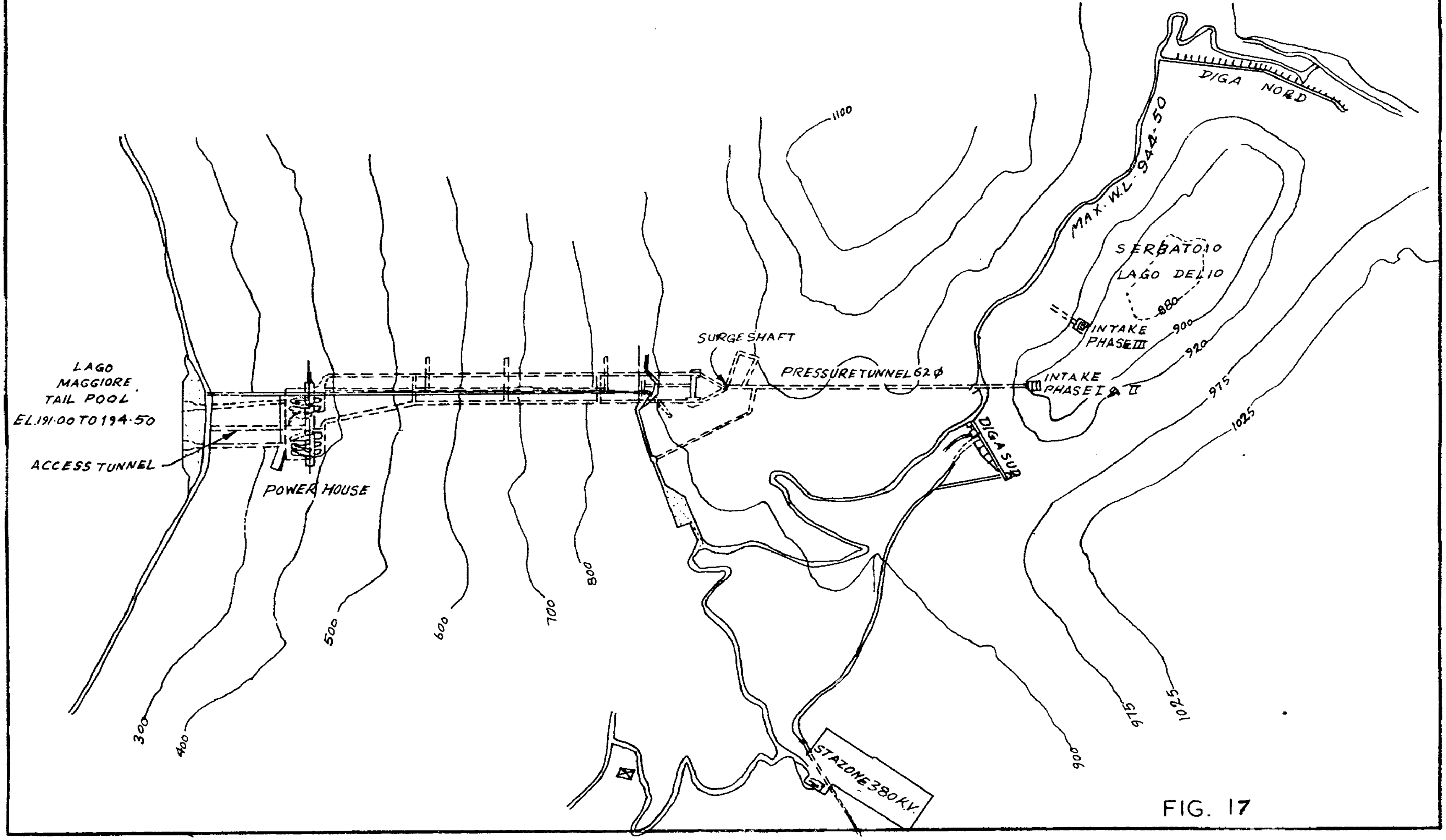


FIG. 17

of water conductor system is the shortest i.e. about 1500 m. Fig. 17 shows the general layout of the Lago Delio pumped storage plant. It will have 8 units of 125 M.W. each housed in an underground cavern of size 196 m x 21 m x 58 m height. Compared to Vianden I where the length of cavern is 330 m for 900 M.W. capacity. Underground arrangement was adopted due to the presence of fissures and intercalation near the surface. The present location is moved 90 m towards the mountain to avoid such faults.

One important aspect in this scheme is the ordering of machineries to different manufacturers so as to encourage the development in this field.

v) UNITED KINGDOM

12. Due to abundant coal availability in the country, in U.K.electrical system is predominantly thermal. The peak variations is generally taken care of by old thermal plant and small hydro stations. However, on account of the universal recognition of the merits of pumped storage and great technological advances in that field, U.K.also started to take interest.

13. Ffestinoig pumped storage plant with 4 units of 90 M.W. is the first large plant to be commissioned in 1963.(24) As already stated in Chapter III, this station is commissioned to operate in conjunction with nearby Trawsfyndd nuclear station. It was expected to save £ 200,000/annum to Central Electricity Generating Board. But in its first year of operation even before the nuclear station was commissioned it saved £ 500,000(25)

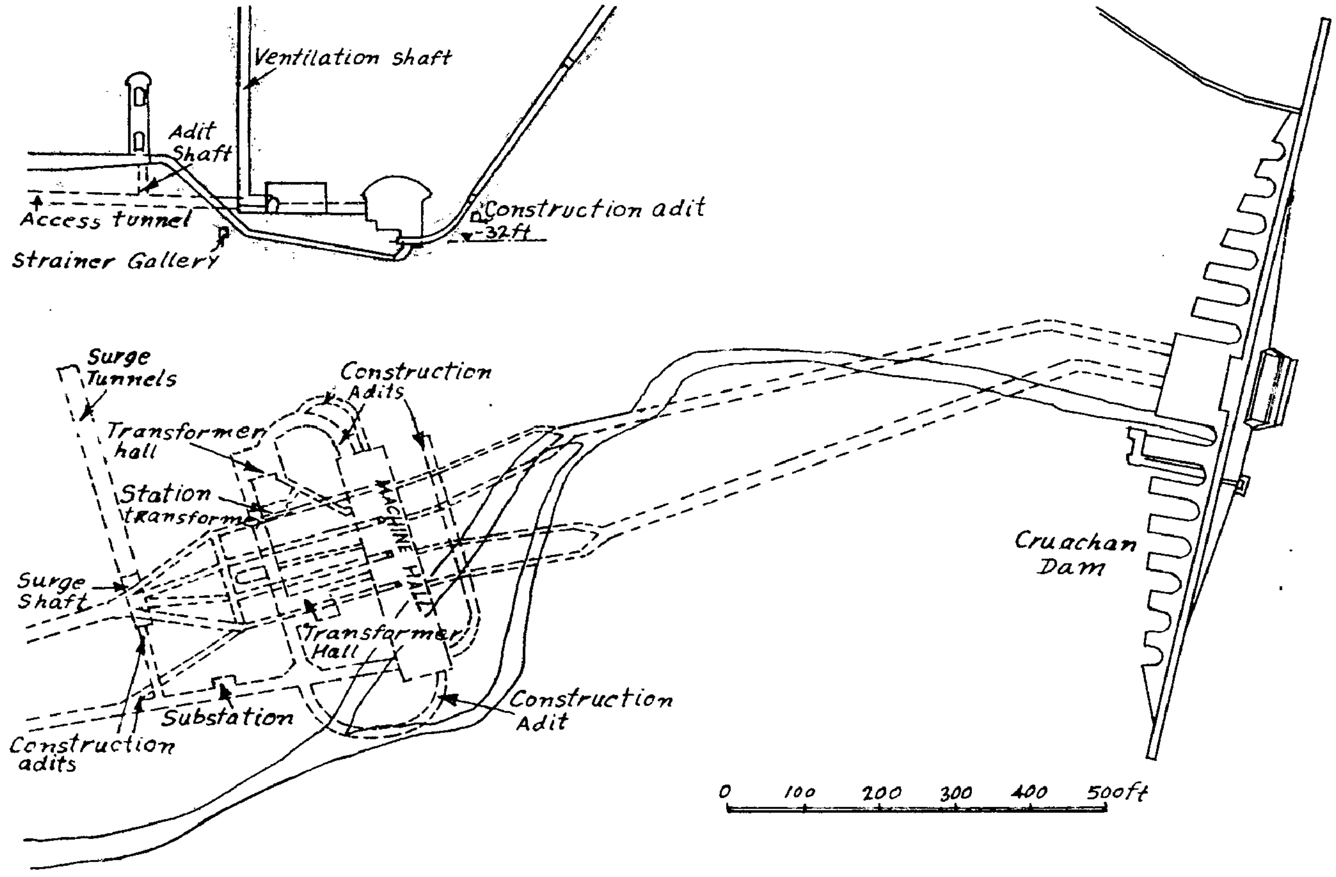


FIG. 18 - HYDRAULIC CIRCUIT OF CRUACHAN STATION. U.K.

This is because it was originally planned to work for 1500 hours pumping and 1000 hours generating per annum. But in 1963 the plant actually worked for 3174 hours pumping and 2593 hours generating thus the time utilisation factor was 77.2% against the planned utilisation factor of 28.5%. This has been due in large measure to the unexpectedly high degree of flexibility of the plant which has made it worthwhile to resort to pumping even during brief day time lull and to call on generating capacity for such phenomena as the evening television peak. Automatic starting both for pumping and generating has contributed to this flexibility but in addition modifications have been made to the method of running the machine on spinning reserve.

14. The first reversible pumped storage plant of 4x100 M.W. capacity came into operation in 1966. At that time excluding U.S.A., the 100 M.W. unit of Cruchan pumped storage plant was the largest under operation in the whole of Europe. A storage dam across a stream is utilised for upper storage and for lower storage a natural lake 'Loch Awe' is utilised. The four machines are located inside an underground cavern of size 90 m x 23 m x 36 m height due to a deeper setting necessitated for its operating head of 367 m for its pumps. Fig. 13 shows the general layout of the Cruchan pumped storage plant, As already described in Chapter III, pony motors are employed for starting the machine in pumping mode.

15. Foyer's with 2 x 150 M.W. reversible turbine is now officially commissioned for operation from April 1975. It uses

the existing Lakes, Loch Mohr and Loch Ness for its upper and lower storages. Due to deeper setting required for its 150 m operating head for pumps, the two reversible machines are located inside two vertical shafts of 50 m deep and 19 m diameter with concrete lined.

16. The two large pumped storage schemes now under active planning are:

i) Loch Sloy with 4 x 300 M.W. capacity, and

ii) Dinorwic pumped storage plant near North Wales of 8 x 225 M.W. capacity.

It has since been realised that larger unit capacity for pumped storage plants was found to be more economical for the size of power house required.

vi) U.S.S.R.

17. U.S.S.R's interest in the pumped storage plant is very recent. In a number of conferences convened for solving the peaking problem, the importance of pumped storage development was accepted by everyone. It was also agreed that the capacity of the plant should be commensurate with the capacity of the power system and should ensure an optimal structure of their generating capacity. Number of probable locations were studied and discussed in the scientific congress held in 1972 in the city of Erevan, Armenian S.S.R. In which 125 specialist from all over U.S.S.R. attended(65).

18. The first pumped storage plant to be commissioned in 1970 is Kiev pumped storage plant of 200 M.W. capacity. The plant generates for 3 hours producing more than 6 M units per

day. During the off peak night hours, the reversible unit operates for 7 hours filling up the upper reservoir. During the remaining hours all units operate as a synchronous condenser.(56) Actually there are six units totalling 225 M.W.of this only three are reversible pumping units with a capacity equal to 120 M.W. i.e. (40 x 3). All the three were put into service by November 1971. The maximum head utilised is about 65 m.[56,43,64(a)]

The power house is of the semi-underground type with low machine room and removable roof cover. The units are serviced by a 250 ton gantry crane.

19. Zagorsk pumped storage scheme near Moscow of 1200 M.W. capacity is largest pumped storage scheme under construction.(64) Just like Japan, the pumped storage extensions has been adopted for an existing Tata H.E.plant of 17m head with 2 x 27 M.W. reversible machine.(67)

vii) <u>OTHER COUNTRIES</u>

20. Switzerland, France, Belgium, Austria have also number of pumped storage schemes under operation. The highest head pumped storage plant under operation is in Switzerland. In France, the largest pumped storage plant under operation is The Revin with an installed capacity of 800 M.W. For upper storage a ring of embankment over a flat hill serves the purpose. The lower storage is created by constructing a dam across La Faux river. The 4 x 200 M.W. vertical reversible unit works under a head of 250 m and located inside an underground cavern

of size 114 m x 17 m x 30 m height. The transformers are located on the surface. To start the machines in the pumping mode 15 M.W. pony motors with dewatering system using compressed air is adopted. It is estimated to cost about 450 million Franc or 550 F per Kw of installed capacity i.e. about Rs. 800/- k.w. which is quite economical.(Pierre A. Gerard, W.P.Nov. 1972 p. 411)[85]. In Belgium the major pumped storage plant under operation is the Coo-Trois Ponts of 6 x 144 M.W. capacity. In the draft tube flap type gates are installed.[14] Motor driven cooling fan, modified umbrella design (thrust and guide bearing above rotor) and three machines are connected to one draff tube are some of the features of the plant. The Belgium grid visualises pumping operation not only at night but also during the mid-day lunch period when off peak power is available. Such pumping operation is not uncommon in Europe as lunch break (and in West Germany even mid morning coffee break) are simultaneous throughout the country. Poland among East European countries has constructed its first pumped storage plant Zydowo of 150 M.W(3 x 50) capacity utilising a head of about 80 m. It has three reversible units. Porombkazher pumped storage plant of 500 M.W. (4x125 MW) using a head of 432 m is currently under construction. It will have an underground power house. There are three more stations under planning.

Several other countries are also seriously planning for pumped storage plants in view of its usefulness as peaking machine. This holds good for India also.

CHAPTER V

OVERALL SUMMERISATION OF PUMPED STORAGE HYDRO DEVELOPMENT AND FUTURE PROSPECTS

1. Under present day conditions uninterrupted supply of electricity, reliability of supply i.e., adequate standby, minimum loss to the economy in the event of failure, high flexibility of power system, supply frequency and voltage have become vital for industrial development and even daily life. Serious consequences of failure in New York in 1965, where there is a high level of electrification should be an eye opener to future power system planners. The economic efficiency of a pumped storage plant must therefore be considered in conjunction with the power supply economics of the country as a whole or in relation to a sufficiently large electric supply region.(58)

2. It is now universally recognized that pumped storage schemes are ideally suited to cope up with varying needs of a transmission system supplying energy in industrialized countries. Very often such systems receive the bulk of the energy from coal or oil fired thermal stations or nuclear power plants, which supply the base loads but are uneconomical when required to supply peak loads of short duration.(45)

3. As one of the speakers at the Scientific Technical Conference held in 1972 in the city of Erevan, Armenian S.S.R pointed out the wide spread construction of pumped storage plant in practically in all the industrially developed countries of the world (Austria) England, West Germany, Luxambourg, the U.S.A., France and Japan) demonstrates their high power

economic effectiveness, when operating as part of power systems having the appropriate capacity. A highly valuable characteristics of pumped storage plant is filling of the night gaps in the daily and weekly load graphs, with a corresponding increase in the minimum load on thermal and nuclear power plants, which improves the conditions governing their operation and the utilisation of their equipment and at the same time reduces the operating costs substantially. This characteristics of pumped storage plant is often not taken into account in the economic analysis. In comparison with peaking thermal electric plants pumped storage plant always ensures a saving in fuel. The capacity of the pumped storage plant should be commensurate with the capacity of the power systems and should ensure an optimal structure of their generating capacities.

Location and size of a pumped storage plant are determined on one hand by the natural conditions, and on the other hand by the distance from the consumption centre and from the main source of pumping energy as well as by the specific conditions in the supply area.

4. When choosing and laying out a pumped storage plant one should always endeavour to utilise the highest possible head and the shortest possible water conductor system from the upper to the lower reservoir.[28]

With the development of interconnections between the individual supply systems, the average distance of the source of the pumping energy became less important than the distance between the pumped storage station and the load centre. Because of the development of E.H.V. transmission and the large capacity of the machine the nearness of pumped storage plant to the load centre is also further relaxed.

5. The growth of nuclear plant will lead to an increase of night energy which can best be utilised by pumped storage installations. Further it is expected for these plants the variable fuel costs will be lower than for conventional thermal plants.[57]

Secondly owing to the low fuel costs a higher utilisation will be sought for nuclear plants so thata daily shutdown of conventional thermal generating station will become more frequent. This is because in the absence of a suitable peaking station, the less efficient conventional thermal plant has to operate as a low load factor peaking station and thereby it may necessitate shut down during off peak hours. This once again favours the construction of pumped storage plant which is very efficient as a low load factor station for peaking purpose and thus permit the better utilisation of conventional thermal plants as a base load in the grid. In recent years the construction of many of the pumped storage plants in conjunction with nuclear power plant and their efficient operation has confirmed the validity of the above statement beyond doubt. Further recent trend is to construct multipurpose power development or mixed power development which brings together hydro electric, pumped storage and nuclear thermal systems in a unique combinations. Such combinations reduce the overall cost by 10 to 11%.(62)

6. Going back to the growth of pumped storage plant until fifties the development was sluggish, but after the development of reversible unit i.e. one single unit to work as turbine in one direction and as pumped in another direction, the growth has become phenomenal. The economy of pumped storage plants with these reversible units increased because of smaller units and smaller power house building, whatever problem arose from this were also solved by enthusiastic manufacturers all over the world. Since the greatest disadvantage was two opposite directions for each operation, different methods of starting for pumping mode are developed and also other unidirectional turbines like Isogyre and Hone turbine are being developed. However, they are still in their initial stages and in future this development may eliminate the disadvantage of two directional motion. Similarly for lower heads "Deriaz" machine is developed, this is a reversible unit to work efficiently even under partial load.

7. Before 1950, the maximum operating head for a francis turbine was about 250 to 260 m. During these twenty-five years. the turbine technology has advanced so much that for a conventional unit with separate pump and turbine, the maximum head for the francis turbine has risen upto 670 m. Similarly in the case of reversible turbine, an operating head of about 500 m has already been achieved in the case of 230 M.W.unit

of Numapara pumped storage plants in Japan. As per the latest information available (in W.P. July 1975), Toshiba, Japan is currently designing a reversible turbine of 315 M.W.capacity for an operating head of 621 m. for a Yugoslavian pumped storage plant. As informed by Mr. Porrie of France in his report in the Rome Symposium, the development of machines for a head of 900 m with multi-stage reversible turbine pump may reduce the cost considerably in future. (Hy.Te . Aug.73).

8. An ideal location for a pumped storage plant for economical development will be the availability of a head between 300 m - 400 m and suitable reservoir storages for upper and lower closeby. If natural lakes of suitable capacity is available it will further enhance the economics of the scheme. One such example is the Lago Delio pumped storage plant of Italy with 1000 M.W. capacity. Here a head of 750 m, was possible to develop between two natural lakes, Lago Delio (as upper storage) and Lago Maggiore (as lower storage) which were only 1700 m apart. Another example is Foyers of 300 M.W (U.K.) capacity using two natural lakes Loch Mohr and Loch ness. However, in most of the cases, at least for lower storage an existing natural lake or storages of another project down-stream are made use of to reduce the cost of pumped storage plant to a certain extent. In such cases to create the necessary upper storage either a valley with a dam across it or the hill top with a ring bund (after choping up the top to have sufficient capacity) is adopted. Examples of such developments are Cruchan with 400 M.W. (U.K.) capacity and Ludington with

1872 M.W. (U.S.A.) capacity respectively.

Earlier it was widely believed, semi underground layout would be cheaper in cost and quicker in construction. Most of the pumped storage plants and hydro stations constructed in U.S.A., Japan, U.S.S.R. and Germany are of this type. However, with the increase in the head of pumped storage plant the setting of the turbine has to be deeper than the minimum water level of the lower storage. Upto a certain depth i.e. 50 m or so cylinderical shaft type arrangement is adopted and beyond that under ground power house is generally preferred. Due to the tremendous increase in the devolopment of high head pumped storage plant, now more than 50 underground pumped storage plants are in operation and construction. In addition to the feasibility of deeper setting in the underground arrangement there are also other advantages stated already in Chapter II. Among these the most important one is the greatest flexibility in locating the power house so that the water conductor system is the shortest. It also improves the operating conditions by reducing the hydraulic losses. As reported by Mr. Savin in an article the underground location yields upto 30% saving in the cost of pumped storage plants.(63)

9. Compared to the working of Ffestinoig pumped storage plant (U.K.) commissoned in 1963(24), where against a plant utilisation factor of 28.5% the actual time utilisation factor was 77.2%. The latest availability factor for some of the

important stations are given below:

1.	Cabin Creek Pumped storage plant(USA)	97.7%
2.	Hiwassee (USA)	98%
3.	Shiroyama (Japan)	98.3%
4.	Hatangi (Japan)	97%
5.	Yagisawa (Japan)	95.6%
6.	Lewiston (USA)	94.6%
7.	Taum Sauk (USA)	92.7%
8.	Smith Mountain (USA)	86.8%
9.	Valdeconas (Spain)	79%

For Smith Mountain, the availability factor was reduced because of two very serious accidents to one of the machines. The generally high availability factor indicates a high degree of reliability of these reversible hydro units as has been typical with conventional hydro units for many years.(51)

10. Summing up the advantages of a pumped storage plant in a nutshell will be:

i) Load factor will be improved, thus overall cost of production per unit is reduced.

ii) More energy will be produced without corresponding increase in the quantity of fuel consumed; whence a saving of total fuel resources

iii) Possible to avoid overloading existing long distance transmission lines during peak period by judicious locating of pumped storage plant.

iv) Overall stability of the network is improved.

v) No water loss as same water can be used again and again.

vi) With different tariff for peak and off-peak energy it is financially profitable also.

FUTURE PROSPECTS

1. Due to the phenomenal industrial growth world over, demand for electricity has outstripped the production. Development of nuclear power has also not yet been able to match with the demand. However, it is hoped it will come to our rescue in future years. Coal reserves are going down and their production is also affected now and then by political or other reasons. Similarly the oil reserves have affected the industry so much by the middle east crisis. Further these fossil fuel reserves are also more and more used for the production of synthetic material.(47)

Because of the above uncertain position in the world regarding reliable and cheap source of power the only alternative left is to exploit water power which also is slowly being exhausted. In this context pumped storage development which provides for hydro power for peaking purposes using the same water again and again may greatly help the situation.

As already described in previous chapters due to the considerable economy affected by large pumped storage plants for working in conjunction with large thermal and nuclear plants, the supply position throughout the world will be stabilised to some extent. Within next twenty years it is expected that the capacity of pumped storage plant will easily exceed 20%.of the overall installed generating capacity. It will provide a valuable measure of system flexibility when so much will otherwise depend on very large fossil fired fuel units. Hence in the coming years a position will be reached when in the absence of an acceptable alternative decisive trend will be in favour of pumped storage development.

In future, planning of large thermal plants with fossil fuel will have to be restricted due to its fuel being better utilised for producing synthetic materials for the community. For example, even in Britain where there is abundant coal reserve it is predicted that atleast 50% of its national generating capacity will be from nuclear sources by the end of this century.

Hence it may be concluded that in near future a rational combination of highly economical nuclear electric plants with special peaking or semi peaking pumped storage plants only can assure an economical and at the same time reliable power supply to the consumers.

2. In view of the above in coming years, development of pumped storage equipments and other methods to develop the scope of pumped storage plants has to be explored.

simple one because the central Government is directly responsible for the development of electric power.(55)

3. In the following paras, some of the future developments in pumped storage contemplated by some of the engineers world over is described:

i) In an article titled "Integration of Pumped storage with Tidal Power" by Thomas L.Shaw (U.K.) describes a proposal to utilise the tidal variations of the Severn Estuary near Bristol, U.K. for tidal power and adds to it by pumped storage scheme.(32) It is briefly as follows:

The scheme was examined on the basis of power storage at a rate of 3500 M.W. for seven hours during the night from which an output of 3500 M.W. is possible once again for 12 hours period during every day i.e. for this rate of storage by night an approximately equal energy content in an average contributed by the tides in a 24 hour period.(47) The scheme provides for storing tidal energy at weekends also since the operations would be reduced. And this additional energy is also available for progressive release as required along the following week days.

Considering the rates and energy values in 1974 with an interest rate of 12% and economic plant life of 50 years the cost/benefit ratio will be about 1:1.

ii) In another article titled, "Condenser Cooling and pumped storage reservoirs" by Eli Setchovich, he has discussed how best the large quantity of water required for future large thermal plants for condenser cooling could be used for developing pumped storage power.(21)

The project contemplates using man made impondment of condenser cooling water of a thermal plant as a lower storage for a 750 M.W. pumped storage plant. It is also shown that this will support appreciable thermal capacities, nuclear or fossil fueled. Such intensive use of bodies of water may also result in additional benefits that accrues from the joint utilisation of same facilities. Other advantages are joint utilisation of some of the plant equipment eg. a joint switchyard and on site availability of inexpensive off peak pumping power with the added advantage of low transmission costs. However, other problems such as the operating mode of thermal plant, pumping and generating mode of pumped storage has to be studied and coordinated with the circulating water system.

iii) In another paper presented by J.G.Warnock and D.C. Willett in the symposium on Hydro Electric pumped storage in Athens in 1972, titled "Underground Reservoirs for high head Pumped storage stations," attention was focussed on a new concept of pumped

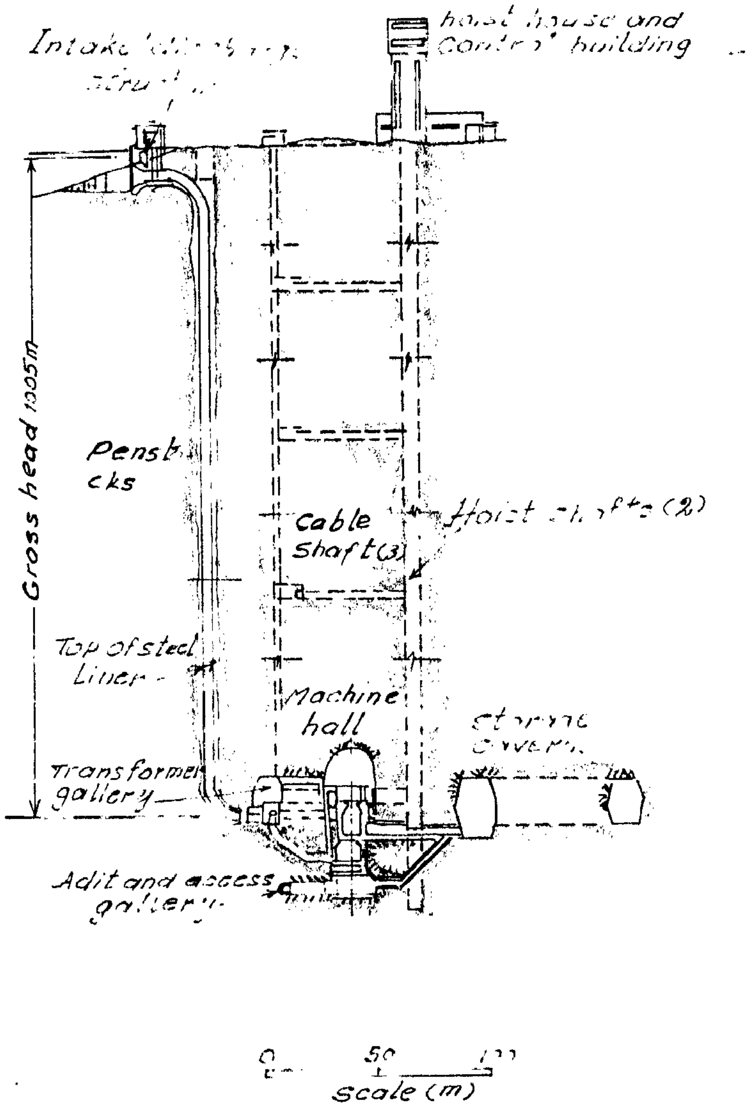


FIG. 19.- CROSS SECTION THROUGH A SINGLE STAGE 3000 MW UNDERGROUND PLANT.

U. G. RESERVOIR FOR PUMPED STORAGE

storage development that is independent of natural topography.(73,79)

It provides convenient locations to suit power system needs and may provide solutions which are less likely to involve environmental constraints. It will prove economically feasible, provided the maximum head capability of a single runner pump turbine can be applied to a two stage developments

The scheme in brief is to use any low lying lake or even sea as the upper reservoir and blasting a cavern deep in underground for use as the lower reservoir. Fig. 19 shows the details of the scheme. This would mean pumped storage plant operation almost anywhere not just where nature designed it. A development of 1000 m head is found to have potential advantage over 450 m which was previously thought of. Because higher head reduces the size of water passages required for generating and pumping but however, increase in the length of penstock and complex generating equipment increases the cost. The author has shown by working out the cost for under ground pumped storage project with a head of 1000 m will become competetive with surface schemes in the 500 m range, sites for which are increasingly difficult to locate and develop. The lower reservoir will be generally in the form of a series of interconnected tunnels of size 20 m width and 30 m height. To have an idea, the quantity of excavation (11 million m^3) for a 3000 MW station will be approximately five times the quantity of excavation for the 5225 M.W. Underground power house for Churchil hydro electric plant in Canada.

In another article by Mr. Savin[63] a further development of pumped storage plant with underground lower reservoirs discussed was the use of special power centres or power islands in the sea with underground pumped storage plant as well as nuclear electric plants. He has worked out the capital cost of such a proposal as $ 60 to $ 130/KW compared to a conventional pumped storage plant of $ 90 to $ 130/KW. The effectiveness of these plants is increased by locating them near the power consuming centre. The author has stated that in U.S.A. a project is being developed for an under water nuclear electric plant of 1000 M.W. capacity located on the bottom of the ocean at a depth of 75 m and at a distance of 40 km. from the coast. Such a nuclear electric plant could be successfully combined with an under water pumped storage plant.

Further, design reconnaisance work is being carried out for a pumped storage plant of this type with 1000 M.W. capacity in North West, New Jersey, U.S.A. The penstocks will be installed in the shaft of (size 3.7 m x 6 m and lined with concrete) an iron ore mine. The power house will be located deep beneath the surface. The upper reservoir will be the setlling pond (area of about 60 ha) of a circulating plant and the lower reservoir will consist of abandoned mine excavation whose volume will be increased by driving several additional tunnels in the lower part. The cost of additional works are estimated at 250 million dollars (i.e. about Rs. 200 crores) and the construction work is scheduled for completion by the middle of 1980.

iv) In another interesting article by Tajio Yoshimoto, (Japan)[86] titled, "The Atashika sea Water Pumped Storage project", he outlines a project for using sea water as lower reservoir and creating an upper reservoir on a mountain top near the sea shore.

In Japan almost all the rivers have been developed for hydro power and it is increasingly difficult to find sites where high enough head and much water can be utilised.

In general, this situation has made it easy to construct pumped storage stations and for this type of plant, there are still many valleys available in Japan for development. The only drawback is most of these valleys are inhabited since olden times. Hence it will pose problems.

Hence he has proposed a scheme at Atashika where the upper reservoir will be located at about 4.5 Km. from the coast line. A 131 m high rockfill dam will store 45 million m^3 of sea water while pumping and later used for generation using a head of about 470 m in an underground powerhouse with 8 reversible units of each 250 M.W. capacity (total 2000 M.W). A nuclear power station is also scheduled close to this area, which is an added advantage for the pumped storage station.

The project would be successful but for the environmental pollution caused by the sea water stored in the upper reservoir.

Now large scale, technical investigations are being carried out by M/S Chubu Electric Co., Japan, (who are planning this) for,

i) Adverse effects on plant growth in the neighbouring area,

ii) Antifouling painting

iii) to overcome marine growth on the tunnel walls

iv) special materials for pump turbines

v) discharging of tailrace waters into the sea and its effect on coastal fisheries

vi) influence of large quantities of salt water stored in the reservoir on surrounding plant, animal and coastal climate etc.

Hence necessity may bring in future many more such surprises which we may not even imagine at present for the development of pumped storage plants.

CHAPTER VI

ECONOMICS

1. Before going into the economics of a pumped storage scheme the salient features may again be recapitulated.

a. Since there is energy loss both in the process of pumping and generation, the efficiency of energy conversion by the pumped storage scheme is approximately 70%. However, the efficiencies of latest machines have improved to as much as 80% and hence this will minimise the energy loss.

b. The main and the only task of pumped storage plant is meeting the sharpest and shortest system peak loads for which purpose peak hydro electric scheme or thermal power plant employing steam or gas turbines can be used or even nuclear power plant with various results.

c. It is known that the pumped storage plant has low direct operating cost, and high energy output. However, the specific capital outlay for a pumped storage plant is greater than that for a thermal plant employing gas turbine units, whereas the economics of the higher flexibility of pumped storage units can be evaluated only arbitrarily.[58]

d. The location of the pumped storage plant is not always near the load centre which affects the cost of power transmission and cost of power generated by the above plant.

2. In an article written by E.J.K.Chapman in Water Power 1963 he had made a comparison of a mixed system in which a load growth in 12 years is satisfied with the addition of more

thermal plant, more nuclear plant and little for hydro and no additional for a pumped storage plant with another alternative with everything same except that increase in thermal is reduced to half and the reduction is added to pumped storage plant and hydro plant. It was shown that by having increased pumped storage capacity the average load factor of the thermal plant is improved by 50% and there was a considerable saving in the production cost. He has shown that the saving is as much as £ 2.5 Million over the former arrangement.(12)

3. However to have better concept in the working of pumped storage plant, the value of specific saving or over-consumption of fuel (fuel expenditure) where the pumped storage plant is placed in operation in comparison with the alternative (replaced) projects for development of peaking sources in the power system is to be determined. Either a sharp peaking hydro electric project or a gas turbine electric plant may be considered as an alternative.

Such a study was made for united power system of North West, U.S.S.R.(75) with the help of an economic Mathematic model. Studies included different alternatives of the initial power economic information of the region, high specific capacity of nuclear plant and different levels of manoeuverability of the thermal electric units of the power system.

The analysis indicated that in all the situations examined, the fuel effect of pumped storage plant is a positive quantity, that is when pumped storage plants are used there is a definite saving of fuel in the power system.

The energy for recharging the pumped storage plant is derived partially from thermal electric plants, operating with fuel oil or with coal in the different systems of the region. Because of the interconnected systems, if there is no pumped storage plant the surplus energy from one system with displace any other thermal electric plant operated either by oil or coal. When the pumped storage plants are put into operation then power station will operate with a smaller reduction of this load during the night hours.

In this article the cost of pumping has been worked out as ... 0.45-0.50 Kopect/unit and the generation cost at 70% efficiency as 0.65-0.7 Kopect/unit.

In case the pumping power is from the same system with high capacity nuclear plant, the pumping cost will be .... 0.3 to 0.35 Kopect/units and generating cost at 70% efficiency 0.45 to 0.5 Kopect/unit.

In all the cases examined, the energy from the pumped storage plant replaces the peaking energy from gas-turbine electric plants as well as from the thermal electric plants. The generation cost of such energy works out to 1.3-0.9 Kopect/unit and the main importance lies in the fact of total savings in fuel cost. The value of fuel effect expressed in terms of fuel consumption or fuel saved will be about 0.2-0.3 tons/M.W. or 0.13-0.20 Kg/unit.

With the increase in the installed capacity the value of fuel effect decreases to a certain extent i.e. from 6.5 rubles/kw for an 800 MW to 5.3 rubles/kw for 1600 M.W.

4. The energy to be stored is produced at stations which are more efficient than those working on the part of the load-duration curve which would be taken over by the storage plant. This results in a saving of fuel. But as already discussed there is a considerable energy loss on conversion, which may be called the pumping loss.

The thermal plant which the storage project displaces has a flexed component of fuel consumption which represents banking or other standby losses. Pumped storage has no such fixed loss, and this represents a saving in its favour. Furthermore, it is to be expected that operation and maintenance costs should be lower for the storage plant than for the alternative steam plant.

On account of these various considerations, some of which are adverse and others are favourable to pumped storage, it is not normally sufficient to study only the economics of the storage project. To be certain of the ultimate effect of introducing a low load factor storage plant dependent on thermal power, it is necessary to study two alternative systems, one with and one without the pumped storage installation, in considerable detail and over a long period of time, say 25 years. The success with which this can be done depends on ability to forecast the trend in the price of coal, the annual improvement in efficiency of steam plant, and the rate of system load growth. It also depends on assumptions which have to be made as to the life of steam plant before it is removed from service as obsolete, the efficiency and incremental cost of operation and maintenance of the steam plant which can be used to supply the pumping energy and the proportion of the total fuel costs which are regarded as fixed and incremental respectively with coal cost at Rs. 70/-tone fixed charges may roughly workout to Rs. 120/- per K.W. and running cost may work out 3 paise per unit.

A study indicates, however, that initially after introduction of the storage plant the overall fuel consumption of the system will be increased, but this increase will be reduced with passage of time until there may become a very small saving. This is due to the effect of retarded improvement of steam plant efficiency lessening as the capacity of the storage plant becomes a smaller proportion of the total on the system.

Though it is necessary to analyse the individual components of the total annual cost, both with and without pumped storage, to be certain what is the maximum capital cost of a storage installation which is economically acceptable, it may be concluded that if the capital cost is less than the cost of a new steam plant it is certain to give an overall advantage. In such a study the effect of transmission must be considered, as the comparison will be effected if the storage plant is remote from where the output can be absorbed.

There may well be cases when the ratio of the cost of providing off-peak and peak load thermal energy is of the order of two thirds which is similar to the overall efficiency of the storage plant. Hence if the storage project is to show a surplus of revenue over expenditure the revenue from sale of the kilowatt capacity must exceed the remaining annual costs of the storage plant, i.e. the capital charges and the operation, maintenance and adminstrative costs. If the storage scheme can be constructed for a capital cost which is no greater than that of an equivalent steam plant, the annual cost will be in favour of pumped storage since the depreciation rate and the operation and maintenance costs of such a plant will be lower.

5. <u>Cost of a particular scheme</u> (Fig. 21)

The following example is the actual project now being taken up for construction in Tamilnadu,India. It is named as Kadamparai stream which is a tributary to Aliyar river, which in turn forms part of the Parambikulam-Aliyar Project complex. The scheme envisages a single pumping stage between the upper Aliyar lake already formed under Parambikulam-Aliyar Scheme as lower storage reservoir and another new reservoir as upper storage across Kadamparai stream. The mean gross head obtainable would be about 400 m. The project is based on an installed capacity of 400 M.W.(4x100 MW) with vertical generator motor and pump-turbines.

KADAMPARAI PUMPED STORAGE SCHEME. TAMILNADU, INDIA.
4 X 100 MW

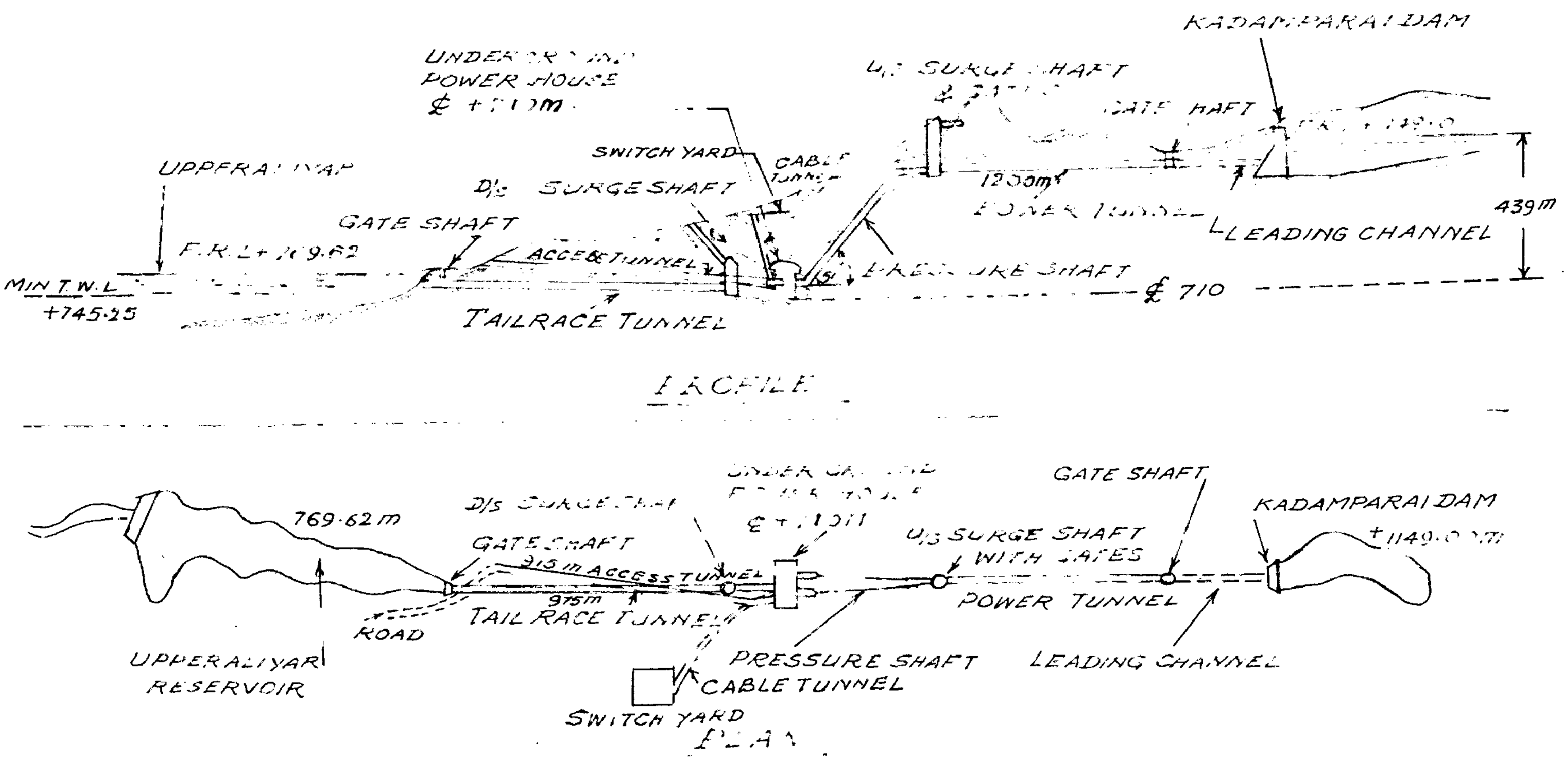


FIG. 21

a) The plant is designed to operate at full load for 4 to 6 hours during morning and evening peak periods. During off peak period i.e. between night 10 P.M. and early morning 6 A.M. it will pump for about 7 to 9 hours replacing the water used for power generation during peak hours. Maximum power drawn is 120 M.W. for each of the four units.(87)

A brief report of the Kadamparai pumped storage scheme is enclosed at the end. Fig. 21 gives the profile and plant layout.

The full load flow during generation = 150 cumecs

$$\therefore \text{The daily storage required} = \frac{150 \times 6 \times 3600}{10^6}$$

$$= 3.24 \text{ million } M^3$$

Storage as per scheme report = 7 million M^3

However, this has been since increased to 30 million M^3 for various reasons as explained in reference(87).

The capital outlay on the project as sanctioned by planning commission in Feb. 1973, is Rs. 3512 lakhs.

The necessity or need for taking up a 400 M.W. pumped storage scheme in Tamilnadu is also explained in the next chapter.

Presently the financial aspect of the Kadamparai pumped storage scheme is worked out in the following pages.

b) <u>Interest and depreciation</u>

The estimated cost of the scheme is Rs. 3512 lakhs and it is approximately made up as follows:

I. Dam, and associated work like diversion flumes, water conductor system, buildings roads etc. = Rs. 1500 lakh i.e. 43%

II. Power station plant and transformer etc. = Rs.2012 lakh i.e. 57%

Interest is calculated at 6% per annum (i.e. in 71-72 rate) and depreciation charges worked out on a sinking fund basis also at 6% interest taking the lives of the above two category of work as 80 years and 35 years respectively. Since the most common method of allowing for the amortization of the permanent works is to make uniform annual payments into a sinking fund which is assumed to accumulate at compound interest. The amount of the annual payments is determined so that at the end of the period of amortisation the values of the fund equal to the original capital.

Taking into account the lives for the two classes, the percentage figures used in assessing the respective sinking fund payments on a 6% interest is as given below.(27) (p.70 Vo.III)

Item I.	Civil works - 80 years	......	0.09%
Item II.	Electrical and mechanical equipments. - 35 years.	.....	0.90%

∴ Total annual sinking fund payment will be

Item I.	43% x 0.09%	......	0.0387%
Item II	57% x 0.90%	.....	0.5130%
			0.5517%

or Say 0.6%

. . Interest and depreciation taken
for working out is 6.6%

c) Annual Running expenses

Generally this will be 1% of the capital cost comprising cost of stores etc. 0.03%, salaries and wages for operation 0.37%, Maintenance and repairs .. 0.40% and general management expenses 0.20%. Also this will work out approximately Rs. 8/- to Rs. 10/- per kilowatt of installed capacity. For the present calculation it is taken as Rs. 9/- per kilowatt.

d) Hence to clarify the feasibility of a pumped storage scheme, the details of Kadamparai pumped storage and its revenue return is furnished below.

KADAMPARAI PUMPED STORAGE SCHEME (Fig.21)

Installed capacity .... 4 x 100 M.W.(400000 KW).

1) The station will generate for 6 hours 400 M.W. giving relief to the peak demand of the grid.

2) The station will utilise surplus energy available in the grid for pumping water for 8 hours during off peak hours between 10 P.M. to 6 A.M. The maximum capacity is 120x4 = 480 M.W. so that if enough energy is available even in 6 hours it can pumpe up the required quantity for peak generation.

Generation Mode

No. of hours of generation in a

gear taking 300 days of working = 6 x 300

= 1800 hours.

∴ No. of units generated with 400 M.W.

... $\frac{400000 \times 1800}{10^{6}}$ million units

= 720 million units.

Energy generated from its free flow

in a 90% year. = 80 million units

∴ Total generation = 800 million units in a year.

Pumping Mode

No. of hours for pumping in a

year taking 300 days of working = 8 x 300

= 2400 hours.

Similarly the energy required for pumping in a year

$= \frac{400000 \times 2400}{10^{6}}$

= 960 million units

The scheme was sanctioned by Planning Commission, Government of India in February 1973. The estimates and percentage return gives below are based on 1971-72 figure.

Data

1. Estimated cost of the project .... Rs. 3512 lakhs
2. Cost of energy sold 12 ps/unit
3. The incremental value of fuel burnt in thermal plant. ... 3.5 p/unit

4. The annual interest @ 6% + depreciation at 0.6% and operation & maintenance charges at Rs. 9/-k.w. ....Rs.265 lakhs

Cost of pumping energy = $\frac{960 \times 10^6 \times 3.5}{100}$

= Rs. 336 lakhs.

∴ Total cost for generating 800 million units = Rs. 336 + Rs. 265

= Rs. 601

Or say Rs. 600 lakhs

∴ Cost of generation per unit

$$= \frac{600 \times 10^5 \times 10^2}{800 \times 10^6}$$

= 7.5 p/unit.

Since there is no difference in tariff for peak energy and off peak energy it is sold only at 12 ps/unit.

∴ Revenue by selling 800 million units

$$= \frac{800 \times 10^6 \times 12}{100}$$

= Rs. 960 lakhs.

∴ Net revenue after deducting pumping charges, interest, operation and maintenance charges, depreciation etc.

Rs. 960 - Rs. 600 = Rs. 360 lakhs

∴ Percentage of return on the capital outlay of Rs. 3512 lakhs $= \frac{360 \times 100 \times 10^5}{3512 \times 10^5}$

= 10.25%

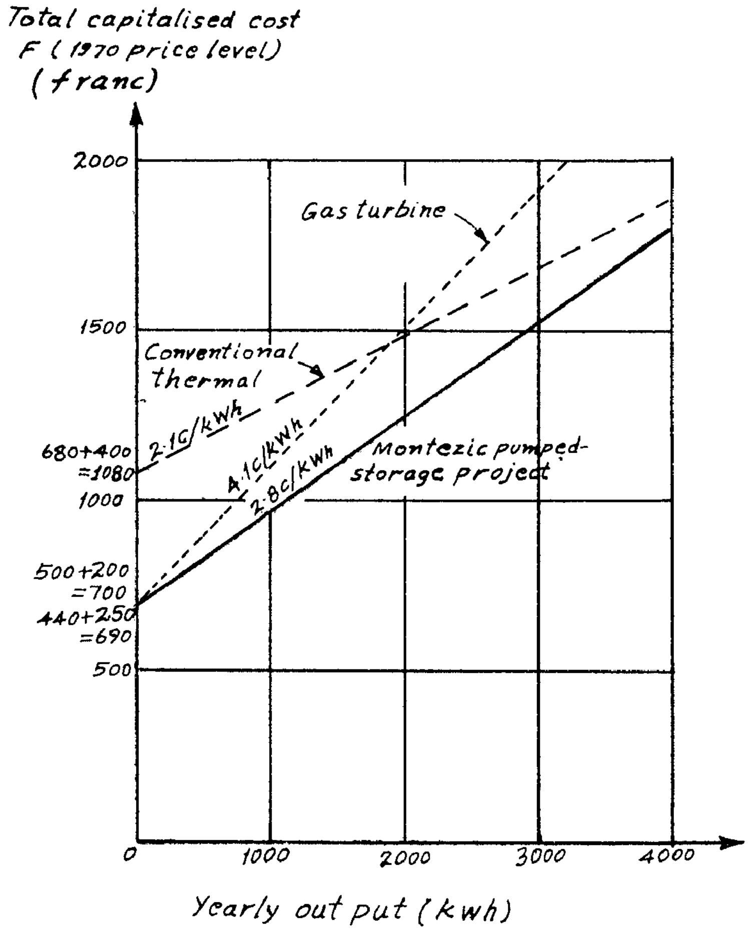


FIG.20 - A COMPARISION OF THE TOTAL CAPITALIZED COST OF PRODUCING 1 KW OF PEAKING ENERGY BY DIFFERENT FACILITIES

The statement I showing the percentage of return after third year of operation also confirms this (statement enclosed).

And cost per kilowatt of installed capacity

$$= Rs.\ \frac{3512 \times 10^5}{400 \times 10^3} = Rs.878.00/KW$$

e) Thus, the scheme is highly remunerative even though higher charges are not adopted for peak energy supplied to the consumers. Secondly the pumping energy taken during off peak hours is absorbed usefully by this scheme which otherwise will go waste to some extent. Thirdly no new thermal or hydro plant will be needed, particularly if thermal plant is replaced in its place, then fuel charges and operation and maintenance charges will increase the overhead charges.

6. By way of conclusion, a graph given in an article by Mr. Jaonns Cotillon, titled "The evolution and pattern of hydro stations in France", is reproduced in Fig.20. This shows a comparison between the total capitalised cost (investment cost plus annual operating capitalised cost) of thermal, gas turbine and pumped storage peaking capacity.

The example chosen for pumped storage plant is Montezic pumped storage plant of 750 M.W. (3 x 250 MW) capacity operating under a head of 410 m and now under construction in France. From the curve it may be seen that the capitalised cost for energy generated by pumped storage plant is the lowest of the three alternative considered, e.g. let us compare the capitalised cost for an yearly output of

Sl. No.	Total expendi- ure.	Revenue earned @ 12Ps/unit	Net surplus or defi- cit in revenue.	Cumula- tive effect on the revenue.	Remarks.
1	9	10	11	12	13
1.	1.50	...	-1.50	-1.50	Construc- tion period.
2.	9.00	...	-9.00	-10.50	
3.	4.00	...	-24.00	-34.50	
4.	1.00	...	-51.00	-85.50	
5.	6.60	...	-96.60	-182.10	
6.	2.40	312.00	+69.60	-112.50	Ist unit will be commissioned on (1.4.1978)
7.	2.20	528.00	+145.80	+33.30	IInd Unit will be commissioned on (1.4.1979)
8.	5.80	744.00	+148.20	+181.50	IIIrd & VIth unit will be commi- ssioned on (1.4.1980)
9.	3.00	960.00	+357.00	+538.50	All machines working

Deficit.

STATEMENT I

STATEMENT SHOWING THE REVENUE RETURN

All figures are in Lakhs of Rupees

Sl. No.	Year.	Fund allotted during the year for construction.	Total Funds.	Interest at 6%, 3% for 1st year & 6% for earlier funds.	Depreciation at 0.6%	Operation & Maintenance @ 1% or Rs.9/-kw	Cost of pumping energy @ 3.5 P/unit (including transmission)	Total expenditure.	Revenue earned @ 12Ps/unit	Net surplus or deficit in revenue.	Cumulative effect on the revenue.	Remarks.
1	2	3	4	5	6	7	8	9	10	11	12	13
1.	1973-74	50.00	50.00	1.50	...	...	...	1.50	...	-1.50	-1.50	Construction period.
2.	1974-75	200.00	250.00	9.00	...	...	...	9.00	...	-9.00	+10.50	
3.	1975-76	250.00	500.00	22.50	1.50	...	...	24.00	...	-24.00	-34.50	
4.	1976-77	600.00	1100.00	48.00	3.00	...	...	51.00	...	-51.00	-85.50	
5.	1977-78	800.00	1900.00	90.00	6.60	...	...	96.60	...	-96.60	-182.10	
6.	1978-79	800.00	2700.00	138.00	11.40	9.00	84.00	242.40	312.00	+69.60	-112.50	Ist unit will be commissioned on (1.4.1978)
7.	1979-80	600.00	3300.00	180.00	16.20	18.00	168.00	382.20	528.00	+145.80	+33.30	IInd Unit will be commissioned on (1.4.1979)
8.	1980-81	212.00	3512.00	204.00	19.80	36.00	336.00	595.80	744.00	+148.20	+181.50	IIIrd & VIth unit will be commissioned on (1.4.1980)
9.	1981-82	...	3512.00	210.00	21.00	36.00	336.00	603.00	960.00	+357.00	+538.50	All machines working

Even after the end of Second year of operation the revenue will be surplus and there is no deficit.

∴ Capital charged at the completion of work ..... Rs. 3512.00 lakhs.

Minimum Net revenue in any year = Rs. 357 lakhs

∴ Percentage of revenue return per year = $\frac{357 \times 100}{3512}$ = 10.16%

say 1000 kwh for all the three alternatives.

Sl No.	Type of generation.	Capitalised cost (1970) in Francs(
1.	Pumped storage plant.	925
2.	Gas turbine	1085
3.	Conventional thermal	1300

(French) 'F' Franc = Re.1.80 approximately)

Hence he has finally concluded that it is far better to install a pumped storage station where good sites are available than thermal or gas turbine for peak energy supply.

CHAPTER VII

IMPORTANCE AND PROSPECTS OF SUCH DEVELOPMENTS IN INDIA

1. The progress and prosperity of a country to-day depends largely upon the quantity of energy it can develop and utilise. Amongst all forms of energy, electricity will continue to be the most sought after on account of its easy transmission and more conveneint use. Level of its consumption in any country or region will continue to be an index of its prosperity. Per capita consumption of electricity in India is yet very low only about 2 to 3% of that in developed countries. Therefore development of all possible electrical resources in the most beneficially coordinated manner is imperative for the progress of our country.

2. Our main resources for power generation are coal and water. It is estimated that our coal deposits is about 80,000 million tons and our annual consumption is about 80 million tons. By the end of Fifth Five Year Plan this may increase to 135 million tons. However, in this respect we have sufficient reserve for sometime to come. Regarding oil we are having only one-third of our annual requirement of 23 million tons. This may improve in coming years by new exploration which are promising. Regarding water our hydro resources are capable of generating 41,160 M.W. Of this so far (March 1974) only 6970 M.W. has been utilised. This shows we have enough resources to develop but due to various reasons, greater development could not be possible yet.[30]

3. As the industrial development proceeds, we will be using more and more of electrical power for the industires. With larger connected loads, the peaking problem will accentuate and also there will be surplus energy which will create a problem for efficient working of the plants. Hence planning has to be directed to development of pumped storage alongwith exploitation of new hydro resources. Ministry of energy is already contemplating embarking upon pumped storage development in a big way. This is the correct approach as along with large thermal stations or Nuclear stations, large capacity pumped storage plants will render the former more efficient both in respect of economy and operational efficiency. There may be some good sites for pumped storage plant which should not be lost by constructing small capacity hydro power stations.

4. Some of the pumped storage schemes which were sanctioned by Planning Commission for construction are as follows:

i) Kadamparai - Tamilnadu - 4 x 100 MW

ii) Kadana - Gujarat - 4 x 60 MW

iii) Nagarjunasagar, Andhra Pradesh - 2 x 62 MW initially

iv) Jayakavadi, 1 x 12 M.W

Head proposed to be utilised at Kadamparai is about the same as at Cruchan pumped storage plant (U.K). Accordingly its design is also more or less similar to it. It has short water conductor system. The existing upper Aliyar reservoir for Aliyar power house (1 x 60 M.W) will serve as lower storage.

It will contribute 400 M.W. of peak power for about 6 hours (including morning and evening peak) by 1980-81, when the peak demand for Tamilnadu may go up to 3000-3500 M.W. at the present load growth of 12½% per annum.

Now the project is under construction and the dam excavation for the upper reservoir having a storage of about 30 million M^3 has been started. Importance and necessity of this project has been explained subsequently.

5. In an article written by Mr. G.K.Mathur in 1966, a mixed pumped storage plant at Ramganga has been conceived, alongwith a nuclear plant and a large multi-purpose reservoir. The proposal is quite attractive. The installed capacity proposed is 2 x 200 M.W. (reversible unit). Maximum head is about 106.8 m. Deriaz type of reversible unit is proposed. India has lot of scope for developing such mixed type pumped storage plant along with its multipurpose irrigation schemes. Nagarjunasagar pumped storage plant and Kadana pumped storage plant are two such examples, and it is learnt D.V.C. are also planning such schemes.

6. Tamilnadu is particularly power starved. Its chief source of power is from lignite near Neyeveli and water resources. It is estimated that about 2000 million tons of lignite may be available. With the latest modification about 6.5 million tons will be mined per year and used for power generation at Neyveli with its 600 M.W. capacity. The other major thermal station is

at Ennore with a capacity of 450 M.W. nearing completion. Further new thermal station with a capacity of 2 x 200 M.W. is provided at Tuticorin and the Kalpakkam Atomic Plant under construction will add about 470 M.W. (2 x 235) within about Vth Five Year Plan. With all these the thermal power may be about 1700 M.W. At present the capacity is about 1030 M.W. Its hydro resources are almost exhausted i.e. out of 3080 MW of hydro developed in southern grid comprising (Tamilnadu, Andhra Pradesh, Kerala and Karnataka), Tamilnadu has developed about 1224 M.W. There are also some hydro plants under planning and construction.

The total capacity may be around 1200 M.W. only. With 12½% load growth its peak demand will reach about 3500 M.W. by 1980-81. To fulfil such a growth of demand the project under planning are not sufficient. Since more than 50% of its installed capacity of 2254 M.W. is from hydro, there will be lot of variation in generation due to Vagaries of monsoon. To have a firm generation footing more and more of thermal stations and nuclear stations should be taken up. For example the 2000 M.W. second mine cut at Neyveli and 1200 M.W. second Atomic plant should be taken up immediately. As the output of these plants will come only after seven to ten years the construction and planning should be started now itself. When such huge thermal and nuclear plants come in operation, further pumped storage schemes will be needed to make use of offpeak surplus power and add to the peaking capacity of the grid without any extra fuel. There are two or three pumped storage schemes with high head under planning. Since Tamilnadu and all its neighbouring states are inter-connected, such plants will be useful for the whole grid to take up fluctuations. More and more of pumped storage plants should come into operation along with large thermal/atomic power plants for developing our industries.

7. Tamilnadu Grid and its need for Kadamparai Pumped Storage Scheme

7.1. At the time of independence in 1947, there were three hydro stations, Pykara, Papanasan and Mettur and one thermal station at Madras city having a total installed capacity of only 139 M.W. By 1957 it rose to 256 M.W. with the addition of Moyar H.E.station, Madurai thermal plant and extensions to Pyakara and to Papanasan. However between 1957 to 1967 the growth of electricity in Tamilnadu was more rapid. In Tamilnadu the major hydro electric and thermal schemes were as follows (by 1967):

I) Hydro Electric Schemes

i)	Periyar I and II stage	140 M.W.
ii)	Kundah H.E.Scheme I & II and III stage	425 M.W.
iii)	Parambikulam H.E.scheme	185 M.W.
iv)	Kodayar H.E.scheme	100 M.W.

II) Thermal Schemes

i)	Extension to basin Bridge power house	30 M.W.
ii)	Ennore thermal scheme	340 M.W.
iii)	Neyveli thermal station	600 M.W. (Central scheme)

From 256 M.W. of installed capacity in 1957, the system capacity rose to 1470 M.W. by 1967. By 1974 the installed capacity in Tamilnadu rose to 2254 M.W. of this hydro contributes more than 50% i.e. 1224 M.W. The balance thermal power is 1030 M.W. (i) Ennore - 340 M.W. (ii) Neyveli - 600 M.W. (iii) Basin Bridge power house - 90 M.W.

By 1978-79 the three hydro stations (165 M.W), one pumped storage station Ist stage (200 MW) Thermal station at Ennore and Tuticorin and Kalpakkam Atomic plant 1st unit (430 MW) will add 1245 M.W. and the total installed capacity will rise to 3499 or say 3500 M.W. Further planning to utilise the cheap hydro potential is progressing. In addition large capacity thermal and atomic plants of capacity more than 1000 MWs each are also under planning. Already two more pumped storage schemes, totalling 200 M.W. are under planning. As per our planning within 10 years there will be 600 M.W. of installed capacity for pumped storage scheme for better utilisation of the large thermal developments like

i) Ennore
ii) Neyveli
iii) Tuticorin
iv) Kalpakkam Atomic plant
v) Neyveli IInd Main cut
vi) Second Atomic plant

all totalling to more than 4500 M.W. A statement showing the schemes under planning as in 1975 is attached at the end.

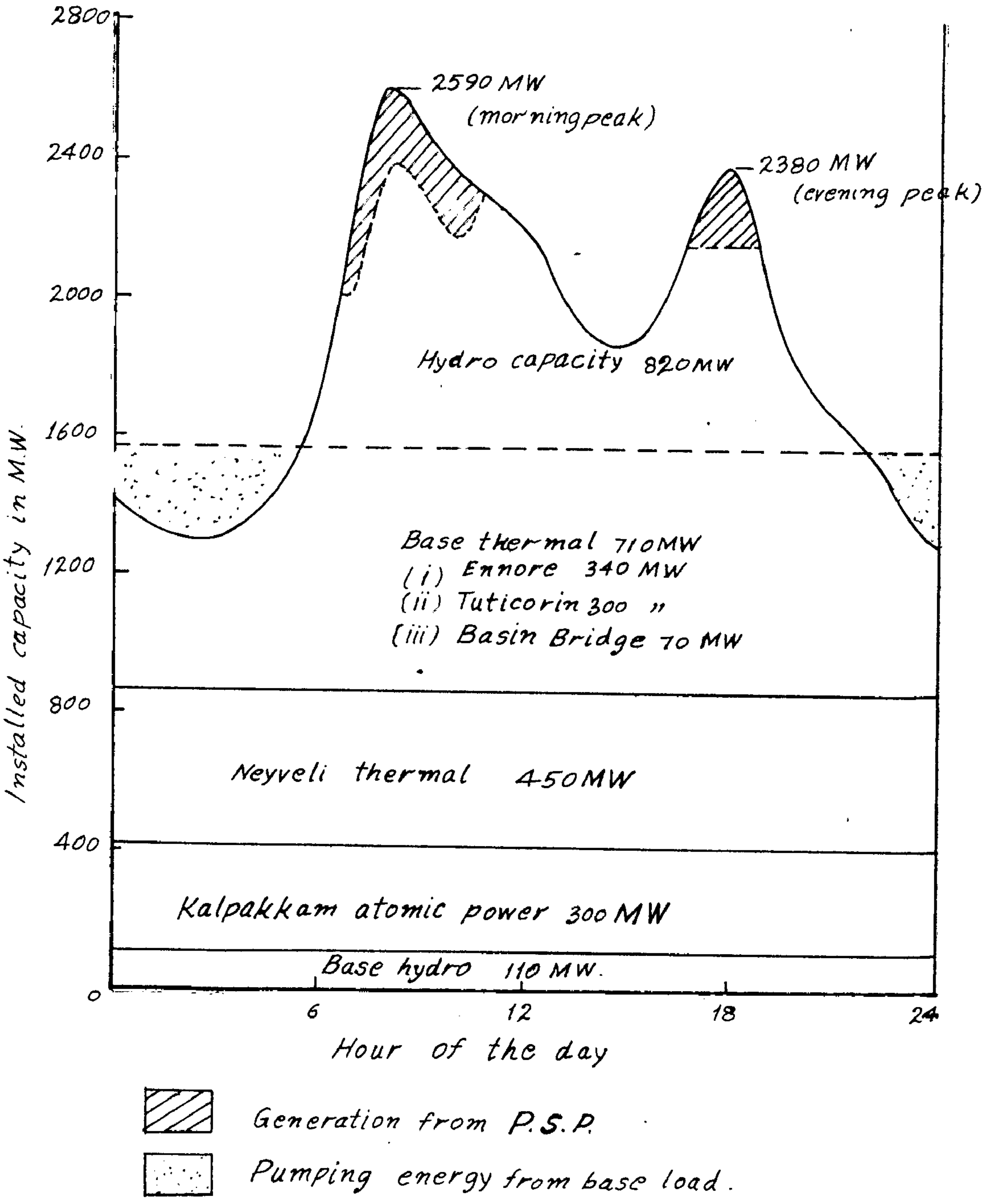


FIG. 22 - A TYPICAL DAILY LOAD CURVE FOR TAMILNADU IN 1978-79

For planning Kadamparai pumped storage scheme a study of the grid capacity and demand for the coming years of 1978-79 and 1980-81 was made in C.W. & P.C. hydro Electric planning directorate. The highest peak of 1972 considered for study at that time was 1275 M.W. At 12½% load growth by 1978-79, this peak demand is expected to become 2590 M.W. A daily load curve for 1978-79 (non-irrigation season) with a peak load of 2590 M.W. (morning peaks) and 2380 M.W. (for evening peak) was prepared, assuming also the same pattern as that for 1972 for hourly demand.

The Fig. 22, shows the typical daily load curve for 1978-79.

The study takes into account the following:

i) As the period considered is non-irrigation season, most of the irrigation controlled stations will not be available for power generation. However, during irrigation season they will be generating at base load stations with the shutdown of some of the units of thermal stations like, Neyveli, Ennore and Basin Bridge for overhauling.

iii) The maximum capacity of thermal station less the consumption of auxiliaries (at 20%) and also for their own use (e.g. Neyveli - though generates 600 M.W. only about 450 MW alone is expected to be given to Tamilnadu grid) is considered. Since there are number of units in a Thermal station, smallest unit capacity for overhauling is considered at this time, so that most of the large units are available for base load generation.

III) By 1978-79, it is expected that the first unit of Atomic plant at Kalpakkam may be able to spare 300 M.W. to Tamilnadu grid, and Tuticorin thermal station may also give about 300 MW to the grid.

IV) During non-irrigation season, such of those high head hydro stations given below with large storages and not controlled by Irrigation will be available for taking care of the daily load fluctuations e.g.

1) Kundah I,II,III and IV stage	535 M.W.
2) Pykara-Moyar	106 M.W.
3) Aliyar	60 M.W.
4) Kodayar, P.H.I and II	100 M.W.
5) Suruliyar	35 M.W.
6) Nellithorai	50 M.W.
7) Servalar	20 M.W
	906 or say 910 M.W.

Less 10% for auxiliaries

The capacity available = 820 M.W.

The total energy available from 820 M.W based on the storage etc. is (as from previous experiences) = 9.33 M.W.

The total base load capacity of the grid

i) Thermal station of TNEB	710 M.W.	= 1570 M.W.
ii) Neyveli	450 M.W.	
iii) Atomic plant	300 M.W.	
iv) Base hydro	110 M.W.	

The total energy available from 1570 M.W. = 37.68 M.U.

∴ The total energy available from the hydro and from base thermal = 9.33

37.68

47.01 m.u.

The total energy required as per the curve 46.18 m.u.

∴ Surplus energy available = 0.83 m.u.

However, from the daily demand curve it was estimated that even though 37.68 m.u will be available from the Base thermal capacity we will be able to use only 36.00 m.u. as power demand is less than our base capacity between 10 P.M. in the night and 5.30 A.M. in the morning, thus about 1.68 m.u. will be-come surplus.

Secondly from 5.30 A.M. to night 10 P.M. there are wide fluctuations in the demand, the demand increases from 1570 M.W to 2590 M.W. in about 2½ hours i.e. the capacity required to meet this peak demand is 2590 - 1570 = 1020 M.W.

Against this the hydro capacity available is only 820 MW

∴ Our system capacity for peaking will be less by 200 M.W. in 1978-79.

The total energy for the curve for the day = 46.18 m.u.

Of this the energy utilisable from Base stations less the surplus = 86.00 m.u

(37.68 - 1.68 = 86.00)

∴ The energy required for the area above the base

= 46.18

<u>(-)36.00</u>

10.18 m.u.

As already stated the energy capability of 820 M.W. hydro is... 9.33 m.u.

∴ Shortage of energy for this period of the day

0.85 m.u.

∴ Between 5.30 A.M. to 10 P.M., in addition to peak deficit of 200 M.W., the energy shortage will be

= 0.85 m.u.

However, it is observed that there will be surplus energy to the tune of 1.68 m.u. available during off peak hours.

Hence the best method will be to utilise the surplus energy available in the grid during off peak hours for satisfying the peak deficit in capacity and energy in the grid.

The Kadamparai pumped storage scheme is planned only for such contingency. Its capacity is fixed as 2 x 100 M.W. initially and then increased by another 2 x 100 M.W. thus totalling to 400 M.W.

Assuming by 1978-79 we are able to install 200 M.W. (as orders for the machineries i.e. reversible unit has already been placed with M/S BHEL/Bhopal and being manufactured by M/S Boving,(U.K.) it will help the grid as follows:

(i) Its 200 M.W. pumps will work for eight hours to pump about 3 million cubic metre of water to a high level storage i.e. Kadamparai reservoir with 30 million cubic metre capacity, consuming an energy of 1.60 m.u from the surplus eneggy of 1.68 m.u. available in the grid during off peak hours.

(ii) During peak demand period in morning and evening it can contribute 200 M.W. of generating capacity for six hours with a total energy contribution of 1.20 m.u. against an energy deficit of 0.85 m.u. in the grid.

Thus the planning of Kadamparai pumped storage scheme in Tamilnadu will be a standing example for optimum utilisation of system capacities and at the same time satisfying the load growth in the country.

KADAMPARAI PUMPED STORAGE HYDRO ELECTRIC PROJECT
(A BRIEF REPORT)

The project derives its name from Kadamparaiar (a tributory of Aliyar) across which the head race pond is proposed. The scheme basin lies between latitudes 10°20' and 10°25' North and longitudes 77°0' and 77°10' East. The project is located in the Anamalai hills of the Pollachi taluk in the Coimbatore district, upstream of the Upper Aliyar Dam executed under the Parambikulam Aliyar Project complex. The scheme is situated in the Poonachi Reserve forest range admidst hills and dales of enchanting scenic beauty and enthralling wild life.

The main Kadamparai Forebay Dam site is 72 k.m. from the Pollachi rail head and 20 k.m. from the Valparai town in Coimbatore district. The power house site is located 7 k.m. from the Upper Aliyar dam camp site.

This is a mixed pumped storage project consisting of a forebay dam across the Kadamparaiar at E.L.+1086.92 m.with a gross storage capacity of 30 million cu.metres at F.R.L.+1149.00 m commanding run off from its direct free catchment area of 22.79 sq.k.m. Also the run off from a catchment area of 60.09 sq.k.m. in the upper reaches of Aliyar will be diverted into this forebay by a series of diversion weirs and flume channels. The power draft is proposed to be drawn through a lined pressure tunnel of length 1248 m, and section 41.28 sq.m. to convey a peak discharge of 150 cumecs required for the ultimate installation of 400 Mega watts. The tunnel ends in a head race surge shaft 18 m. in diameter and 57 m. deep. Two tunnels take off from the surge shaft to an underground P.H. The two Nos. steel lined underground pressure shafts, each 486 m. long and diameter 4.0 m and inclined at 51^{o} to the horizontal convey the power draft to the machines. Each pressure shaft will bifurcate into two shafts 3.0 m. diameter at a Y junction at the Power House end to feed a 100 M.W. reversible machine.

An underground power house with a machine cavern 91.5 m long x 26 m wide x 36.5 m high will house both the 13 No. transformers and the 4 Nos. 100 M.W. reversible pump turbines working under a maximum gross head of 405 m. with the elevation of the centre line of the distributor being kept at +710.00 m. (3?.25 m. below the minimum tail water level to avoid cavitation.) The tail waters are proposed to be conveyed through a lined tail race tunnel 975 m long and cross section 41.28 sq.m. with a discharging capacity of 150 cumecs to the existing Upper Aliyar Reservoir which will function as a tail race pond for the power house. A cable cum ventilation tunnel of diameter 4.6 m. and length 237 m. will take the power cable to the outdoor switchyard. The power house cavern will be approached by means of an access tunnel 7.0 m. wide x 6.5 m high and of length 915 m. from the foreshore of the Upper Aliyar Reservoir. The approach tunnel will be connected to the Upper Aliyar dam and Attakatti camp, the nearest places of approach through suitable branch roads.

The project is mainly designed, in addition to the utilisation of the natural flows from the free and diverted catchments upstream of the Kadamparai Dam, as a pumped storage project to meet a part of the likely deficit in the grid during peak hours in future by utilising the off-peak energy that will become available from the Ennore Thermal/Kalpakkam Nuclear Stations now under execution. Thus, the main benefit from this project will be the supply of peak energy to the grid and preservation of the capacity value of the station during irrigation closure season.

To suit the site conditions and terrain and reckoning also the technical and economic feasibility, the project has been envisaged as an underground installation with the powerhouse and water conductor system proposed to be located completely underground. When the project is completed, this will be the first underground installation in Tamil Nadu and the second Pumped Storage project in India, the only other project being the Nagarjuna Sagar pumped storage installation in Andhra Pradesh.

The project is proposed to be implemented in two stages, the capital outlay on the project at the end of the first stage being Rs. 2143 lakhs and the total cost of the project being Rs. 3512 lakhs. This affords 400 Megawatts of firm peaking capacity and about 720 million units of peaking energy per annum to the Tamil Nadu grid. Cost per kw of the project works out to be Rs. 878/-. This scheme would normally be operated as a pumped storage scheme excepting during the monsoon periods, when the free flows in the basin will enable the station to be operated as a conventional scheme to generate about 79 million units.

The power generated is proposed to be stepped up to 230 K.V. and fed into the Tamil Nadu grid at Udumalpet by means of two single circuit 230 K.V. lines.

GENERATION SCHEMES - PROPOSED AS ON 1975 FOR TAMILNADU

HYDRO

1.	Akkamalai	25 MW
2.	Cholathipuzha	60 MW
3.	Coonoor-Kallar	30 MW
4.	Hogenakal	800 MW
5.	Koniar Pumped storage	100 MW
6.	Kundah Ultimate stage	205 MW
7.	Lower Mettur	160 MW
8.	Lower Moyar(Kukkalthorai)	40 MW
9.	Manimuthar	65 MW
10.	Paralayar	35 MW
11.	Pykara Ultimate stage	2 x 50 MW
12.	Shanmuganadhi	30 MW
13.	Upper Amaravathi	20 MW
14.	Upper Thambraparani	165 MW
15.	Valar Pumped Storage	100 MW

THERMAL

16.	Neyveli II Thermal Station	1000/1200 MW

NUCLEAR(Govt.of India)

17.	Extension at Kalpakkam	470 MW (200 MW to Tamilnadu)
18.	Second Nuclear Plant near Tuticorin	1000 MW

TABLE I

DEVELOPMENT IN HIGH HEAD PUMPED STORAGE PLANTS

a)

Name	Country	Capacity M.W.	Head m	Remarks
1	2	3	4	5
a) Existing or planned Francis turbines for heads of over 450 m and outputs over 50 MW				
1. Ferrora	Switzerland	3x72	552	
2. Murray I	Australia	10x118	520	
3. Usta	Norway	2x92	510	
4. Rana	Norway	3x121	495	
5. Suldal II	Norway	1x70	565	
6. Sundsparm	Norway	1x103	460	
7. Rosshag	Austria	4x58	672	Highest for Francis
8. Hornberg	W.Germany	4x231	652	
9. Pradella	Switzorland	4x75	494	
b) Recent orders for multistage high head storage pumps for delivery head over 650 m and inputs over 50 MW.				
10. Hongrin	Switzerland	4x59	848	
11. Roncovalgrande (Lago Delio)	Italy	8x100	743	
12. Letesava	Italy	2x52	680	
13. San Fiorano	Italy	2x140	1438	
14. Rosshag	Switzerland	4x59	687	
15. Hornberg	W.Germany	4x255	664	

TABLE II

MAJOR FRANCIS REVERSIBLE PUMP TURBINES

Name	Country	Surface or Under-ground	Head ft.	Submer-gence ft	H.P. in 1000
1	2	3	4	5	6
1. Ronkhausen	W.Germany	S	863	52	99.5 2x70 MW
2. Shinnarihaga-wa.	Japan		278	-	104.5
3. Ikehara I	Japan	U.G.	374	33	107
4. Yagizawa	Japan	-	318	29	117
5. Oroville	U.S.A.	U.G.	500	15	120
6. Cruachan	U.K.	U.G.	1206	150	142 4x100 MW
7. Muddyran	U.S.A.	S	353	35	138
8. Azumi	Japan	-	430	-	143.5
9. Ikehara II	Japan	U.G	374	33	148
10. Yards creek	U.S.A.	S	656	25	150.5
11. Nagano	Japan	-	352	-	154
12. Cartersdam	U.S.A	S	345	-	173
13. Villarino	Spain	U.G	1280	160	181 (4x125 MW)
14. Coo-Trois pont	Belgium	-	896	-	194.5
15. Jocassee	U.S.A.	-	294	-	206
16. Kinzua (Seneca)	U.S.A.	S	646	-	207.5
17. Foyers	U.K.	S	550	130	227
18. Cabin Creek	U.S.A	S	1190 (362 m)	37	223 (2x166 MW)
19. Castaic	U.S.A	S	1000	50	275 (2x261 MW)

Table II (contd.)

1	2	3	4	5	6
20. Taum Sauk	U.S.A.	S	790	32	295
21. Kisen-yama	Japan	U.G	726	98.5	328
22. Northfield	U.S.A.	U.G	745	106	345
23. Cornwall	U.S.A.	U.G	1050	50	345
24. Mortezuma	U.S.A.	U.G	1710	16	94
25. Ludington	U.S.A.	S	350	25	..

TABLE III

LIST OF PUMPED STORAGE SCHEMES
EXISTING, UNDER CONSTRUCTION & PROPOSED

Country	Station	No.& type.	Head m	Station capacity MW	Year
1	2	3	4	5	6
I. Austria	1. Achental	4 P&S.	385	85.9	1928
	2. Rodund I	4 P.S.	328	230	1952
	3. Rodund II	2 P.S.			
	4. Kaprun-Limberg	2 P.S.	364	115	1956
	5. Lunersee	6 P.S.	875	233	1957
	6. Reisseck	3 P.S.	1770	60.4	1957
	7. Innerfragant (Oschenik)	2 P.S.	1050	58	1968
	8. Zemm, Upper (Rosshog)	4 P.S.	672	230	1971
	9. Qetz Valley UG	4 P.S.	1100	4x132	U.C.
	10. Malta (Upper)	6 R T.	203	90	Proposed
	11. Malta (Main)	6 P.S.		540	
	12. Oschenik II	1 P.S.	1050	29	
	13. Riedi	4 R.T.		360	
	14. Breitenau	4 R.T.		350	
	15. Antersback	4 R.T.		160	
II. Australia	1. Tumut 3	3 F.	151	1500 (6x 283)	
	2. Tumut 3	3 R.S.			Under construction.
	3. Bendeela	2 R.T.	122	80	Proposed
	4. Kangaroo Valley	2 R.S.	440	160	
III. Belgium	1. Coo Trois(U.G) Pont I	3 R.T.	269	432	1971
	2. Pont II	3 R.T.	266	432	Proposed

Table III (Contd.)

1	2	3	4	5	6
IV. Brazil	1. Vigario	4 R.T.	29	44	1952
	2. Santa Cecilia	4 R.T.	13.7	21	1952
	3. Pedreira C	3 R.T.	27.1	44.7	1953
	4. Primavera	4 R.T.	129	494	Proposed
	5. Pacaluba	R.T.		553	
	6. Caraguatatuba	R.T.		690	
	7. Sao Felix	4 R.T.		115	
	8. Paranoa	R.T.		107	
V. Bulgaria	1. Belmeken	1 F.S.	700	83	1972
	2. Antonivanovis	1 F.S.	122	50	1973
VI. Canada	1. Sir Adam Bock	6(Deriaz)	25	198	1957
	2. St.Joachim(U.G)	3 RT.	355	1200	Proposed
VII. Czecho-slovakia	1. Devin		111	517	Proposed
	2. Kamenice		194	439	"
	3. Dobshina III		596	275	"
	4. Koprova Dolina		894	415	"
	5. Sutova		235	552	"
	6. Kninick		204	134	"
VIII. Colombia	1. Alto Muna	2 RT.	135.7	30	Proposed
IX. East Germany	1. Bleiloch	2 FS.	58	40	1932
	2. Hohenwarte I	2 F.S.	66	42	1958
	3. " II	8 FS.	305	320	1965
	4. Niederwartha	6 FS.	143	129	1960
	5. Wendefurt	2 FS.	124	80	1968

Table II (Contd.)

1	2	3	4	5	6
X. Finland	1. Avanta	4 RT.	109	280	
	2. Parainern I	2 RT.	200	40	Proposed
	3. " II	2 RT.	285	200	
	4. Päijanne I	3 RT.	136	240	
XI. France	1. Lac Noiv	4 FS.	126.5	100	1938
	2. Vouglans	1 RT.	92	53	1973
	3. Emosson	2 PS.	750	128	1972
	4. Revin	4 RT.	245	660	Under construction
	5. Lacoche	2		160	Proposed
	6. Montezic U.G.	RT.	400	800	
XII. Hungary	1. Predikaloszek I	3 FS.	507	307.5	Proposed
	2. " II	6 FS.	507	615	
	3. Heguistete	4 F.	351	300	
	4. Tokay		405	270	
	5. Hossuhat		204	240	
XIII. Italy	1. Provvidenza	2 FS.	255	152	1951
	2. Villa Garonauo	2 FS.	416	134	1960
	3. Late Sava	2 PS.	624	104	1963
	4. Brasimone	2 RT.	378	338	1973
	5. Lago Delio	8 PS.	732	1040	1971/72
	6. St.Fiorano II	2 PS.	1403	200	1972
	7. Fadalto	2 FS.	107	240	1971/72
	8. Chiotas-Piastra	4 PS.	990	540	Planned
	9. Rovina Piastra	1 FS.	540	105	"
	10. Taloro	FS.	200	240	"

Table III (Contd.)

1	2	3	4	5	6
	11. Piani di Ruschio	FS.	560	480	
XIV. Japan	1. Oguchigawa III	2 PS.	621.2	17.9	1931
	2. Shiroyama	4 RT.	153	260	1964
	3. Ikehara U.G.	4 RT.	120.5	380	1964
	4. Yagisawa	3 RT.	93.5	261	1965
	5. Nagano	2 RT.	97.5	226	1963
	6. Shinnarihagawa	3 RT.	84.3	234	1968
	7. Azumi	4 RT.	134.9	436	1969
	8. Midono	2 FT. 2 RT.	80 79.8	128 128	1969
	9. Takane I	4 RT.	135	251	1969
	10. Numappara	3 RT.	478	732	1973
	11. Shin Takase	4 RT.	230	1320	Proposed
	12. Masegawa I	2 RT.	105	296	1972
	13. Kisenyama(U.G.)	2 RT.	220	480	1970
	14. Shin Toyone(UG)	5 RT.	230	1150	1972
	15. Atashika I	RT.	382	496	Proposed
	16. Nikappu	2 RT.	94	210	1970
	17. Agehara	4 RT.	459.6	1088	1970
	18. Okutataragi(UG)	4 FS.	406	1212	Under construction.
XV. Luxembourg	1. Vianden - I	9 FS.	278	900	1964
	2. " II	1 RT.	276	200	1973
XVI. Norway	1. Jukla (Folgefona)	1 RT.	142	38.4	Under construction
	2. Stavali	1 RT.	277	120	
	3. Sysen	2 RT.	239	180	

Table III (Contd.)

1		2	3	4	5	6
XVII. Poland	1.	Zhidovo	3 FP	77.5	150	Under constructio
	2.	Solina	2 RT	60	42.4	1968
	3.	Porambka Zhar	-	442	265	Proposed
	4.	Porombka Zhar Chupily	-	605	282	"
	5.	Kasinka		520	290	"
	6.	Psheska		660	305	"
	7.	Snezhka		198	150	"
	8.	Smotniki		104	180	"
XVIII. Republic of Ireland	1.	Turlough Hill	4 RT	282	292	1973
XIX. Rumania	1.	Lotru	7 FS	809	500	Proposed
XX. Spain	1.	Valdecanas	3 RT	75	225	1965
	2.	Torrejon	4 RT	48	133	1967
	3.	Puento Bibey	4 FS	336	400	1967
	4.	Villarino	4 RT	405	540	1968
	5.	Ibondelp	3 PS	980	103.5	1969
	6.	Guillena	3 RT	230	216	Under construction
XXI. Switzerland	1.	Ruppoldingen		319	1.35	1904
	2.	Robiei	4 RT	410	160	1968
	3.	Isogyren type	+ 1	400	10	1972
	4.	Hongrin(U.G.)	4 PS	878	240	Under constructio
	5.	Sarganserland	3 FS	483	262	Proposed

Table III (Contd.)

1	2	3	4	5	6
XXII. U.K.	1. Ffestiniog	4 FS	310.5	360	1963
	2. Cruchan U.G.	4 RT	362	400	1966
	3. Foyers	2 RT	173	300	1974
	4. Loch Sloy	4 RT	267	1200	Proposed
	5. Camlough	2 RT	195	460	
	6. Lough Shanogh	2 RT	272	460	
XXIII. U.S.A.	1. Hiwasee	1 RT	74	60	1956
	2. Lewiston	12 RT	30	240	1962
	3. Fairfield	8	45.7	496	Proposed
	4. Taum Sauk	2 RT	263	408	1963
	5. Yards Creek	3 RT	232	339	1965
	6. Smith Mountain	2 RT (2F)	60 (60)	132 (300)	1965
	7. Cabin creek	2 RT	374	300	1966
	8. Muddy Run	8 RT	125	800	1967
	9. Oroville (U.G.)	3 RT (3 F)	205 (205)	293 (351)	1968
	10. San Luis	8 RT	99	424	1968
	11. Kinzua	2RT (1F)	250 (262)	396 (26)	1970
	12. Northfield(U.G.) (mountain)	4 RT	250	1000	1972
	13. Ludington	6 RT	110	1872	1973
	14. Blenheim Gilboa	4 RT	348	1000	1973
	15. Carters	2 RT	132	250	1974
	16. Jocassee	4 RT	95	610	1974
	17. Elbert I	1 RT	135	100	1975
	18. Kaysinger Bluff	6 RT	24	160	1977

Table III (Contd.)

1	2	3	4	5	6
	19. Castaic	6 RT 1 PT	324	1200 50	1977
	20. Bearswamp	2 RT	235	600	U.C.
	21. Marble Valley	5 RT	270	1250	Proposed
	22. Stony Creek	6 RT	297	1950	"
	23. Blue Ridge	8 RT	80	1600	"
	24. Montezuma (U.G.)	4 RT	515	500	"
	25. Merrill Lake		335	500	"
	26. Blair Mountain	3 RT	671	525	"
	27. Cornwall (U.G.)	8 RT	354	2000	"
	28. Havasee	4 RT	305	1000	"
	29. Racoon Mountain	4 RT	317	1528	U.C.
	30. Tocks Island	5 RT	360	1300	
XXIV. U.S.S.R.	1. Kiev	3 RT	65	120	1970
	2. Zagorsk	6 RT	100	1200	Proposed
	3. Tata.P.S.(Extension)	2 RT	17	54	"
	4. Arsona	-	-	840	"
	5. Taldy Kongana	-	-	730	"
XXV. West Germany	1. Waldeck I	4 FS	296	140	1932
	2. Hausern	4 FS	187	110	1933
	3. Witzneu	4 FS	216	220	1943
	4. Waldshut	4 FS	133	160	1951
	5. Happy Burg	4 FS	204	160	1958
	6. Raisach Rabenkite	3 FS	179	97.5	1955/61
	7. Gees Thacht	3 FS	80	105	1958

Table III (Contd.)

1	2	3	4	5	6
	8. Glems	2 FS.	283	90	1964
	9. Erzhausen	4 FS.	288	220	1965
	10. Sackingen U.G.	4 FS.	400	360	1967
	11. Ronkhausen	2 RT.	266	140	1968
	12. Hornberg	4 FS.	625	970	U.C.
	13. Waldeck II, U.G.	2 FS.	320	440	U.C.
XXVI. Yugoslavia	1. Lisina	2 FS.	343	33	1973

Note:

U.G. - Underground P.H.
U.C. - Under Construction
R.T. - Reversible turbine
F.S. - Francis turbine - Separate pump
P.S. - Pelton Wheel - " "

R E F E R E N C E S

1. A.N.Singh - A report on the participation in I.A.H.R. Symposium in Rome, 1972.

2. Asynchronous starting of a 230 MVA synchronous machine in Vianden II. P.S.Station, Brown Boveri Review, July 1974, p. 31.

3. Avdec V - Zagorsk - P.S.Station, Hydro Technical Construction, April 1972 pp 318.

4. Arokiaswamy, N.S.S. - Scope and utility of P.S.S. Journal of the T.N.E.B. Jan-Dec. 1969, p.5

5. A Survey of P.S.Potential in Switzerland, W.P.May 1973 p.160

6. Basic Task of the Hydro Power Construction - Hydro Technical Construction, Jan. 1974, page 4.

7. Baldwin,B.L., Significance of present Hydro Power Development in the European part of the U.S.S.R., Hydro Technical Construction June,1974, pp. 497.

8. Bear Swamp P.S.P. (U.S.A.)- Journal of Bostan C.E. Section (ASCE) July 1974, pp 132.

9. Bernalski. T., Engineering-Economic Design Basis of P.S.S. Hydro Technical Construction April 1972, pp. 340.

10. Bulgaria P.S. H.E. Project, W.P, Sept. 1968, pp. 374.

11. Cornwall Pumped storage project - Water Power July 1965 pp 255, W.P. Nov. 70 pp. 376.

12. Chapman, E.J.K., Value of water power in a mixed system water Power, April 1963, pp.169.

13. Castaic Power Station, Escher Wyss News, Vol. 47, 1974.

14. Coo-Trois Ponts - P.S.Station, Belgium, W.P.Feb. 1970 p.46.

15. Conference on P.S.held at Milwaukee, U.S.A., W.P. Aug. 1971, PP 312.

16. Davis-Sorensen - Hand Book of Applied Hydraulics - Pumped storage - 25.1 and Hydraulic Machinery 26.78.

17. Design, Construction and Operation of the Zydowo P.S.S.in Poland Hydro Technical Construction, July 1972 pp 558

18. Deriaz Machine - W.P. March 1964, pp.100.

19. Eustratios Comninellic - Ludington P.S.Project, Journal of the P.D. of ASCE, May 1973, pp 69.

20. Emil Mosonyi - Water Power Development, Volume II. P.S.Development pp 887-1063.

21. Eli Safchrovids - Condenser Cooling and P.S.reservoirs - Journal of P.D. of the ASCE, July 1971,pp.611.

22. Editorial, W.P. January 1970.

23. Effect of P.S. on Thermal Plant fuel consumption, W.P. October 1971, pp 371.

24. Ffestiniog, P.S. Development, W.P. May 1963, pp 85 Augutt 1964, pp 323.

25. Foyers, P.S.S., W.P. May 1968, pp 87.

26. Frohntrolzes, Dr. Ing.J. - Operation of P.S.Station in the Federal Republic of Germany, W.P. Oct. 1973, pp 374.

27. Gutherie Brown - Hydro Electric Engineering Practice Volume II and III.
Vol.II Chapter XVIII - pp 648 to 686
Volume III Chapter VII pp 134 to 151.

28. Hans Blind. Dr.Ing., Planning of P.S.Plant, W.P.June 1967, pp 226.

29. Horizontal and vertical arrangement of P.S.P., W.P. July 1967, pp 287.

30. Has Tamil Nadu got enough power - M.Rashid Ahmed, Indian Journal of Power and River Valley Project, May 1975, p. 5.

31. Irrigation and Power - October 1971, pp 309 (Editorial on P.S. Power).

32. Integration of Pumped storage with Tidal power (by L.Shaw.) - Journal of the P.D. of ASCE Jan. 1971, pp 159.

33. Isogyre pump turbines, W.P. Jun 1973, W.P. Jan.64 pp.41.

34. James D. Hamlin - Experiences with large pump turbines at Niagara Falls.

35. Jaegar, C., Peak load and pumped storage power stations. The English Electric Journal, May-June 1964.

36. Jaquet,M. - Some special problems in pump turbine development, Escher Wyss News - Volume 47 1974/ No.2 pp.20.

37. Ludington P.S.P. - Journal of P.D. of ASCE, May 1973 pp.69

38. Keowee-Toxaway Power System - Journal of the Civil Engineering Division, ASCE, June 1975,p.46

39. Muddy Run P.S.P. (U.S.A.), Engineering News Record, 7th April 1966, pp.90

40. Mathur,G.K., Mixed P.S. at Ramganga in conjunction with a Nuclear Station. Indian Journal of Power and River Valley Projects Jan. 1966, p.10.

41. Main types of Machine Buildings Arrangement on present day P.S.S. - G.A.Pretro.Hydro Technical Construction, April 1972, pp.328.

42. Norway Energy Rate in 1967 - W.P. Dec. 1970.

43. Operation of the Kiev P.S.P. Hydro Technical Construction August 1974, PP 740.

44. Okutataragi, P.S.Station of Japan Mitsubishi Heavy Industries Technical Review No.1, Feb. 1975, pp. 21.

45. Pumped storage for efficient power supply - some aspects of the Hongrin - Lemon Scheme, Switzerland. The Civil Engineers in South Africa, April,1973 p.97

46. Power Plan (Generation) for the decade 1971-81 - Indian Journal of Power and River Valley Project April 1972, pp.133.

47. Pumped storage-What is the future - Part I and II - W.P.Sept. 1974, pp 312, Oct. 1974 pp 343.

48. Pumped storage stations on the Azusa River-Japan, Hydro Technical Construction April 1972,pp 336.

49. Prezekwa S.M., Polish Experiences in the planning of P.S S. Hydro Technical Construction,April 1972 pp 346.

50. Pumped storage stations of the world and their importance in Electric supplies in future. Hydro Technical Construction April 1972, pp 354.

51. Pumped storage-state of Art - Journal of the P.D.of ASCE July 1971, pp 675.

52. Pumped storage schemes - under planning in U.S.A., W.P. June 1965, pp 202.

53. Pumped Project in Japan - Shintoyne P.S.P. Civil Engineering in Japan, Vol.12, 1973.

54. P.S.Project - Special Issue, 1970, W.P.March 1970.

55. Regional interties and National Supergrids, W.P. Jan 1963, pp. 263.

56. Robuk, N.N., Investigation of transient phenomenon on a model of a reverssible turbine at the KIEV P.S.P. Hydro Technical Construction,Mar.74 pp.247.

57. Review of P.S.plant in Germany, W.P.Nov. 1967, p.460.

58. Rudnicky,V., The importance of P.S.S. in the supply economics of power systems (Polish Experiences)- Hydro Technical Construction,April 1972 pp 551.

59. Rashid Ahmed, M.., Kadamparai- A peaking energy paradise - Journal of the T.E.B, Jul.-Dec. 1972 P.5.

60. Rodund II, P.S.Scheme, W.P. Nov. 1973, pp. 413.

61. Siebensohn - Trends in U.S.Hydro Equipment Design,Part I and II - Water.Power, Feb.1974, pp 44-47 March 1974 pp.92.

62. Seminar on the theme "Aspects of the Design of pumped storage plant" hydro technical construction Jan. 1974,pp 53.

63. Savvin,M., Constructional Characteristics of P.H.of modern pumped storage plant Hydro Technical Construction, Jan.1974, pp. 74.

64. Swiss pumped storage symposium 1964 - Water Power Feb.1965-pp61.

64.(a) Sumulson,B.D., Kiev P.S.S.Hydro Technical construction April 1972 pp. 313.

65. Towards the wide spread stimulation of the study of problem relating to pumped storage Hydro Technical construction(ASCE) July 1973 pp 677.

66. The Lean Project Concept in the economic design of P.S. H.E.P. The world power Conference Sept.1974 (RICH.G.R),Water Power Jan.1965 p.17,Feb.75 p.76.

67. Tata H.E. and P.S.Extension - Hydro Technical Construction April 1972, pp. 321.

68. Takashi Hashimoto - Power Station Design Trends in Japan,Part I,II and III W.P. April 1968, pp.146 May 1968 pp 199 June 1968 pp.243.

69. Venice Peak Load Symposium - 1963 Part I, II and III, W.P.,Oct. 1963, pp 432, Nov. 1963 pp.467, Dec. 1963,pp.516.

70. Vianden I, P.S.P. Part I,II - W.P.July 1964,pp 285 Aug. 1964, pp. 328.

71. Vianden II - W.P. August 1971, pp. 342,

72. Waldeck II- U.G.pumped storage station - Siemens' Review, 6/75, pp.249- 8/69 W-P.Mar.70, pp. 211.

73. Warnock - J.G., Underground reservoir for high head P.S. Stations, W.P. March 1973, pp.81.

74. Waldect I - W.P. Aug. 1971, pp.275.

75. Zeligen, A.N., Determination of the fuel effects of pumped storage plant. Hydro Technical Construction, Jan. 1974 pp. 34.

75. Zeligen,A.N. - Determination of the fuel effects of pumped storage plant, Hydro Technical construction, Jan. 1974., P.34.

76. A Brochure on Kadamparai P.S.S. - Published by T.N.E.B.

77. Cruchan - P.S.P(U.K.) - Extract from W.P.Jan. 1966.

78. Cornwall P.S.S. - New York State U.S.A. - W.P.Nov.1970

79. World power conference held in Moscow, W.P. Dec. 1968 p.483 Underground Pumped storages.

80. Patrick.J.G., The Cluster layout - a New Concept for Pumped storage - W.P. Sept. 1972 p.339.

81. Joannes Colillon, The Evolution and Pattern of Hydro Stations in France, W.P. Nov. 1972, p. 395.

82. Editorial on P.S.S. - W.P. Jan. 1970.

83. Takamura Sujuki - The main trends of H.E.Development in Japan - W.P., Feb.1972, p.43. 51, 65.

84. New 1800 M.W., P.S.S. in U.K. - W.P., July 1972, p. 234

85. Pierre R.Gerard - The Revin P.S.P., W.P. Nov.1972, p.411.

86. Tajio Yoshimoto, The Atashika Sea Water P.S.P., W.P. Feb. 1972, p. 57.

87. S.L.Narasimhan, "Pumped Storage Scheme - Its impact on overall power development in the context of optimum utilisation of water power (M.E.Desertation) Page 103.