FOURTH UNITED NATIONS
INTERNATIONAL CONFERENCE
ON THE PEACEFUL USES OF ATOMIC ENERGY
Geneva, Switzerland, 6-16 September 1971

A/CONF. 49/P/798
SWEDEN
June 1971

THERMAL ENERGY STORAGE IN ROCK CHAMBERS - a complement to nuclear power

P H Margen, AB Atomenergi, Studsvik, Sweden

Summary

Within about a decade from now, the nuclear capacity on several generation systems will have become larger than the night load, thus increasing the incentive to exploit cheap night energy for daily storage schemes. In Sweden, energy storage schemes using rock cavities have been studied for a number of years. These include pumped storage schemes with lower magazines well below ground surface and gas turbine schemes with compressed air magazines. Recently preliminary studies have been made of a third form - that of storing hot high pressure water in rock cavities with a simple thermal insulation. One method of utilizing this water is as feed water for a nuclear power station, the water in the store being heated from about 73°C to 217°C at night, and the stored hot water being fed directly to the Nuclear Steam Supply System (NSSS) during the day. An increase in turbine output by about 25% can then be achieved at peak periods due to the elimination of the h.p. steam bleeding for unchanged reactor power. About 35 kWh of electricity can be recovered per m^3 of storage volume, i.e. 30 times as much as if one m^3 of cold water had been allowed to descend 450 m under gravity to the lower magazine of a pumped storage plant. This illustrates how much more effective hot water storage utilizes the space of a rock cavity than does cold water storage for a pumped storage plant even at very great depths.

The paper describes the circuit proposed and the design of the accumulator to meet the requirements concerning thermal insulation (to avoid exposing the rock walls to daily temperature cycles), avoidance of risk of leakage of slightly active feed water to the surrounding ground water even under severe accident conditions such as pipe and tank ruptures, and water chemistry to avoid water containing impurities or dissolved gases from reaching the feed water circuit. A preliminary cost analysis is given which shows that the proposal allows the generation of additional blocks of peak load power at annual load factors of 15 to 40% at generation costs which are about half that of the best fossile fuel plants at typical fossile fuel costs.

1. Introduction

Daily storage of energy has been used on electricity systems for many decades for the purpose of converting cheap off-peak power to more valuable peak load applications. Some examples are given in table 1. Pumped storage schemes using two open reservoirs are perhaps the most common method today. Thermal storage was used widely in the 1920's in Ruth's accumulators which stored hot water in steel pressure vessels and then obtained steam by pressure reduction, feeding this saturated steam to a turbine to meet very short daily peak loads. Thermal storage is still used widely in district heating schemes with water at low pressure, where the accumulator reduces low pressure bled steam demands for district heating at peak electricity demand periods. The use of steel pressure vessels for storing hot power station feed water was proposed by Marguerre 1958 (1) and the author made proposals 1958 and 1959 for storage of hot water for flash steam energy generation in rock cavities (2, 3).

Lately novel energy storage schemes have been studied in Sweden in some detail - namely the excavation at some 450 m below ground level of a rock cavity which could serve as the lower reservoir of a pumped storage scheme (4) or as a compressed air reservoir for a gas turbine plant (5), thus avoiding the need to operate the compressor at peak load periods. The latter proposal is at an advanced stage of study, and a prototype plant may be constructed during the 1970's.

With the exception of the pumped storage schemes with two open reservoirs where costs depend on geographical conditions, most of the proposals listed in table 1 have either a very low energy storage capacity per m^3 of storage volume (e.g. the pumped storage reservoir with submerged lower magasin), or very high capital cost per m^3 (e.g. steel pressure vessel for Ruth's accumulator or Marguerre's feed water store). The result is the same - namely a high contribution of the reservoir costs to the cost of energy. This contribution is so high, i.e. 2 to 4 mills/kWh even within very high utilisation, that it cancels any advantage in running costs at base load, over peak load plant. (Reservoir costs must be treated as running costs in so far as the design daily load factor affects the required reservoir capacity and thus reservoir cost.) Hence such plants may have their use for very short peak load duties, but cannot be used for medium load factor operation, which would require savings even in running costs. One exception - the gas turbine plant with air magazine - has a lower reservoir cost contribution but is linked inevitably to a high fuel cost plant and thus nevertheless restricted to very low load factor operation.

As the introduction of nuclear plants on the power systems of the industrial nations proceeds, the time will soon be reached - on some systems in the early 1980's, others late 1980's - when the nuclear capacity (or sum of the nuclear capacity and run-off river hydro plant capacity) exceeds the night electricity demand. At that stage electricity is available at night at only the running cost component of nuclear fuel, and thus lends itself particularly well to input to a daily energy storage plant. Hence the search after economic forms of energy storage plants will be intensified.

The proposal made in this paper is covered by the last item (6b) in table 1. It adapts feed water storage to a nuclear station, and thereby makes use of the very high energy storage per m^3 made possible by a reservoir operating over a temperature range of some 144°C. It adapts the rock cavity thermal storage to some recent design techniques, thereby achieving the very low cost/m^3 made possible by rock cavities as opposed to steel pressure vessels. The net result of this combination is a contribution of the magazine cost to the energy cost by only about 0.45 mills/kWh, which, added to the running cost of nuclear fuel, still leaves a major cost incentive compared to fuel oil - thereby allowing nuclear plants to take up serious competition at an early date with fossile fuel plants also in the medium load factor range.

Table I Various types of energy storage plants

Type of plant	Type of store	Energy stored per m^3 kWhe/m^3	Capital cost per m^3 $/$m^3$	Capital cost per kWhe store capacity $/kWhe	Store's contribution to energy cost[i] mills/kWhe
1. Traditional pumped storage	Natural or artifical lakes	variable over a wide range			
2. Ruth's accumulator	Steel pressure vessel	10[ii]	260	26	7.1
3. Warm water accumulator (dist. heating)	Low pressure steel vessel	5	60[iii]	12	3.3
4. Pumped storage with underground magazine	Rock cavity 450 m under ground	1	12	12	3.3
5. Gas turbine with compressed air magazine	Rock cavity 400 m under ground	5.5	14	2.55	0.7
6. Feed water heating	a) steel pressure vessel b) insulated rock cavity	35 35	220 58	6.30 1.66	1.7 0.45

i) based on full utilisation of store 300 d/year & 8.24% cap. charges p.a.
ii) initial pressure 30 bars, final pressure 15 bars
iii) applies for large accumulators. About twice this value applies in most practical installations at present as these use smaller accumulators

2. Basic circuit

Fig. 1 shows the proposed basic circuit. The warm water accumulator is shunted across a train of medium pressure feed heaters, which heat the feed water from T_1 (typically 73°C) to T_2 (typically 217°C) at night. More than the normal feed water quantity needed by the boiler is passed through these feed heaters at night. Thus the excess (see white arrows) can be recirculated through the accumulator to the input point. As hot water is fed in at the top of the accumulator and cold water taken out at the bottom, the separation surface between hot and cold water falls during this operation, and the accumulator becomes charged with hot water at T_2.

During the peak day demand period (see black arrows) the flow through the medium pressure feed heaters ceases. Instead cold water is pumped into the bottom of the accumulator at T_1, and hot water at T_2 is taken out at the top. In the example in Fig. 1 this is further heated some degrees by a high pressure feed heater to make use of the fact that the bled steam pressure during the day, when no feed heating takes place, is somewhat higher than at night, when bled steam feed heating is at a maximum.

As no steam is bled to the medium pressure feed heaters during the peak demand period, the turbine output is increased by some 25% compared to the normal output obtained without energy storage from the same reactor power. This excess power is thus obtained without increase in reactor capacity. The only extra capital costs incurred are those for the increase in turbine plant and feed water system, and those for the accumulator.

Fig. 2 shows the process on a temperature entropy diagram with idealised isotropic processes. Curve 1 represents schematically the expansion corrected for feed heating in a conventional nuclear plant, curves 2 and 3 those for the plant with the proposed storage scheme at day and night respectively. The area between curve 1 and 3 is the energy being stored per unit time, that between curves 1 and 2 the energy being recovered from store per unit time. Curve 3 can be adjusted for more or less bleeding of steam at night. Thus, for a given duration of the night storage time, different number of hours of day time peak load operation can be achieved, if the volume of the storage magazine is adjusted to the desired number of hours.

Fig. 3 shows a daily system load curve for a storage plant with a 7 hour night storage period and an equally long energy recovery period. This will be treated as the reference condition in the economic analysis.

3. Accumulator

Bare rock excavations are basically cheap - - of the order of 5 $/m^3 for large volumes at limited depth. For a pressure of 20 to 30 bars of interest for the current application, a rock cover of 50 to 60 m above the highest point of the cavity should be sufficient. For the current application the rock cavities must be complemented by a number of components for reasons given below.

3.1 Thermal insulation

The daily storage cycles produce cyclic temperature variations which could produce gradual deterioration of the rock walls, if these were not protected by thermal insulation. Thermal insulation using stagnant water is feasible, but expensive when so large surfaces are involved. Some twenty to thirty parallel thin plates would have to be used to create the necessary number of gaps, and stainless steel would have to be used to limit corrosion. The result is expensive and still gives fairly high heat losses.

As a result it has been decided to design for a dry insulation of conventional fibre in air. The water is then contained in a thin walled steel vessel given the same pressure as the air between the vessel and the rock walls by an open cold water surface as shown, for instance, by the alternative designs, Fig. 4 and Fig. 5. The vessel is then exposed only to the static head of water, and can be made of relatively thin steel plates. Heat losses can be restricted to about 2% of the heat loaded each day into the accumulator, and can be removed by circulating the air slowly upwards in the gap between the insulated tank and the rock walls by a circulator situated outside the main pressurized cavity. It is then passed through a cooler before being returned to the bottom of the gap. There is in addition a "degrading" of heat at the separation surface between water at T_1 and T_2

due to slight convection, producing an energy loss assessed to be equivalent to a further 1% heat loss.

3.2 Water quality

It is important that the high quality of the feed water in a nuclear station not be impaired by impurities and dissolved gases. For that reason a continous slight outflow of water is arranged through a narrow passage, A, towards the tank or part of a tank having an open water surface, B. This "sealing flow" of water prevents water containing dissolved gases from the water/air interface from reaching the high pressure feed water system. A corresponding flow quantity is leaked from B to a point where the water can be de-areated - e.g. the power station condenser as in Fig. 5.

3.3 Outleakage of activity

In certain nuclear reactors the feed water circuit can contain low activity, despite the total flow purification schemes often used. In PWR's this can occur as a result of fuel pin holes and small leaks in the steam generators, in BHWR's as a result of corrosion product in the direct cycle. No such active water must reach the surrounding ground water.

The steel plate vessels for the proposed designs prevent leakage in normal circumstances. Should, however, a water pipe burst within the rock cavity or the vessel spring a leak, water would flow into the air gap. The rock cavity wall can be made leak tight by injection with cement, and the requirement of make-up air for the compressor gives in fact a continous check concerning the quality of the tightness. To provide nevertheless even greater security against the consequences of a steel vessel leak, the rock excavation can be surrounded at intervals of one to two meters by small bored holes set under pressure by water to a level slightly higher than that of the air within the vessel* Normally some sealing water will then leak into the air gap from the surrounding holes if the cavity is not fully tight, and be removed by a pump. Even after a tank leak, the leakage will then still be from the outside to the inside, and no activity can leak out. To restore matters to normal conditions, the pressure in the cavity would be reduced by blowing air and steam - the latter through the special blow-off pipe connected to the station stack as shown by the double line on Fig. 4. Thus pressure will fall to the ground water pressure and outleakage is then impossible.

The above mentioned arrangements for reducing the accumulator pressure can also adequately deal with the extremely unlikely occurances of a major dislocation occurring in the rock face, creating a larger air leak. By bringing the accumulator pressure to a low level, outleakage of water can be prevented.

The above discussion shows that, with the proposed features, even extremely low risks of outleakage of activity can be prevented.

3.4 Consequences of external pipe rupture

If any of the water pipes leading from the rock cavity to the power station would burst outside the rock cavity, water could flood the station or leak to the surroundings. To prevent this risk, double valves can be fitted on each such pipe at the point where it penetrates the barrier between the cavity and the unpressurized pipe shaft. The valves are closed by signals

---

*This method is under study in Sweden for rock cavity containment of nuclear stations near population centres in the investigation discussed in [6] and may be tested soon in this connection in a small model rock cavity.

of overpressure in the pipe shaft or power station rooms, by over temperature signals, and by signals concerning excessive velocity in the pipes. The precautions are thus similar to those for a reactor safety enclosure.

3.5 Expansion volume

The main difference between the designs illustrated in Fig. 4 and 5 is the means of providing a volume for the thermal expansion of water in the accumulator as the accumulator is charged with hotter water. In the design Fig. 4, this expansion volume is provided by a steam space within the vessel.

To prevent flashing of water in the hot feed water line between the accumulator and the station level due to the lower static pressure at the higher level, the pressure within the accumulator should be H m water head above the saturation pressure at temperature T_2 - e.g. about 4 bars above 22 bars for $T_2 = 217^{\circ}C$ and H = 45 m. To achieve this and yet maintain a volume of steam, the steam dome must act as a pressurizer with a slight external input of hotter steam, which replaces heat losses in that area and maintains a water surface temperature 4°C above T_2. This can be achieved conveniently by connecting the first bled steam connection to the steam space as shown in Fig. 4, and supplying a throttling valve in that line for regulating the pressure to maintain the water level in the water lock constant. (To achieve heat transfer in the feed heater, the steam temperature in the first bleed steam connection is of course some degrees hotter than T_2). The air pressure in the chamber is maintained between stipulated limits by a small compressor and blow-off valve, in case some leakage occurs.

Of course flashing of water in the hot feed water line could also be prevented without the provision of higher temperature steam for pressurization, if an extra pump is provided to increase the pressure of the water in that line. However, extra pumps and pumping energy are expensive, and thus the solution outlined above is preferable.

With the alternative proposal, Fig. 5, the main accumulator vessel is always maintained full of water, but is connected to a small tank within the rock cavity with an open water surface, providing the pressure equalisation to the air. In this case expansion volume is provided by an open tank at ground level. At night this is gradually filled by excess delivery of the condensate pump as the water in the accumulator expands, and during the day (when the valve V1 is closed) the expansion tank is gradually emptied as water is discharged from it to the condenser for de-areation prior to returning it to the pressurized system. All other water levels in the system being maintained constant by the appropriate control functions of the associated pumps or regulating valves, the expansion tank automatically takes care of all volume changes in the water system.

3.6 Costs

Table II shows the required dimensions and estimated costs for accumulators associated with an 1800 MW thermal power reactor (600 MWe without accumulator, 750 MWe with), assuming a design duration of the additional 150 MWe output of 7 hours. Such an accumulator requires 29500 m^3 effective volume which is achieved by two storage tanks 30 m high and 26 m diameter.

The excavation costs are actually based on a station with four such reactors requiring eight storage tanks which can have two common pipe shafts (one for four tanks) and one common access tunnel for removing the masses to the surface. On this assumption excavations are estimated to contribute 10 $\$\ m^3$ effective accumulator volume to the cost, including tunnels. The thinwalled carbon steel vessel (24 mm near bottom, 8 mm near top) contributes as much as 22 $\$/m^3$, the thermal fibre insulation 10 $\$/m^3$ and various auxiliaries and pipes a further 10 $\$/m^3$ according to very preliminary estimates. Including interest under construction, planning costs etc, a total cost of 58 $\$/\ m^3$ is thus obtained.

For a utilization of 300 days/year capital charges of 8.24% p.a. (7% interest, 28 years), and an energy storage of 35 kWh/m^3 (see section 4) the annual capital charges contribute

$$\frac{58 \cdot 1000\ \text{mills/m}^3 \cdot 0.0824/\text{year}}{35\ \text{kWhe/m}^3 \cdot 300/\text{year}} = 0.45\ \text{mills/kWh}$$

to the cost of energy recovered annually from the accumulator.

This applies if the heat store is fully charged and discharged each day of the 300 assumed operating days per year. If instead there is a lower average degree of utilization defined by the factor f,

$$f = \frac{\text{average daily operating hours}}{\text{max daily operating hours permitted by heat store capacity}}$$

the accumulator contributes instead an amount 0.45/f mills/kWh to the energy cost. Usually f would be close to 1.0, as the running cost component of nuclear fuel (see section 6), would compete very favourably with the running component of fossile fuel plant. Hence one should operate the reservoir to full capacity on each day operation, if possible.

3.7 Energy reservoir for essential station supplies

The accumulator supplies also a valuable local energy store which can safeguard auxiliary supplies, and thus replace the otherwise necessary diesel or gas turbine units. A small steam turbine can be connected to the steam line used for blowing steam from the accumulator and for pressurization, and be supplied from this line when other steam sources fail. This is especially convenient in the case of the scheme Fig. 4, where a steam volume exists within the accumulator which can immediately start the house turbine. In the case of the scheme, Fig. 5, an air turbine could be used fed from air in the gap, backed up by the steam house turbine once the air pressure has fallen sufficiently to create a steam space within the accumulator vessel. Clearly the arrangement Fig. 4 is, however, simpler in this respect, and this could be one of the major advantages of this arrangement.

4. Turbine and auxiliaries

The turbine plant is basically conventional except for the design modifications outlined below. Quantities cited refer to the reference design condition of accumulator discharge in 7 full load hours.

The high pressure steam bleed points must be designed for double normal bleed flow rates, to allow for the additional bled steam quantities at night. The larger bled steam line can be accomodated on the available casing space for most conventional designs.

The medium pressure heaters must be designed for double water flow rates and double heat rates to meet the night charging requirements. As night energy is cheap, one can, however, accept double the normal logarithmic temperature difference for heat transfer at night, which compensates the increase in heat rate, so that no increase in heat transfer surface is needed. Hence the only additional feed heater surface required is that for the proposed small high pressure feed heater, Fig. 1. Hence there is only a small increase in feed heater costs relative to the large (25%) increase in electrical output.

Table II Accumulator data for 150 MWe (624 MWt) 7 hour peak supply

	Tank		
1.	Required effective volume at 35 kWhe/m^3	29500 m^3	
2.	Brutto dimensions: 2 cylinders, 30 m high x 26 m dia	31500 m^3	
3.	Steel weight (excluding water lock)	780 tons	
4.	Cost at 0.7 $/kg + 20% for water lock, foundations etc		0.65 M$
	Dry insulation		
5.	Total insulation area	5970 m^2	
6.	Resistivity	10 W/m^2	
7.	Mean air temp in gap between rock and insulation	80°C	
8.	Heat loss/day as per cent of daily heat to store[iv]	2.1%	
9.	Capital cost of insulation at 50 $/$m^2$		0.30 M$
	Excavation		
10.	Main cavity at 125% of brutto tank vol & 6 $/$m^3$	0.24 M$	
11.	Excavation cost for 1/4 of one tunnel & 1/2 of pipe shaft[v]	0.05 M$	
12.	Total		0.29 M$
13.	Auxiliaries & pipes to surface (approx)		0.30 M$
14.	Total (4) + (9) + (12) + (13)		1.54 M$
15.	Grand total, including planning & interest during construction		1.70 M$

[iv] $$\frac{5970\ m^2 \cdot 10\ W/m^2\ {}^\circ C\ [(217+73)/2-80]^\circ C \cdot 24\ h}{624 \cdot 10^6\ W \cdot 7\ h} = 0.021$$

[v] Applicable for station with 4 x 150 MWe accumulator arrangements.

Two feed water pumps in series (p_{m1} and p_{m2}) are provided, instead of the conventional single pump. The resulting cost increase is, however, nearly compensated by the fact that the design pressure of the medium pressure heaters is reduced by about a factor 3.

For saturated steam turbines of the type needed for water reactors, the question of moisture removal from the high pressure blading system must be examined for the peak load operating period. Normally, such moisture removal takes place via the bled steam connections. This is still possible during accumulator discharge for the first h. p. steam bleeding point as this feeds the high pressure heater even during the peak load period, and it is also possible for the 4th bleeding point, as this coincides with the cross-over from the high pressure to the low pressure cylinder. If this proves to be insufficient, one can allow one of the two intermediate bleed steam tappings to supply steam to a house turbine for auxiliary suppliers. As proposed earlier, the steam supply to this turbine can also be safeguarded by a connection directly to the accumulator.

As shown by the calculations in appendix 1, the extra turbine output obtainable for standard vacuum is 25%, requiring an additional turbine exhaust area of 38% of the conventional value. Since the peak load duty has limited duration, it would be economic to design for slightly higher vacuum and slightly smaller exhaust area, but this possible reoptimisation has been ignored. Thus the output of an 1800 MW thermal rating reactor is increased from 600 MWe to 750 MWe by the storage discharge.

Turbine plants for water reactors presently cost about 60 $/kWe, including condensors, auxiliaries, turbine buildings etc. The increase from 600 to 750 MWe requires no increase in the surface of the feed heaters (other than the small extra high pressure heater), but rather large increases to the turbine exhaust and condenser, of the type which can be achieved by going from a 6 exhaust to an 8 exhaust machine. It is estimated, in these circumstances, that the marginal cost for the increase from 600 to 800 MWe is slightly less than the 60 $ kW cited above for the average cost. However, 60 $ kW will be used in the subsequent calculations for the reference condition.

For a longer discharge time of the accumulator at the same heat rate, the heat quantity stored daily must be increased, and hence also the heat input rate to the accumulator during the strictly limited night load trough duration (7 hours). This increase in charging heat rate increases the night heat load on the feed heaters, and thus their cost for a given design temperature difference. When a correction is made for this, the marginal cost of the turbine plant and feed heating system can be expressed as the following function

C = $ (53 + h) per extra kWe,

which coincides with the value $ 60/kWe given above for h = 7 hours/day.

At a capital charge rate of 8.24% p a (7% interest, 35 years) this gives for instance

S (4.37 + 0.82)/kW p a

= S 4.37/kW p a + 0.275/f mills/kWh

if the station operates 300 days/year at an average daily capacity factor, h.

The annual operating cost incurred by the increase in turbogenerator capacity should be moderate, e g about $ 1 /kW p a.

5. Economy

At present nuclear fuel for LWR:s has a running component of about 1.25 mills/kWh under conditions in Sweden. The modifications brought about by the modifications associated with the heat storage cycle produce the following heat losses and gains over the daily operational cycle when expressed as percentage of the electrical energy stored in the accumulator.

Losses:	a) Thermodynamic loss produced by the increase in temperature difference in medium pressure feed heaters due to higher night loading (see Appendix 1)	7.4%
	b) Result of heat loss in accumulator	3 %
		10.4%

Gains:	Influence of efficiency improvement due to extra h. p. heater	3 %
	Net loss	7.4%

Hence the real running fuel cost for the additional peak load power is 1.25/(1.000 - 0.074) = 1.35 mills/kWh.

With the figures cited above and in paragraph 3 and 4 the total annual cost is evaluated in table III and compared with typical costs for oil fired plant with oil at 36 cts/million BTU.

Table III. Cost comparison with oil fired plant

Capital charge rate = 8.24% p. a. (7% int. 28 years); 300 days op. /year.

$$f = \frac{\text{average daily operating hours}}{\text{max daily operating hours permitted by accumulator/capacity}}$$

Cost item	Peak load supply from Thermal Storage Plant at Nuclear Station $/kW	Oil fired Station 40% efficiency, 36 cts/10^6 BTU fuel, $ 116/kW	Ratio
1. Fixed cost components			
1.1 Plant capital charges $/kW p a.	4.77	9.55	
1.2 Operation and maintenance	1.00	2.50	
1.3 Fuel (stored externally)	-	0.70	
Total	5.77	12.75	
2. Semi-running components from design load factor dependent charges: mills/kWh			
2.1 Feed heater component "	0.27/f	-	
2.2 Accumulator component "	0.45/f	-	
Total	0.72/f	-	
3. True running comp. (fuel) "	1.35	3.76	
4. Item 2 + item 3 for:			
f = 1.0 "	2.07	3.72	
f = 0.8 "	2.25	3.76	
5. Overall costs for h = 7 h/day			
f = 1.0 (= 2100 h/year) mills/kWh	4.72	9.84	1:2.08
f = 0.8 (= 1680 h/year) "	5.68	11.35	1:2.00

It will be seen that both the "running costs" (included the variable costs of the magasin and feed heating plant) and the "fixed costs" are about half those for conventional oil fired plant, and hence the overall costs are also about half (item 5). The proposed plant has thus a very powerful potential for reducing power costs. It should be stressed, however, that for nigh values of h, more important turbine design variations than those discussed in paragraph 4 would have to be undertaken, for instance to have room on the turbine casing for rather large bled steam pipe connections.

6. Time for economic introduction

On the Swedish system, the combined capacity of run-off river hydro- and nuclear plant is expected to begin to exceed the system night demand throughout the year in about 1985. First in that year, thus, the full benefits shown in table III will be attainable. However, the part of the benefit arising from the saving in fixed costs is attainable already earlier.

A reduction in the night output from the nuclear plant caused by the additional bleed steam demand for charging the accumulator would then be compensated by increasing the night output of fossile fuel stations. Thus no benefit in fuel costs would be achieved - indeed a slight loss due to the heat losses in the accumulator. This would, however, be very small compared to the large saving in capital charges made possible by the elimination of the boiler in the fossile fuel plant.

In accordance with this reasoning it would be fully justifyable to commission a thermal storage complement to a nuclear plant in say, 1978, reap benefits in capital charges compared to fossile fuel stations unit until 1985, and thereafter reap the full annual benefits. The overall benefit over the life of the plant assessed on a present worth basis would still be very high indeed.

Thermal storage plants installed at a later stage, e. g. in the late 1980s and 1990s, could be designed successively for higher daily load factors by supplying larger storage magasins and feed heaters, thus utilizing the whole growing night "load trough" in the electricity demand.

7. Other considerations

The proposal involves a number of advantages for nuclear reactors apart from the direct economic advantages of the additional block of very cheap medium load factor power discussed above. The advantage of a large local energy magasin for securing auxiliary power has already been mentioned. More important still is the fact that the reactor can operate continously at a contant load while the turbine meets load variations. Thus the nuclear fuel and other nuclear components can operate at continous conditions without stress and temperature cycles induced by load variations, and this should increase the fuel life achievable without damage, and even improve the performance statistics of other components. These advantages - though difficult to assess numerically - may well be very important.

The turbine load control can be achieved simply by operating a valve in the medium pressure feed heater line, which controls the proportion of feed water taken through the feed heaters, the remainder passing through the accumulators. For lower powers, also a valve in the accumulator shunt should be operated, to reduce the flow in this shunt further. Finally, for the lowest powers, the pump p_c is started to produce recirculation through the accumulator in the reverse direction, i. e. to charge the accumulator. Rapid regulation is achievable.

The present report has been restricted to describing a basic proposal. Several means exist of further increasing the peak load power contribution attainable with heat storage by refinements to the circuit, especially for covering peaks.

There are also means of combining heat storage for peak power generation in the manner described in this paper with heat storage for low temperature applications such as district heating, desalination etc, by using the hottest part of the temperature range of the stored water for the former application, the colder part for the latter. These refinements will be published elsewhere.

8. Concluding remarks

The preliminary investigation described in this report suggests that feed water storage in rock chambers promises major economic and technical benefits.

Hitherto it has been assumed that nuclear power plants would initially cover only the base load part of the power supply, later the base load and medium load part, leaving the peak load duty to fossile fuel plants of various types. With the proposal described in this paper nuclear power plants complemented by thermal stores could take over the medium load duties from fossile plant at a much earlier date, and eventually even the major part of the peak load duty. The next step is now to prepare a more detailed technical and cost analysis in cooperation with potential users.

9. Acknowledgement

The author wishes to thank engineers from the State Power Board and ASEA-ATOM for stimulating contributions to the discussion of several design problems.

10. References

[1] Fritz & Ferdinand Marguerre: German patents, Dec. 1958 and May 1959. (Expired).

[2] P.H. Margen and H. Carruthers: Swedish patent 1958.

[3] P.H. Margen: "Thermal storage in rock chambers". June 1959. Nuclear Engineering.

[4] Nils Berg: New types of peak load power stations", Svenska Kraftverksföreningen 1968:6. (In Swedish).

[5] H Josephsson: Gas-Turbinen für Spitzkraft - eine Analyse. Konferenz für Spitzenstrom Deckung. Budapest 1969.

[6] Stig O.W. Bergström et al.: "Combined district heat and electricity production in Sweden, and related safety problems". Geneva Conf 1971. P 1311.

List of figures

List of symbols used

A = narrow sealing passage
B = pressure balance tank
C_1 = air circulator
C_2 = air compressor
E = open expansion vessel
H = optional aux. turbine taking emergency supply from accumulator
I_d = dry insulation
I_w = wet insulation
K = air cooler
M = moisture separator
p_c = recirculation pump
p_k = condensate pump

p_{m1} & p_{m2} = 1 st and 2nd feed water pump
R = rock chamber
S = stack (to which steam blow-off line can be connected, fig. 4)
U = unpressurised pipe duct
v_1 = non-return valve
v_2 = regulating valve
x = sealing flow to prevent intrusion of dissolve gases
▬ = main flow
— = aux. systems
-·-- = steam
═ = air
—▷ = night flows
-➔ = peak load flows (day)
—➤ = continous flows

Appendix 1

SUMMARY OF THERMODYNAMIC CALCULATION

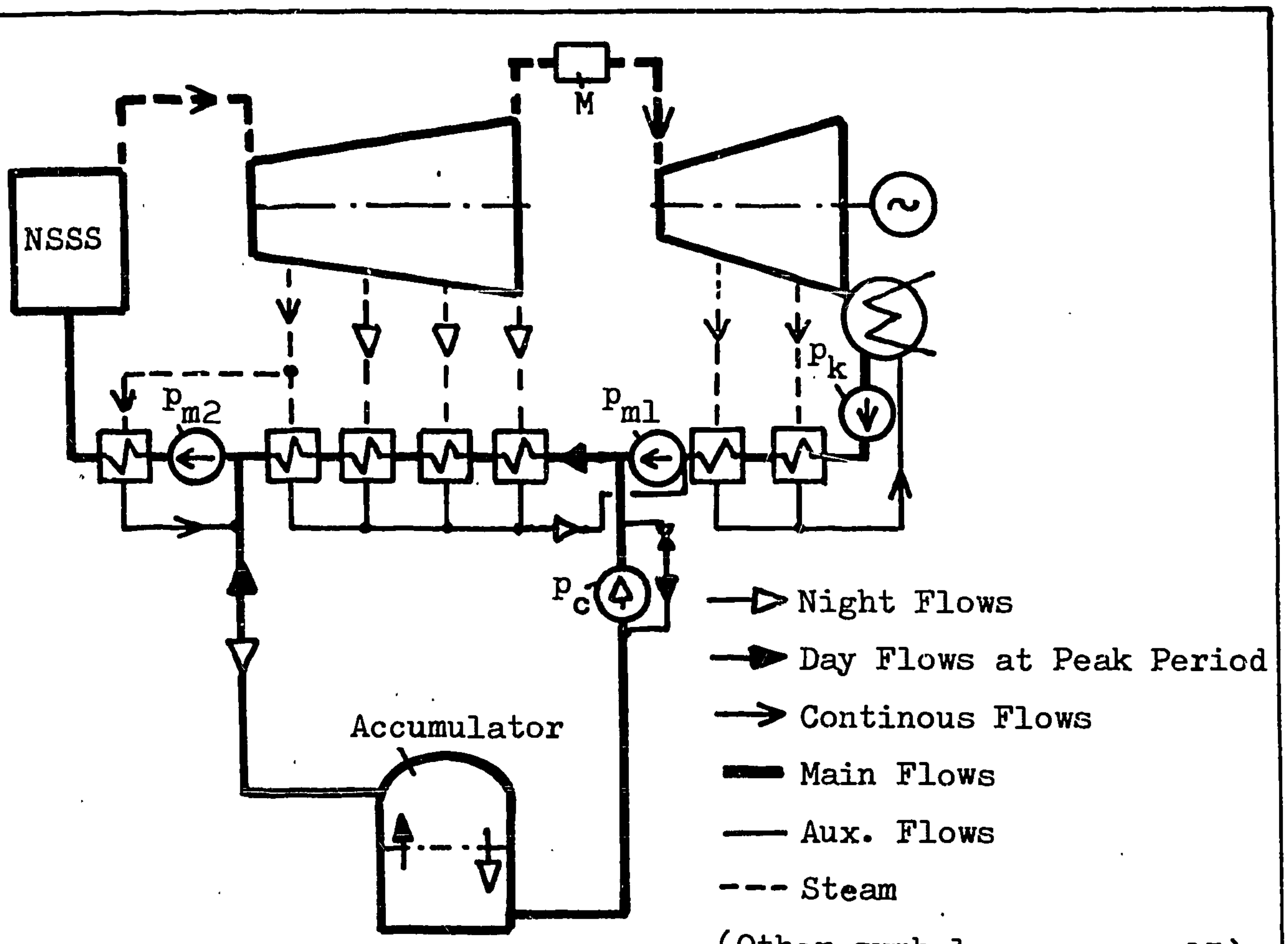
General assumption for simplified basic calculation

6 feed water heaters with 32°C rise per heater. $T_1 = 73°C$, $T_2 =$ $= 217°C$. Turbine stop valve temperature 270°C (55 bar). δ = terminal temp. diff. for feed heaters. η = efficiency factor to correct adiabatic efficiency for blade losses, generator losses, and turbine auxiliaries.

Results ($\delta = 3°C$):

	With feed heating kJ/kg	Without h.p. feed heating kJ/kg	Difference	
			kJ/kg	%
Given: η =	0.75	0.747	-	-
1. Heat in NSSS to working fluid	1859.6	2483.9	624.3	33.6
2. Turbine work	595.0	744.0	149.0	26.0
3. Heat rejected in condenser	1205.1	1665.1	455.0	37.7
4. Efficency	32.1 %			
5. Values corrected for h.p. feed heater:				
a) Turbine work (149 x 1.02)			152	25.2
b) Heat rejected in condenser			452	37.5
6. Electricity stored in accumulator after deduction of 2% heat loss during discharge x 0.7% unrecivered heat stored in steam expansion space, kJ/kg (152 x 0.973)			148	
$\text{kWhe/m}^3 = \dfrac{148 \text{ kJ/kg}}{3600 \text{ s/h} \times 0.001185 \text{ m}^3\text{/kg}} =$			35	

During night, heat load on feed heaters is doubled, which doubles the log. mean temp. differences, which gives $\delta = 13°C$. An increase in δ of 10°C reduces practical turbine work by 11.3 kJ/kg = 7.4% of 152 kJ/kg.



(Other symbols,see page 13)

Fig. 1 Basic Circuit

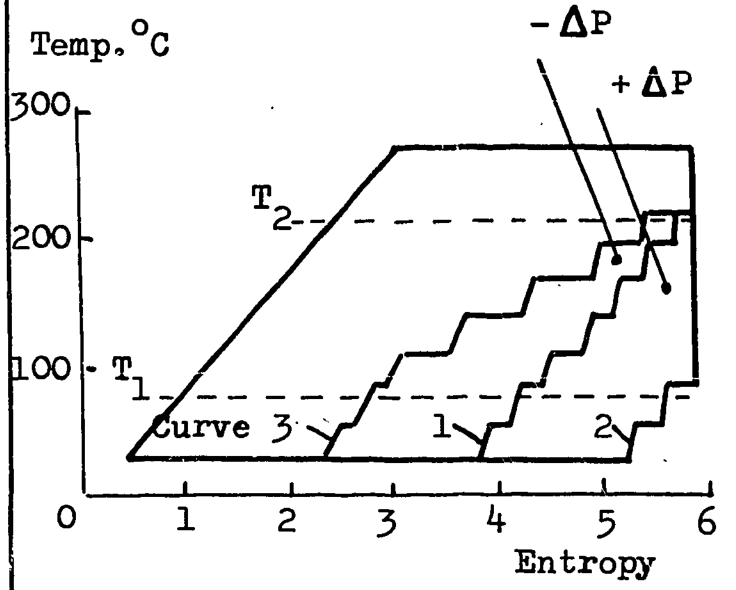


Fig. 2 Temperature/Entropy Diagram for Ideal Cycle.

- ΔP = Reduction in turbine work due to steam bled to charge accumulator.

+ ΔP = Additional turbine work due to avoidance of h.p. feed heating during day.

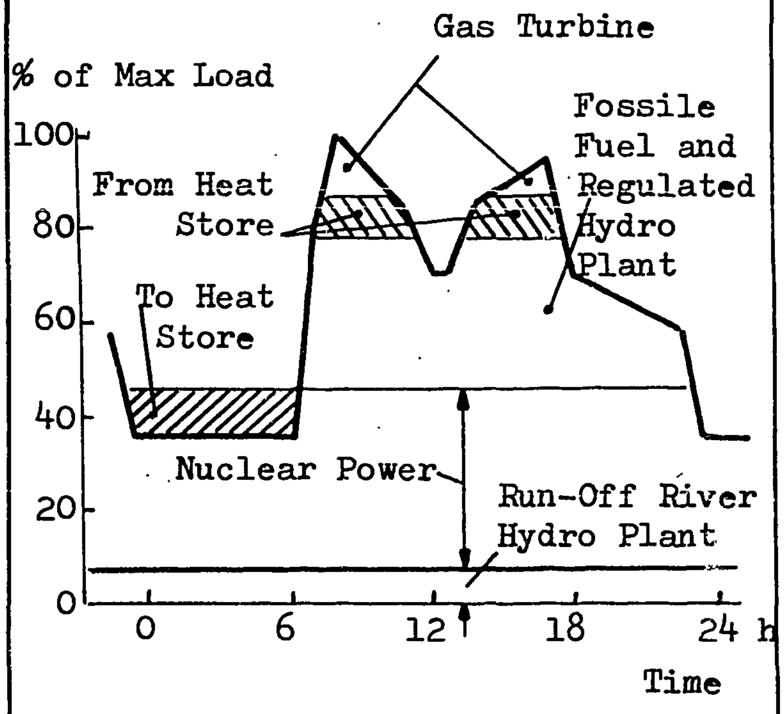


Fig. 3 Thermal Storage Plant Operation for Typical Daily Load Curve.

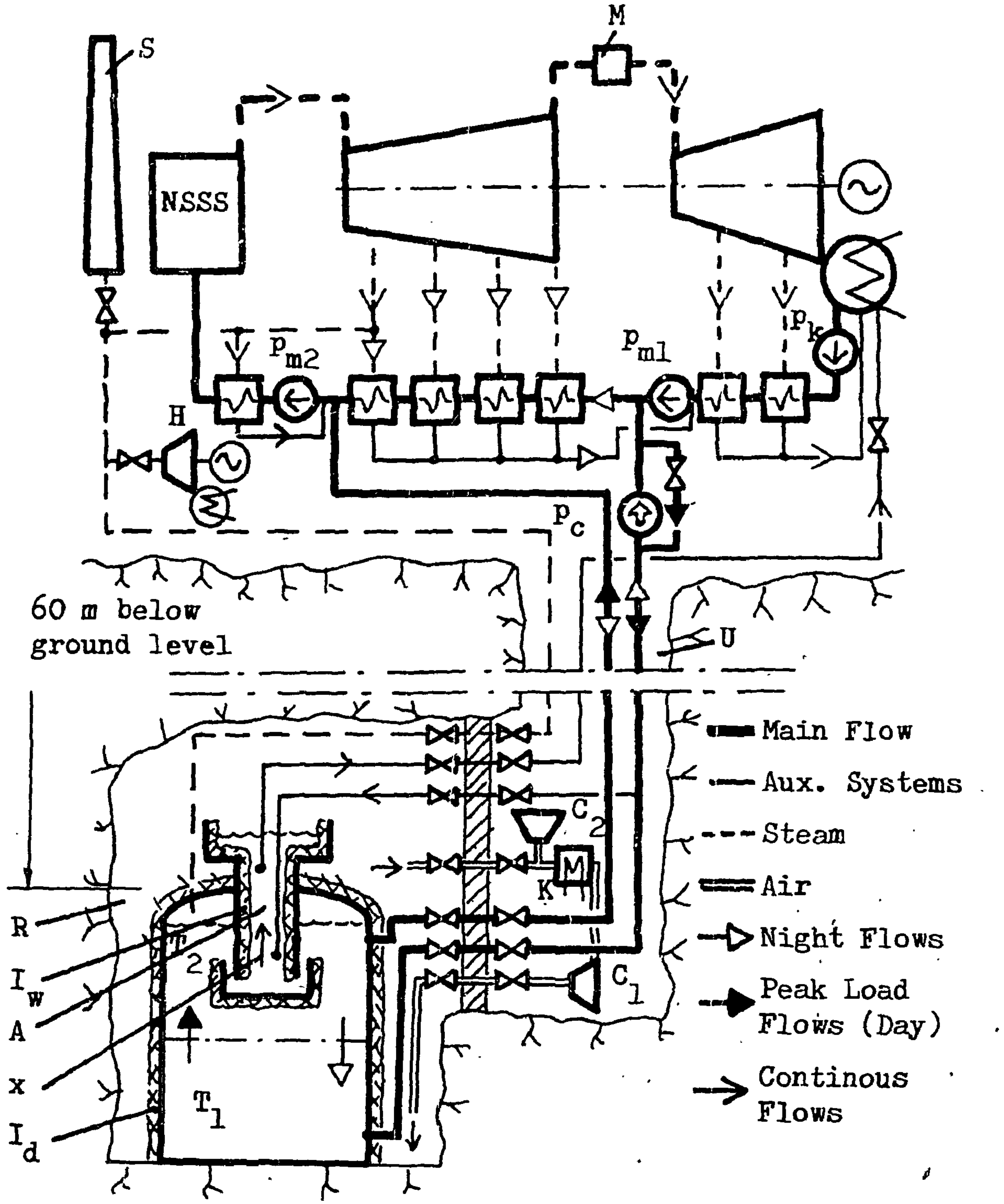


Fig. 4 Variant with Dry Insulation & Expansion through Internal Steam Volume

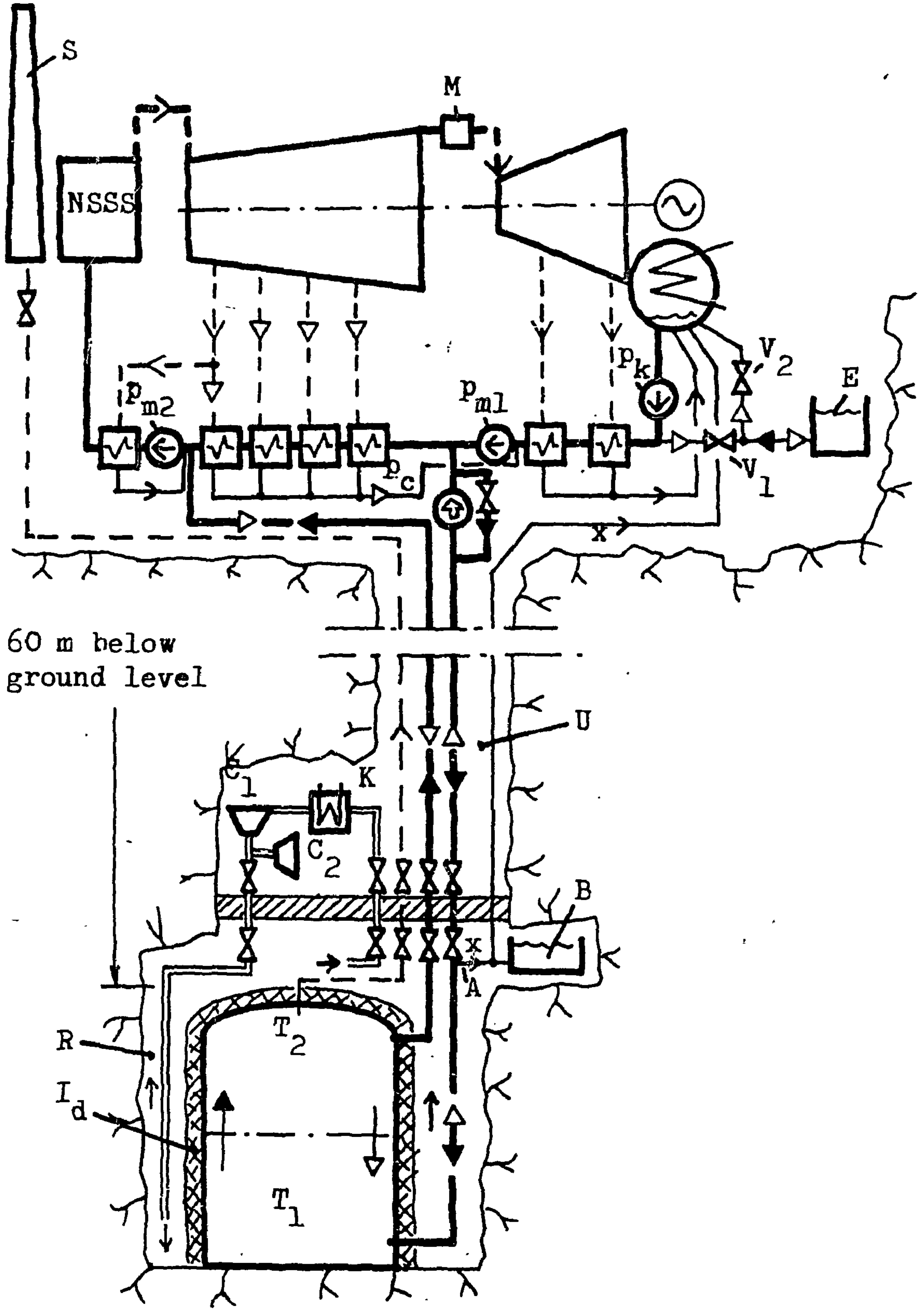


Fig. 5 Accumulator with Dry insulation & Open Expansion Volume at Ground Level.