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FORMATION OF STORED HEAT BY MEANS OF BLED STEAM DURING TIMES OF LOAD REDUCTION AND ITS USE IN PEAK LOAD TIMES

E. Bitterlich

Translation of "Bildung von Speicherwärme mittels Entnahmedampf in Lastsenken und deren Nutzung in Spitzenbelastungszeiten," Technische Mitteilungen, Vol. 60, No. 9/10, September/October 1976, pp. 488-499.

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E. Bitterlich, Certified Engineer
Deutsche Babcock, Ltd., Oberhausen

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16. Abstract

The technical possibilities and economic advantages of integrating hot water storage systems into power plants fired with fossil fuels are discussed. The systems can be charged during times of load reduction and then used for back-up during peak load periods. Investment costs are higher for such systems than for gas turbine power plants fired with natural gas or light oil installed to meet peak load demand. However, by improving specific heat consumption by about 1,000 kcal/ k@h, which thus reduces the related costs, investment costs will be compensated for sa that power production costs will not increase.

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E. Bitterlich
Deutsche Babcock, Ltd., Oberhausen

The Use of Storage Systems to Equalize Load Variations /488*

The demand for electrical energy is subjected to both daily and seasonal variations (Fig. 1). In order to be able to cost effectively meet this demand at any time, more and more in recent years there has developed a specialization of different types of power plants with various specific characteristics. According to the primary use of these power plants during their entire life time the following distinctions are made:

- base-load -- KW (with 5,000-7,000 use hours per year)
- medium load -- KW (with 2,500-5,000 use hours per year)
- peak load -- KW (with 2,000 use hours per year).

In what follows we will be primarily interested in covering the peak load (Fig. 1, right-slanted cross hatching).

Because of their short life-times thermal peak load systems and quick support systems with less than 2,500 use hours per year are less efficiently laid out from the thermodynamic stand-point. These systems are particularly inexpensive (300-400 German marks per kW, for instance), but they have a relatively high level of specific

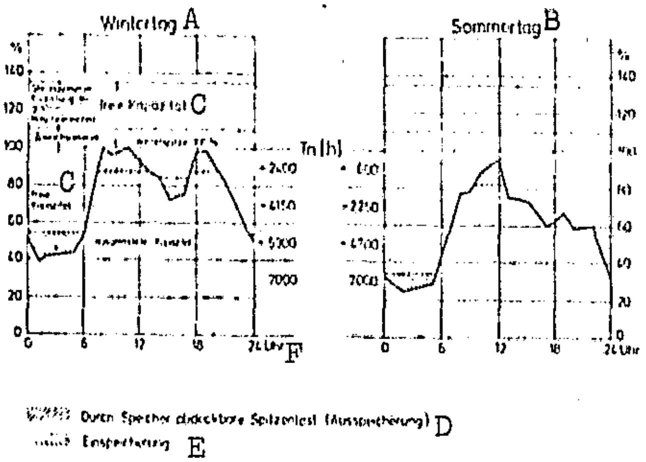

Fig. 1. Typical daily load diagram [0].
Key: A) Winter day
B) Summer day
C) Free capacity
D) Peak load which can be covered by storage (release of storage)
E) Storage build-up
F) Time in hours

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* Numbers in the margin indicate pagination in the foreign text.

heat consumption (3,200-3,400 kcal.kWh), among other things because of the relatively high start up and shut down losses or because of the no-load consumption. Depending on their layout and use, thermal peak load systems are either kept heated as quick support systems or as quick start systems they are started up afresh in each case when there is demand. The time required for the output to be readied in these cases ranges between 2 and 10 minutes. For frequency stability and for balancing very short-term load demands the storage capability of the steam generators with their auxiliary apparatus is also used in different ways. Hot water storage systems integrated into the steam circuit process extend this possibility. At the present time their use is limited to exceptional cases.

In what follows, hot water storage systems will be investigated in terms of the economic and technical feasability of using them for meeting peak load demands.

Hot Water Storage

Hot water storage as an instant reserve has been described by Marguerre [1]. Schröder [2] discusses it for unit power plants. The basic idea here is to store feed water of higher pressure and higher temperature than that present in the feed water reservoir and to mobilize this reserve when there are rapid increases in load.

During periods of partial load the hot water storage tank is filled from the feed water reservoir which works as a deaerator with gradually pre-heated condensate. The water is heated by taking steam from the turbines in the preheaters. The simplified circuit diagram in Fig. 2 shows the low pressure preheaters (1-4) on the right and the medium pressure and high /489 pressure preheaters (5-9) on the left; in the middle are the storage reservoirs, specifically the cold water reservoir (10), hot water reservoir with mixing preheater and deaerator (11) and the hot water reservoir (12). During the filling process water is taken from the feed water container and driven by menas of a special storage tank feed pump (13) through the storage water preheaters (14,15) and is fed through a filling valve (16) into the hot water storage tank which is constructed as a mixing preheater (12). The tank is emptied through the discharge valve (17) back into the feed water container. Thus by using for the most part already existing parts of the system the release of heat takes place in a stepwise fashion and the hot water is released into the individual feed water preheater stages.

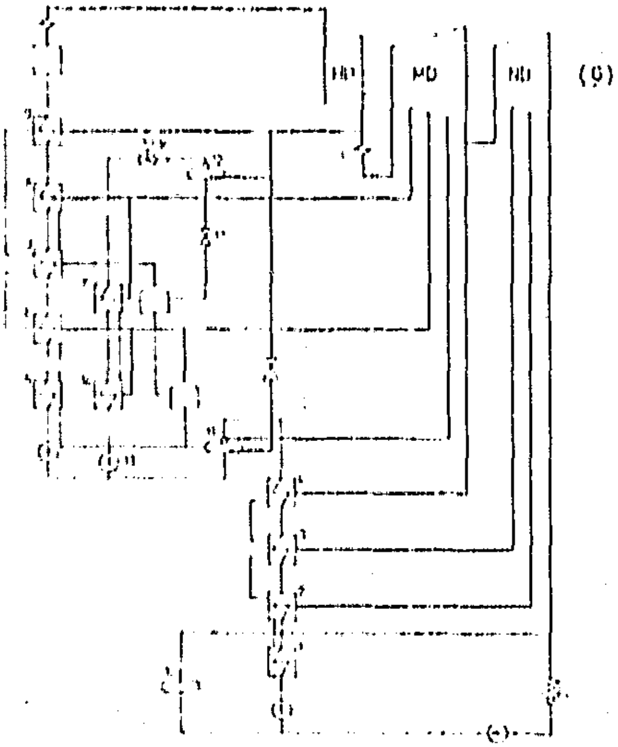

Fig. 2. Storage circuit, according to Schröder [2].

The efficiency can be increased if in addition to the feed water storage tank a cold water storage tank (10) is provided which is filled while the hot water storage tank is being emptied and vice versa, while the water level of the feed water tank is kept constant.

The process should in particularly be used in cases where the transition behavior of heating is sluggish and the storage capacity of the steam generator is small and short-term, rather large load jumps are demanded.

In 1958 Margen [3,4] suggested for the purpose of increasing storage capacity that hot water be stored in underground rock reservoirs and used for heating condensate. Later, in 1972, he suggested using the unused heat output of nuclear reactors during the period of night time load drops for the production of hot water, storing the hot water in an underground rock cavern and removing it during the peak load time [5]. The principle is shown in Fig. 3.

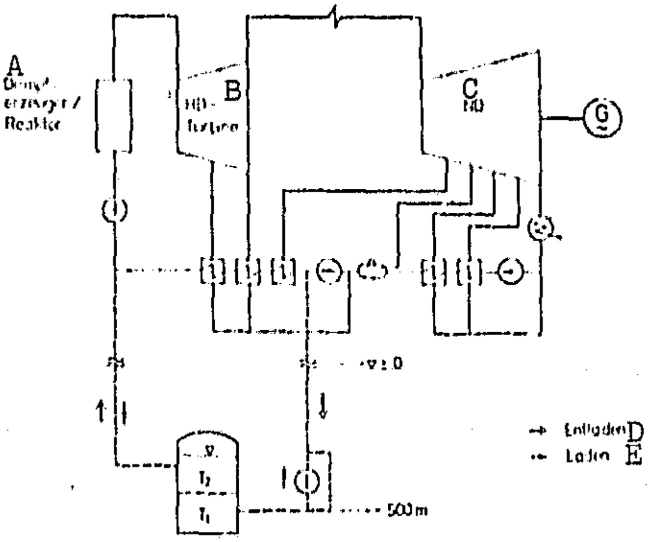

Fig. 3. Storage diagram, according to Margen [3].

Key:
A) Steam generator/reactor
B) High pressure turbine
C) Low pressure
D) Discharge
E) Charge

The storage container (1) is shunt connected to the medium pressure and high pressure preheaters. During filling, the water is fed into the top of the container and cold water is removed from the bottom. The interface between hot and cold water drops during the filling process until the temperature of the container is essentially that of the hot water T_2.

During removal in the peak load period the feed water is removed from the top part of the container with temperature T_2 and the water of temperature T_1 is conveyed downward. The outlets for the high pressure preheaters during this time are closed.

During the filling process the feed water of temperature T_1 is warmed up to T_2 in the high pressure preheaters. To be sure, this includes both the feed water used for generating output and the excess amount which is conveyed to the tank (black arrows). Accordingly, the reactor is used both as a source of heat for generating output and as a source of heat for charging the storage tank.

For considerations of economy this distinction is therefore necessary because heat from the nuclear reactor is available for charging the storage tank without additional fuel costs. Without having to increase the thermal output of the reactor, it is possible, according to Margen, to increase the output of the turboset up to 25% in so far as the turboset, feed water preheaters and storage reservoirs are laid out according to the maximum load conditions.

Using Hot Water Storage to Increase Output During Peak Load Periods for Conventional Thermal Power Plants /490

Drawing on the above discussion, we will investigate below whether and under what conditions hot water storage systems present an economically reasonable alternative to present traditional concepts even for thermal power plants which are fired with fossil fuels.

To make a judgement here requires consideration of the following factors:

1. Comparison with other possibilities of covering peak load demands,
2. The specific construction costs for an increase in output,
3. The specific heat consumption
    - for base output
    - for increase output and
4. The interaction between the specific heat consumption of

b base output and that of increased output for power plants with hot water storage facilities.

Demand for Peak Load Power Plants in the Federal Republic of Germany

Incentive to Build Hot Water Storage Systems to Meet Peak Load Demands

In 1974 the installed bottleneck output in the Federal Republic of Germany was 70,120 MW. The average use time was 4,450 hours per year. In the absence of exact statistical figures on this point it can be assumed that according to the systematic annual load curves about 15-20% of the installed bottleneck output of less than 2,500 hours per year was used.

Today in West Germany the installed output of peak load power plants is about 9,000 MW. This breaks down as follows:

- pump-fed power stations	approx. 25%
- gas turbines	approx. 25%
- thermal power plants[1]	approx. 50%.

Thus in the next 10 years the demand for new peak load power plants will be about 6,000-7,000 MW. Since the construction of pump-fed power plants is related to geographical conditions, which would seem to allow only limited additional construction of this type of power plant, new peak load power plants therefore -- as in the recent past -- would be oil or gas fired systems, namely:

- gas turbine systems or jets (using light oil for fuel) for = 1,500 hours per year and
- steam turbine systems (gas or oil fired) for 1,500-2,500 hours per year.

This type of system could be replaced in part or completely by new medium load power plants to be built in conjunction with

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[1] This output is not determined statistically.

hot water storage systems if the hot water storage containers of sufficient size can economically and safely be constructed and if these storage tanks require no additional local restrictions.

Use of such systems would entail the following advantages:

1. Meeting peak demand with thermal power plants fired with heavy oil or even coal in place of clean thermal peak load power plants which are fired with light oil or natural gas;
2. Avoidance of startup, shutdown and heat maintenance losses in peak load power plants by activation of instantaneous reserves from hot water storage tanks;
3. Reduction of fuel usage by generating peak demand with specifically correspondingly low heat consumption levels which are the norm in today's base load power plants.

By altering the technique in the recommended manner fuel costs would thus be replaced by capital costs. From the standpoint of political economy the advantage would lie in replacing valuable lght oil or natural gas with heavy oil or coal and in balance of payment savings brought about with an overall decrease in the consumption of hydrocarbon fuels which have to be imported.

An estimate of possible savings using figures projected for 1980 presents the following picture:

Energy demand	about 500 TWh
"Shiftable peaks" of energy demand	about 15% = 75 TWh
2/3 storage power plants	about 50 TWh

Improvement of specific heat consumption from 3,100 to 2,300 kcal/kWh

with Hu = 10,000 kcal/kg the possible annual fuel savings based on the cost of light oil would be:

B = 4 million tons of oil ≙ 1.0 billion German marks in foreign exchange currency.

On the basis of these figures alone, in the interest of reducing primary energy demand and for purposes of preserving energy reserves there should be an interest in developing storage systems for covering peak loads.

Specific Production Costs and Construction Costs

In order to be able to judge the economic feasibility of solving this problem we will make a comparison with existing common technology. It is assumed that in the individual distribution networks there exists a collective of base load, medium load and peak load power plants and that the use is controlled by the load distributor based on cost considerations.

The following equation applies for the production costs for electrical work k in a power plant:

$$k = 1000\,\alpha \cdot a \frac{r\,(1 + \varepsilon)}{t} + 100\ c_b\,\frac{r\,(1 + \varepsilon)}{t}$$
$$\bar{W}\,p_w \cdot 10^{-4} + b \left[\frac{\mathrm{Pfg}}{\mathrm{kWh}}\right] \qquad (1)$$

whereby,

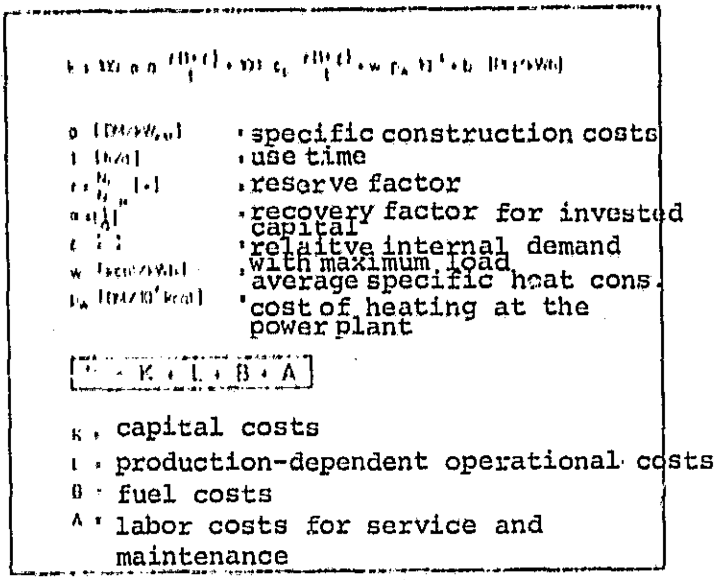
a [DM/kW$_{inst}$] = specific construction costs
t [h/a] = use time
$r = \frac{N_E}{N_{max}}$ [kW/kW] = reserve factor
α [DM/DM · a] = recovery factor for invested capital
ε [kW/kW] = relative internal consumption with maximum load
W [kcal/kWh] = average specific annual consumption
p_w [DM/Gcal] = heating cost at the power plant
b [Pfg/kWh] = labor dependent maintenance costs
c_b [DM/kW · a] = operational output-dependent annual costs
Note: DM = German Marks, Pfg = German Pfennigs

The individual terms can be defined in the following simplified expression:

$$\boxed{k = K + L + B + A\ (\mathrm{Pfg/kWh})} \qquad (2)$$

K = capital costs
L = operational, production dependent annual costs
B = fuel costs
A = labor costs for service and maintenance.

A review of the cost structure gives, for example, Fig. 5 for a soft coal power plant.



[illegible]

a [illegible] = specific construction costs
t [h/a] = use time
r [illegible] = reserve factor
a [illegible] = recovery factor for invested capital
ε [illegible] = relaitve internal demand with maximum load
w [illegible] = average specific heat cons.
p_w [illegible] = cost of heating at the power plant

$\boxed{k = K + L + B + A}$

K = capital costs
L = production-dependent operational costs
B = fuel costs
A = labor costs for service and maintenance

Fig. 4. Power production costs k

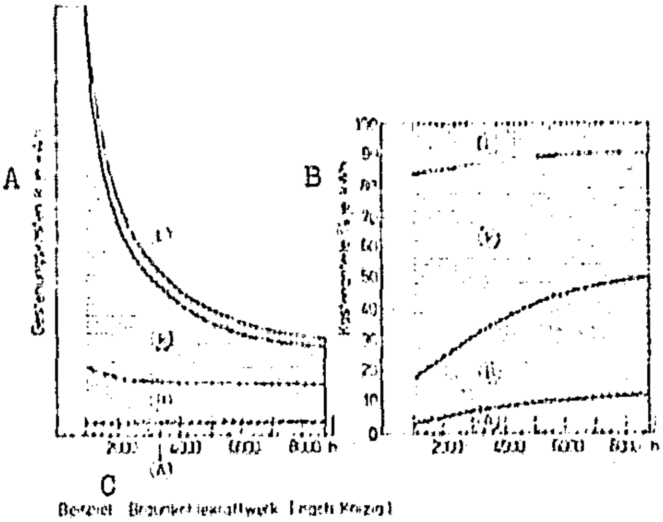


Fig. 5. Composition of production costs.
Key: A) Production costs k per kWh
B) Ratio of costs in % per kWh
C) Example of soft coal power plant (after Knizia)

From the figures it can be seen that the effect of fuel costs with low levels of annual use hours is relatively small, whereas the effect of capital costs is large by comparison. Therefore it is above all necessary to find a solution which is particularly cheap in terms of investment costs for the production

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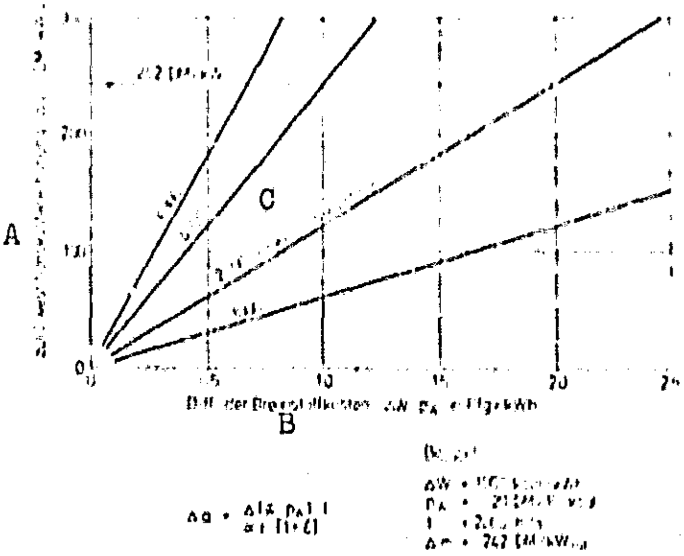

Fig. 6. Permissible investment costs.
Key: A) Permissible increase in investment costs Δa in German Marks per $kW_{inst.}$
B) Difference in fuel costs
C) Illegible

of peak load work.

The aim of the following considerations is in a comparison of production costs to interchange fuel costs B and capital costs K and make the term ΔK as much smaller as possible than the term B in order to reduce the power production costs k. /491

It is assumed that the work and production of a peak load power plant can be taken over by a base load power plant "rebored" power furnished with storage facilities.

Should this be economically reasonable, then the annual production costs for the electrical work of the expanded power plant for reasons of economy must correspond at least to the "combined costs" for the two individual power plants. By appropriate transformation one can determine the economically permissible increased expenditure for "expanding" a system from equation 1.

$$\boxed{\Delta a = \frac{\Delta (W \cdot p_W) \cdot t}{a \cdot r \cdot (1 + r)} \cdot 10^{4} \, (DM/kW_{inst})} \qquad (3)$$

The terms L and A from equation (2) are for the time being set at 0 for purposes of easier manipulation.

The specific construction costs for expanding the base system are then:

$$\Delta K = (a_2 + \Delta a) \cdot N_2 \qquad (4)$$

and the total costs of the system amount to

$$K = K_1 + \Delta K = a_1 \cdot N_1 + (a_2 + \Delta a) \cdot N_2 \qquad (5)$$

Fig. 6 gives a graphical representation of the permissible increases in investments costs. For example:

$$(\Delta W = 1000 \text{ kcal/kWh}; \; p_w = 20 \text{ DM}/10^6 \text{ kcal}; \; t_2 = 2000 \text{ h/a}).$$

With these values, according to (3) with a capital interest rate of 14%, a reserve of 10% and an internal demand of 7% we get a permissible additional expenditure of

$$\Delta a = 242 \text{ DM/kW inst.}$$

For a base power plant of 600 MW an additional peak output of about 90 MW (15%) with a specific heat consumption w = 2,300 kcal/kWh can be obtained by closing the removal valve.

If for purposes of comparison one takes as a basis a peak load power plant of the same output with a specific investment expenditure of a_2 = 350 German Marks per kW inst. and w_2 = 3,300 kcal/kWh, the additional costs ΔK for the storage system may be:

$$(350 + 242) \cdot 90 - 53.3 \text{ million German marks.}$$

This comparison suggests that it is technically possible to construct a storage system witnin the limits of these additional costs.

Specific Heat Consumption

Since in equation (2) the production costs are about 40% dependent on B great importance is to be attached to a lower specific heat consumption for the expanded system without adversely affecting the heat consumption of the base system.

With a periodically functioning irreversible process with storage facilities the general balance equation is written as follows:

$$\int_{t_0}^{t_e}\left(\int_{1} \frac{T-T_u}{T}\,dq - \int_{2} \frac{T-T_u}{T}\,dq\right)dt = \int (a_{12} - T_u \Sigma \Delta S_{irr})\,dt$$

This is the general circuit process equation with a time integral.

Thus, in order to obtain as much useful work a_{12} as possible, it is important that the addition of heat q_1 take place at the highest possible temperature T and that the heat removed q_2 is as close as possible to the ambient temperature T_u. Losses due to an increase in entropy ΔS_{iff} are to be held as small as possible. In any time cycle the potential of a storage tank of an initial state at time t_1, after passing through any intermediate value without loss, is brought back after completion of the process to the initial state at time T_e, then there is no change in the work a_{12} in the case of a closed /492 system. Thus a storage tank does not affect the degree of thermal efficiency and in turn the specific heat consumption within a time cycle, if during this cycle all of the energy collected in the storage tank is reconveyed to the process without loss and the remaining exchange processes take place at an unchanges temperature level. From this we can derive the following basic requirements for minimizing additional losses for a thermal power plant with hot water storage.

1. The "hot storage tank temperature" T_2 must be equal to the temperature of the feed water -- with the plant operating at full base capacity -- at the site where the storage water is mixed

into the base process, i.e. charging with the base process at full preheater temperature and full preheater pressure.

2. The pressure of the storage tank must be at least high enough so that no evaporation occurs at temperature T_2.

3. The number of bleedings which can be used for peak load operation to increase output is determined by the amount of "additional output".

4. The maximum possible usuable additional output is obtained when the hot storage tank temperature is chosen equal to the feed water temperature behind the last high pressure preheater ($T_2 = T_{sp}$). This calls for the closing also of bleeder valve E1 and thus causes an increase in the amount of flow through the reheater (in case it involves a process with a reheater).

5. Throttle valve losses are to be avoided!

Losses due to friction in the inflow and outflow lines should be measured to the extent that it is economically reasonable.

6. The pressure increasing pump P must have a good degree of efficinecy.

7. The "cold inflow temperature" T_1 is to be selected at least sufficiently high that before entering the storage tank the water can be thermaly deaerated.

8. The heat losses of the storage tank are to be kept small by means of good insulation or by returning the heat into the process.

The Hot Water Storage Tank

Storage Conditions, Arrangement in the Circuit

Based on these facts, a constant pressure storage tank, i.e. a hot water storage tank, is reasonable in that the hot storage tank temperature is equal to the feed water input temperature in the steam generators.

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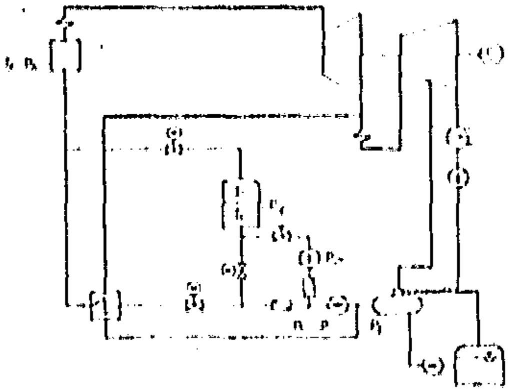
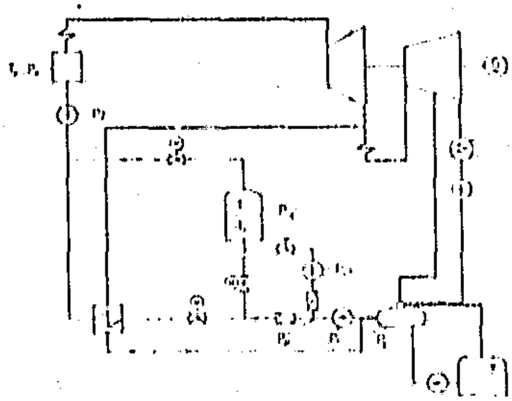


a) Storage after primary feed pump
with full pressure
container pressure about 260 bar
pump



b) Storage tank after intermediate
pump with partial pressure
Container pressure about 50 bar
pump

Fig. 8. Storage tank and pump locations.

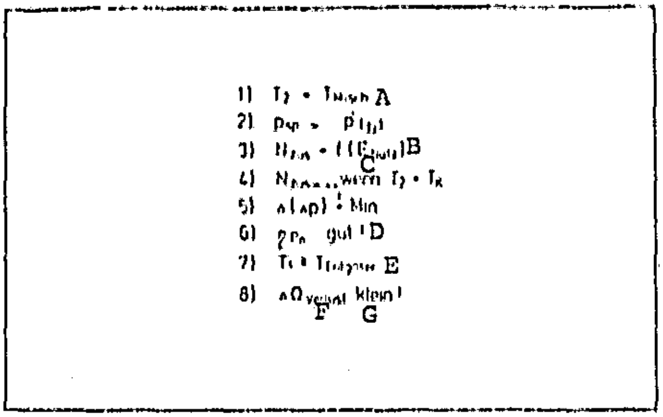


Fig. 7. Requirements for a hot water storage system in order to achieve thermodynamically optimal conditions.
Key:
A) Combined
B) Useful
C) If
D) Good
E) Deaerator
F) Loss
G) Small

With respect to the storage tank pressure, the circuit connections shown in Fig. 8 are thermodynamically equivalent. In the upper diagram 8a the storage tank is under full pressure of 260 bar which is built up by the feed pump (P). The pressure increasing pump (P_{dl}) has only to overcome the pressure loss due to friction and must be designed for the maxiumum amount of flow during charging (about 50%). The feed pump P delivers 100% mass flow to the full steam generator input pressure P_k. In the lower diagram 8b the storage tank is exposed only to an intermediate pressure, which is to be chosen sufficiently high so that no boiling occurs at the boiler feed water input temperature T_k (50 bar in the diagram). Appropriately, one should choose the following pressure:

The pressure increasing pump P_D is again to be laid out as in case "a." Both pumps P_1 and P_2 have to deliver the full mass flow in two stages with different high temperatures (T_1, T_2). They are appropriately installed in a housing with heat insulation and then also receive a power source. Because of the lower construction costs circuit "b" is more favorable (lower storage tank pressure, lower pump costs).

Warm water and hot water are jointly stored in the hot water storage tank. The two are separated by means of the difference in density. At the interface between the hot medium /493
and the warm medium the losses due to mixing can be reduced by means of a simple floating disc. Depending on the storage state of the hot water storage tank this has either a temperature of T_2 (full) or T_1 (empty). This gives rise to a difference in volume of 30%. This volume difference could be compensated for directly in the hot water storage tank. In this case, however, the hot water storage tank must be accordingly oversized and in the discharged state (T_1) would have a suitably large cushion of steam. The other more economical solution is to compensate for the volume difference by setting up an additional warm water storage tank.

If the low pressure preheaters are used in conjunction with storing output the cold water container must be set up behind the condensate pump. The temperature of the container is then that of the condensate. This circuit is shown in the upper diagram "a" in Fig. 8.

The warm water storage tank is appropriately connected in parallel to the deaerator. The advantage of this second solution is that no additional throttle valve losses of any kind occur.

In order to design the circuit as simple as possible the warm water storage tank is filled using the condensate pump. By means of this arrangement the volume difference can be compensated for solely by means of the particularly inexpensive warm water container and the hot water storage tank is completely filled without a cushion of steam. As a pressure limiting measure the hot water storage tank is fitted with an overflow line.

Maximum Additional Output -- Storage Tank Size

The maximum additional output of the turbine is between 12 and 15% and is a function of the total amount removed and the position of the removal valves which can be closed at times of peak demand.

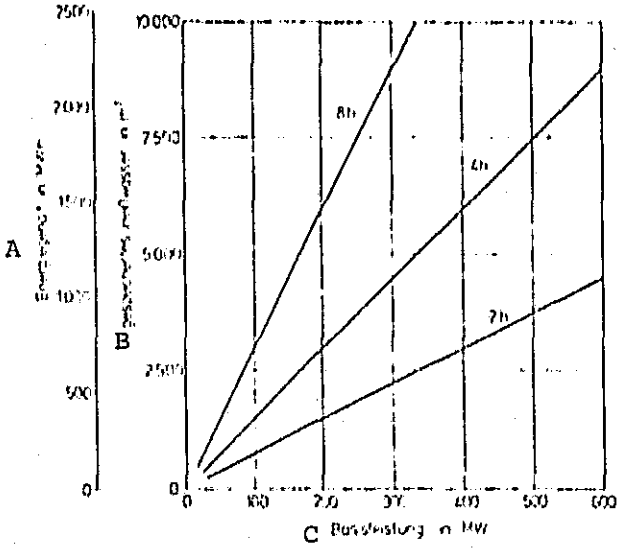


Fig. 9. Storage tank size and energy content.
Key:
A) Energy content in MWh
B) Stored hot water in m^3
C) Base output in MW

The size of the storage tank is determined by the maximum base output and the discharge time (Fig. 9).

A numerical example will serve to illustrate this point:

For an already constructed 600MW base power plant the feed water current, for example, is 400 kg/sec and has a temperature of 245°C. A daytime storage tank must be able to collect the full flow of feed water for 4 hours at full load. The hot water volume for this is about 8,500 cubic meters. For a weekend storage tank with a supply period of about 20 full load hours the hot water volume is about 42,000 cubic meters.

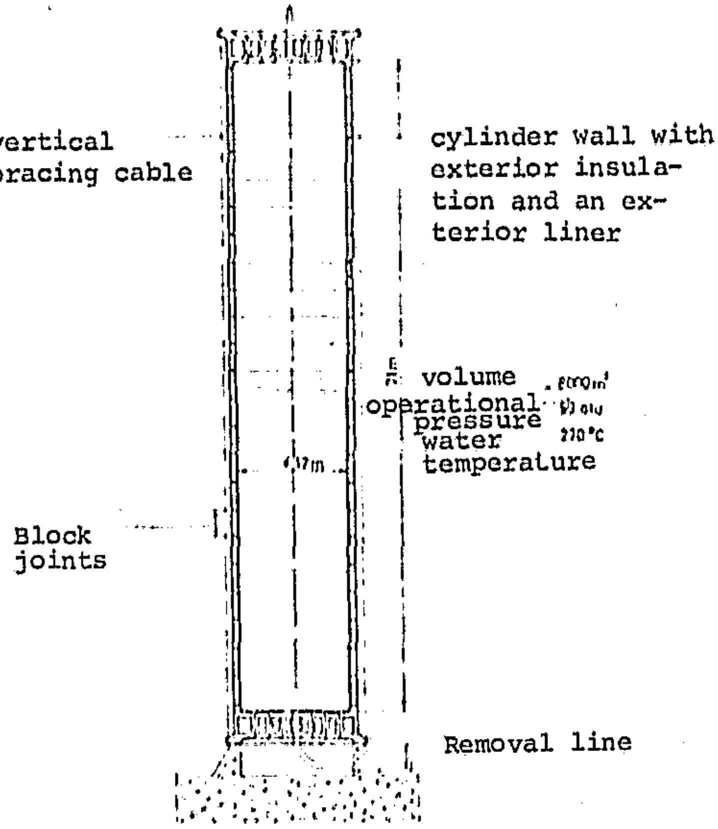


Fig. 10. Prestressed cast pressure container.

Construction Design -- Steel Container Costs

Because of the wall thicknesses which increase in proportion with diameter and pressure the costs of steel containers quickly become uneconomical. The wall thickness, even for larger containers, for reasons of cost should be limited to a maximum of 30-50 mm. Because of this a whole battery of steel containers (25 units) is required for the large amount of hot water which has to be stored. Therefore, steel containers for storing hot water are not cost effective. However, they are suitable as warm water containers for lower pressures.

Prestressed Cast Containers (PCP Containers)

Newly developed are the PCP (prestressed cast pressure) containers. Fig. 10 shows the construction design of such a container with a volume of 8,000 cubic meters. It is 21 meters in diameer and about 70 meters high.

The support construction consists of individual cast iron blocks 500 mm thick in circular segments weighing up to 30 tons

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apiece. The blocks are joined by means of tounge and grove. The forces are taken up by means of axial and circumferential bracing cables. In the example the container is sealed by means of a steel inner liner. The insulation is on the outside. For further details refer to the pamphlet put out by Siempelkamp [6].

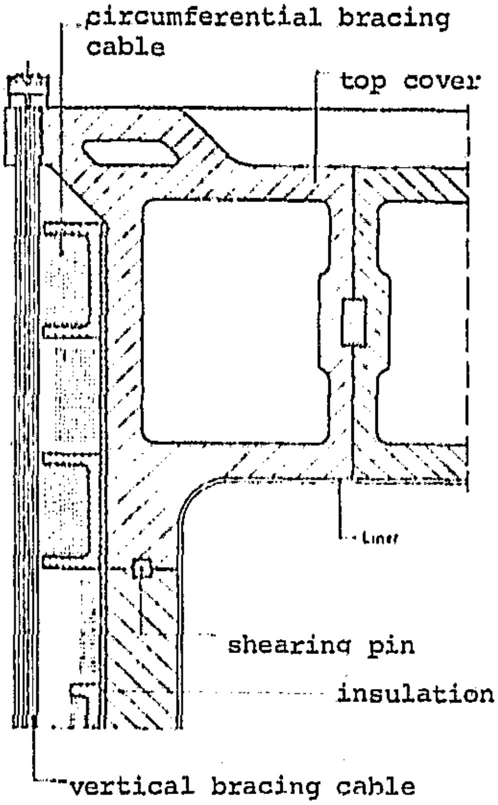


Fig. 11. Prestressed cast pressure container.
Key:

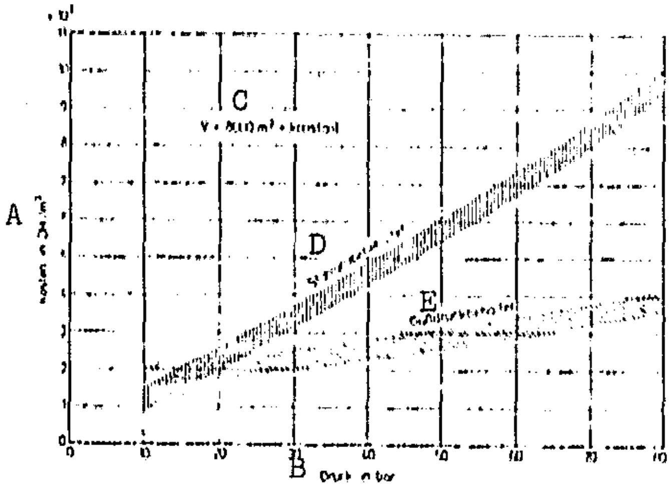


Fig. 12. Pressure container costs
Key:
A) Costs in German Marks per m^3
B) Pressure in bar
C) Constant
D) Steel pressure container
E) Cast iron pressure container

Dimensions with respect to volume and pressure and temperature requirements can be realized with this construction design which meet the needs of a hot water storage tank. Because of the unique construction of the PCP storage tank the costs rise considerably more slowly with increasing pressure and temperature than in the case of steel containers (Fig. 12).

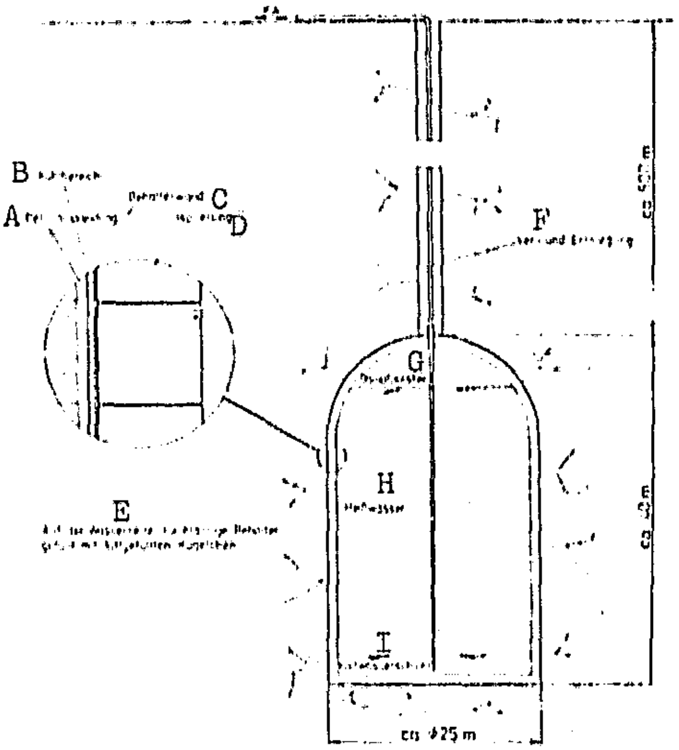


Fig. 13. Hot water container, version with reinforcement against chamber walls and interior insulation.
Key:
A) Concrete exterior
B) Cool region
C) Container wall
D) Insulation
E) Containers porous on the up-stream face filled with small air-filled balls
F) Input and removal line
G) Steam cushion
H) Hot water
I) [Illegible] water layer

Rock Chamber Reservoirs

If the process requires the storage of very large amounts of hot water rock chamber reservoirs can also be suitable. Fig. 13 shows such a chamber reservoir with /494 interior insulation. In this system the pressure of the water is transfered to the surrounding rock. Since the pressure of the soil increases lineararly with depth, specifically at a rate of 20,000 N/m^3, the pressure of the stored water is directly related to the required depth of the chamber. Here it must be borne in mind that the pressure of the stored water also increases at a rate of 10,000 N/m^3.

For the above example of hot water pressure at 50 bar the required storage depth is 500 meters. The pressure in the reservoir itself therefore becomes $50\ \text{bar} + 500\ \text{m} \cdot 10\,000\ \text{N/m}^3 = 100\ \text{bar}$

In the figure shown here the steel liner is supported directly against the rock. The exterior counter pressure of the enveloping rock keeps the container free of tension during operation. In this case the steel container must be installed in such a way that at the average wall temperature it stands perpendicular in the rock because of thermal expansion. At higher temperatures the expansion will be inhibited by the rock and compressive stresses will arise in the wall. At lower temperatures tensile stresses arise due to the interior pressure. The amount of deviation from the average wall temperature determines the required high temperature yield point of the steel to be used. Another version is shown in Fig. 14. Here the steel container in the chamber is constructed independently. The outer counter pressure which keeps the container free of tension is kept in equilibrium by a suitable external gas pressure.

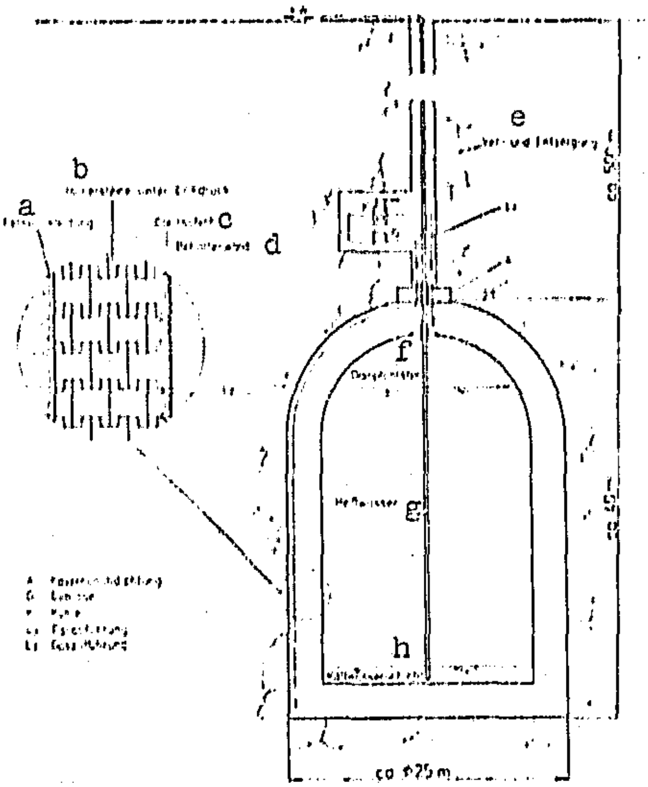


Fig. 14. Hot water container, version with reinforcement by external pressure and with external insulation.
Key: a) Rock exterior, b) Insulating rock under gas pressure, c) [Illegible] layer, d) Container wall, e) Input and removal line, f) cushion of steam, g) hot water, h) cold water layer, A) Chamber seal, G) Blower, K) Cooler, L_a) Gas removal, L_z) Gas input

The required external pressure can only be produced if the chamber is hermetically sealed. To be sure, this is naturally the case with salt masses. However, normal rock contains so many cracks that seepage water can infiltrate and gas can escape. The chamber must then be sealed by technical means. In addition, a special regulating system must make sure that even when the reservoir is completely empty the internal and external pressure are in agreement.

The use of rock chamber reservoirs of different types certainly requires more detailed studies. In particular, a detailed project study still needs to be made in order to determine costs.

Safety Aspects -- Site Selection

The stored energy content of the hot water is about 240 kWh/m^3 and thus for a 600 MW daytime reservoir it is about 1,900 MWh, and for a weekend reservoir about 9,500 MWh. (The enrergy content usuable as electrical work still has to be multiplied by the efficiency factor of the process.) Because of the large amount of stored energy the safety aspect must especially be borne in mind. For reasons of economy it is desireable to integrate the reservoir as directly as possible into the power plant. This should be possible for prestressed cast iron containers. However these are to be constructed in the open. Leaks would be indicated by the formation of vapor clouds. Due /495 to the characteristics of the prestressed system the container is to be considered burst proof. With respect to the characteristics of the bracing cable construction it is not to be expected that sudden material failure will occur. Regular inspections can be made. Inspection checks are simple. No restrictions are imposed for the acutal site of the power plant.

From the standpoint of safety, steel containers of larger dimensions should if possible not be used if they are under pressure and filled with hot water. As already determined earlier, the use of steel containers should therfore remain limited to lower pressure and lower temperatures.

By contrast, rock chamber reservoirs represent no risk if the rock pressure is so high that even if the steel jacket fails it can accomodate the pressure of the system. Inspections and, in particular, possible repairs are more difficult to carry out than in the case of a PCP container. Therefore in the selection of the power plant site, it is also necessary to consider the appropriate soil testure along with the usual limiting conditions. It must be assumed that for conventional thermal power plants such reservoirs can therefore be used only in exceptional cases.

An Example of a 600 MW Base Power Plant with Hot Water Reservoirs

Design Criteria

A 600 MW base power plant with simple reheating and a thermodynamically optimum design will produce peak output by closing the high pressure and medium pressure removal valves.

During peak load all of the feed water will be removed from a hot water reservoir whose temperature is that of the feed water at the steam generator input at ≈ 100% load. The reservoir is filled and emptied according to the processes described earlier. The reservoir pressure will be about 50 bar; the additional output will be sufficient for 4-hour peaks.

Additional Output

For a specified process a calculation gave an additional output of about 15%, corresponding to 90 MW. A cost efficient design results when:

- the steam generator with all auxiliary equipment is designed for 600 MW and
- the basic design of the steam turbine, including exhaust steam pipe and condenser, is likewise designed for 600 MW and the accompanying steam conditions.

Change of State in the Turbine during Peak Load

The changes of state are plotted in the "h,s" diagram in Fig. 15 (solid lines = base process). If the removal valves E1-E4 are closed, a change in the output distribution in the turbine results (values in parentheses).

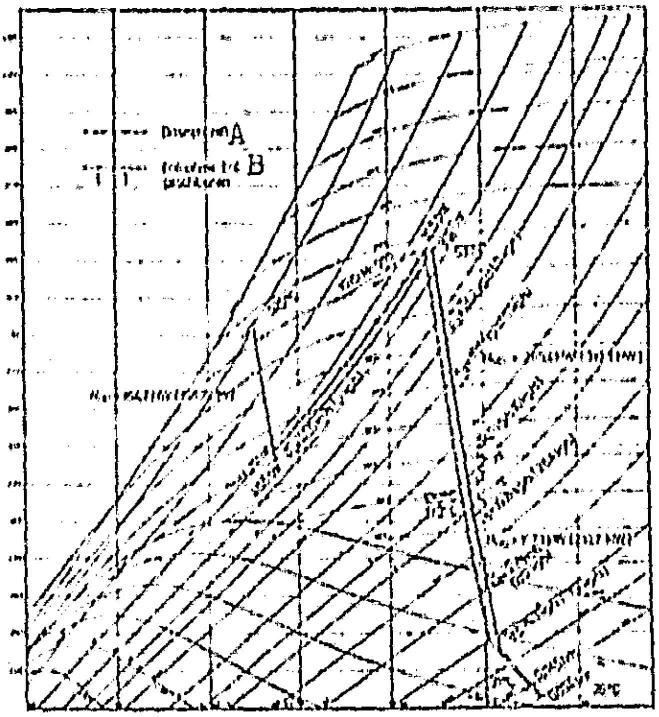


Fig. 15. "H,S" diagram of changes in state in the turbine.
Key:
A) Base process
B) Removal valves 1-4 closed

As a result of the higher mass flow through the individual parts of the turbine there is an increase in the stepped intermediate pressures. Thus with turbines in which the construction of the "cold end" has not been altered the vacumn and the separation pressure at the reheater increase (dotted line).

For reasons of strength the changes in the amount of flow and stage pressures require the turbine blades to be reinforced, in particular for the last stages.

In spite of the relatively small increase in the vacumn from 0.034 bar to 0.045 bar the specific volume dedreases by as much as 23%, and since the flow of exhaust steam increases by about 25%, the velocity in the exhaust stages and condensate input increases by only about 2%.

As a result of the increase in temperature of the exhaust steam of about 5°C in conjuntion with the rise in pressure the concentration in the condenser also rises, whereby the amount of waste heat given off into the surroundings can be carried off. A /496 precondition for this is an increase in the cooling capacity. Depending on the coooling system, a sufficiently large amount of fresh water in the case of direct cooling or an increase in the amount of cooling water in the wet cooling tower or an increase in the exchange surfaces along with a simultaneous increase in the size of the pumps and blowers must be ensured.

Boiler and Pipelines

A portion of the deterioration in gradient at the cold end of the turbine (about 6 kcal/kg) is compensated for by the fact that during peak load the reheater is run uncontrolled and an injection is not applicable.

The following advantages for the medium pressure portion are connected with this method of operation:

1. The reheater fired by the flue gas has to be designed only for the base thermal output. This dispenses with an additional construction expenditure for the steam generator.
2. Because of the higher reheater input pressure the specific volume drops, and the pressure loss of the reheater hardly increases as a result of the approximately equal velocity in the pipeline systems.
3. The temperature at the reheater output decreases with this method -- assuming a 2.5% basic injection -- by about 5°C.
4. As a result of this one moves approximately on a line of uniform strength (Fig. 16).

This change of state is desireable since it allows the hot reheater line to be used at high pressure and without an increase in cross section without the loss in pressure significantly increasing in these jucntion lines.

Only the cold reheater pipelines are to be designed for a higher pressure of about 4 bars. Because of other operational reasons, however, this reserve is already present in most cases.

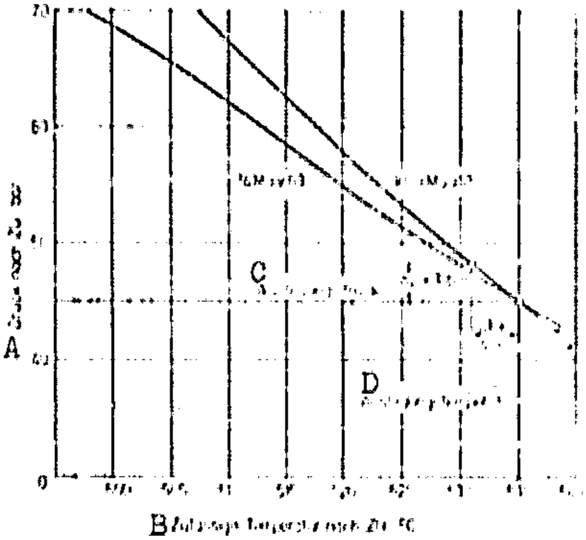


Fig. 16. Permissible reheater temperature as a function of the pressure behind the reheater.

Key:
A) Pressure after reheater in bars
B) Permissible temperature after reheater in °C
C) Design pressure
D) Design temperature

As for the electrical side, the generator and transformer must be designed for the peak output. This means that the excitation output and cooling capacity are to be increased accordingly.

Preheater Design for Charging the Hot Water Reservoir

The design of the preheater system is effected to an important extent, since it is to be used as the heat exchanger for charging the hot water reservoir. To be sure, it is theoretically possible to recharge the reservoir at any time during which the electrical output is smaller than the base output (600MW). Usually, however, the charge time available during a time cycle will be the determining quantity. It is crucial for the dimensions of the preheater.

If it is assumed that the charge time is 12 hours, then the preheater output in the case of a 4-hour peak (100% mass flow out of the reservoir) must be increased by 4/12 = 1/3, provided that with the reservoir exactly as much steam is removed as is removed at peak load against a load 100% smaller.

In order not to worsen the degree of concentration and thus the Carnot process the prewarmers are designed with a 33% greater heating surface. The bleeding taps and pipelines are to be increased accordingly.

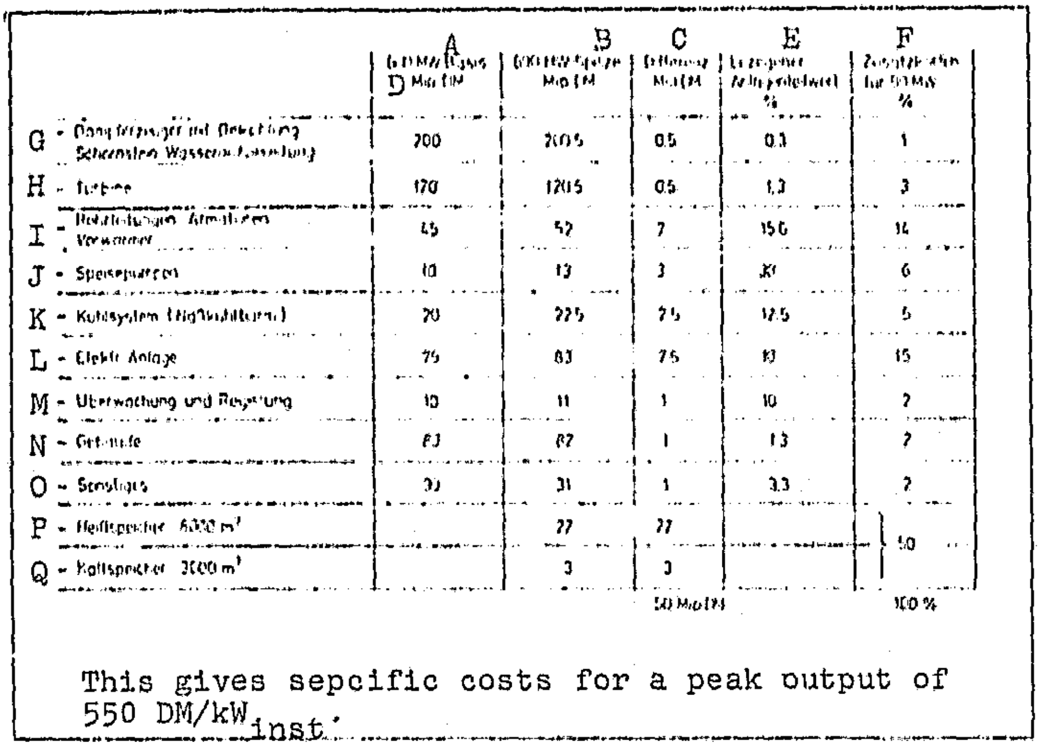
Irreversible Additional Losses

For the process shown in Fig. 15, the following figures were calculated using the data given under the heading "Maximum Additional Output -- Reservoir Size":

1. Heat losses: with respect to the maximum charge of the hot water reservoir	0.64%
2. Lost pump work	
2.1 Discharging = 4-hour peak: with respect to 90MW	0.025%
2.2 Charging - 12 hours	
a) loss due to the larger amount of flow through the high pressure preheater: with respect to 90 MW	0.083%
b) Loss due to higher pressure loss of the "circuit water" in the high pressure preheaters: with respect to 90 MW	0.075%
2.3 Sum of 2.1-2.2: with respect to 90 MW	0.2%

Costs

The investment costs for the hot water storage system were estimated for the project. They were about 50 million German Marks, distributed as shown in the following table (Fig. 17). In a comparison between the two alternatives of a (1) separate base power plant and peak load plant and (2) a hot water storage system integrated into a base power plant, cost advantages still emerged for the hot water storage system due to savings in production, labor and maintenance costs.



	A D 600 MW Basis Mio DM	B 600 MW Spitze Mio DM	C Differenz Mio DM	E Erzeugter Anlagenteilwert %	F Zusatzkosten für 90 MW %
G - Dampferzeuger mit Bekohlung Schornstein Wasseraufbereitung	200	200.5	0.5	0.3	1
H - Turbine	170	170.5	0.5	0.3	3
I - Rohrleitungen, Armaturen Vorwärmer	45	52	7	15.6	14
J - Speisepumpen	10	13	3	30	6
K - Kühlsystem (Naßkühlturm)	20	22.5	2.5	12.5	5
L - Elektr. Anlage	75	83	7.5	10	15
M - Überwachung und Regelung	10	11	1	10	2
N - Gebäude	81	82	1	1.3	2
O - Sonstiges	30	31	1	3.3	2
P - Heißspeicher 6000 m³		22	22		50
Q - Kaltspeicher 3000 m³		3	3		
			50 Mio DM		100 %

This gives sepcific costs for a peak output of 550 DM/kW_{inst}.

Table 17. Added cost estimate for a PCP hot water storage system.

Key:	
A) Base	H) Turbine
B) Peak	I) Pipelines, aramtures, preheaters
C) Difference	J) Feed pumps
D) Million of German Marks	K) Cooling system (wet cooling tower)
E) Relative partial value of the system	L) Electrical system
F) Additional costs for 90MW	M) Inspection and regulation
G) Steam generator with [Illegible], smoke stack stack, water [illegible]	N) Building
	O) Other
	P) Hot water reservoir
	Q) Cold water reservoir

Concluding Evaluation -- Development Tasks

The above discussion has shown that it is technically possible and reasonable to integrate a hot water storage system into a modern power plant fired with fossil fuels. The investment costs to be expended for an output peak are specifically higher than, for example, for a gas turbine power plant fired with natural gas or light oil. However, by improving the specific heat consumption by about 1,000 kcal/kWh which thus reduces the related fuel costs these investment costs will at least be compensated for so that the power production costs will not increase.

The available output reserve for meeting the peak demand, which is only limited with respect to time, is certainly a restriction. Against this, however, is the economic advantage which can be around 30% as a result of a reduction in primary energy use to cover peak load with thermal power plants.

Althoug it was not at all possible to go into detail here on this point, it can be stated that the economic advantage of hot water storage systems can even more considerably be increased by a power/heat coupling. With an increase in the size of the warm water container this could simultaneously be used as a reserve for heating heat.

Hot water storage systems can also obviously be used for combination blocks. /497

So far the construciton of large hot water storage reservoirs with volumes between 8,000 and 50,000 cubic meters has not yet been realized. Smaller, prestressed cast iron pressure containers are under construction. Project studied are in progress for rock chamber reservoirs. The programs are in part publicly funded. Unlike for nuclear power plants there is no danger of contamination with conventional thermal power plants if the hot water of the primary circuit is stored directly. This results in less stringent safety requirements which suggest the use of such systems first of all for conventional power plants and the collection of data.

This also applies, for example, for older power plants with limited load change rates, which due to a limitation of the permissible temperature change rate could not otherwise be used as immediate reserve output or for frequency stabilization.

On the whole it seems desireable to further optimize the total process with hot water storage systems. This applies to thermodynamic optimization with regard to component matching as well as to cost optimization.

Besides the development of large containers, a few partial problems should also be investigated and solved in the best way possible from the engineering point of view. As an example we may mention the following:

1. The mixing behavior of hot and warm water at the free interface.
2. The development of interior isolation which is pressure proof and water proof.
3. The development of a two-part feed pump with heat insulation.
4. Optimization of the automatic control system.

All of these problems can be reviewed and solved.

Public support of this research is justified, in my opinion, in view of the economic advantage in reducing the primary energy use in thermal peak-load power plants fired with fossil fuels and in view of the related possibility of saving at the present time on a yearly basis on the order of 1 billion German Marks in foreign exchange.

With respect to the increasing proportion of large base load nuclear power plants, rapid development of hot water storage systems is also desireable from the technical standpoint.

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Discussion: Formation of Stored Heat by Means of Bled Steam During Times of Load Reduction and Its Use in Peak Load Times

T. Bohn, Jülich Nuclear Research Facility

What are the advantages of hot water reservoirs with respect to steam reservoirs? And another question: what power production costs can be expected with hot water storage - peak load systems? Are they lower than with gas turbine peak load plants?

E. Bitterlich, Deutsche Babcock Ltd., Oberhausen: /498

As to your first question, if you'll recall the thermodynamic criteria specified (Fig. 7), there it was first of all shown that all irreversible losses should be avoided. If you use a steam reservoir, then this means using a constant pressure reservoir with a varying pressure level, i.e. you charge it at a higher pressure, let it discharge and therefore, if you cannot always be filling this system at different points in this process, you will therefore get throttle valve losses. The gist of this recommendation actually lies in the fact that we avoid this irreversibility using the medium of water without a change of state and without additional irreversible losses and with quite conventional means and methods as a result of connecting up a reservoir at the right point.

As to the second question, we can start by saying that the specific heat consumption can lie in an order of magnitude from about 3,100 to about 3,300 kcal/kWh and 2,000 use hours per year can be assumed; that the installed output was based on the specific investment costs of 350 DM/kW, a specific heat price of 20 DM/Gcal was assumed and thus we get specific power production costs of about 12-14 German pfennigs per kWh. The entire consideration is based on the fact that the production costs k are not supposed to be changed, i.e. can consist of combined costs from the production costs of a base power plant and the production costs of a peak power plant. The work produced annually remained the same, the production costs, including the power production costs, remained the same, but by virtue of the fact that the specific heat consumption of a peak-load power plant can altogether be decreased from 3,100 to at present 2,100-2,300 kcal/kWh, here we get the advantages. In principle, we are not doing anything else here than replacing fuel costs by investment costs.

W. Schock, Mannheim Super Power Station, Ltd., Mannheim:

We have had displacement reservoirs in operation for more than 40 years and can supply ample data on operational experience. It is obvious that connecting the displacement reservoir in parallel to the regeneration system gives the possibility, depending on the capacity design (4-5 hours), of increasing the bottleneck output by 12% without adversely affecting the efficiency of the system. They run at 80 atm -- we designed the system for 20 atm and got by with steel containers (18 meters high, 3 meters in diameter) -- I wonder if one should go to the pressure state of 80 atm. You can already reach 70% of the possible amount if you choose a pressure stage at which one comes to reasonable container dimensions.

Another question: as the diameter of the container increases, naturally the mixing zone between the cold water and the warm water becomes larger. If you do not use the reservoir every day you you get a very large mixing zone?

E. Bitterlich, Deutsche Babcock, Ltd., Oberhausen

You mentioned a diameter-to-height ratio of 3:20. Also in my data this ratio was about 1:6. On this point I can fully

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accept your statements, and I believe that I clearly pointed out where there are still development problems here. Based on our calculations so far we believe that the high pressure stage produces considerable additional output. For present day 600 MW blocks (feed water temperature from 245 to 260°C) you do not need to exceed 50 bars with the storage container pressure. If you'll recall the increase in specific costs for pressure containers as a function of pressure, then it is precisely an advantage of the prestressed cast iron pressure container that the costs increase at a slower rate. Since one must have the basic equipment in the first place, we believe that it is better to accept this stage. To establish that the mixing cannot be such an important criterion, I am encouraged by a talk I had with a submarine captain. For according to him even the oil tankers were run with open bottoms, i.e. that only the difference in specific gravity kept the oil and water from mixing. To be sure, viscosity coefficients and other things also come into play here. But this comparison is to be taken more as a joke.

P. V. Gilli, Graz Technical University, Austria:

The thermal energy storage suggested by the speaker in the form of feed water storage by means of prestressed cast iron pressure containers (PCP) is a very advantageous way of covering peak loads when the turboset and, in particular, the generator are suitable for overload. In general, designing the turboset for overload will be possible with new coal power plants to be built. In individual cases it may even be possible with existing coal power plants to take advantage in this way of the over capacities of the turboset with respect to the steam generator. This then results both in cost-favorable peak output and a higher degree of storage efficiency. In this connection, the storage pressure made economically possible by the PCP corresponding to the pressure in front of the reheater is without doubt the most reasonable solution.

With nuclear power plants, because of the high plant costs in conjunction with low fuel costs there exists an even greater incentive for peak load production by means of thermal energy storage in the power plant. Whether the suggested arrangement can be used depends on whether it is possible to overload the turboset. With types of reactors with units smaller than the limiting output of the turboset -- for example, with a heavy water reactor -- this will be the case in an analogous way as with a conventional power plant. With the current light water reactors, on the other hand, these for the most part involve limiting output machines so that by definition an overload is not possible. Here, however, there exists the possibility of providing special peak load turbines, which by the way are not tied to the 15% overload limit in the case of feed water storage but are largely independent in their design.

Also the construction and design of storage systems is largely independent in the case of a separate peak load turbine. For the high pressures and large containers made economically feasible by the use of PCP containers, gradient reservoirs and expansion reservoirs are especially interesting along with sliding pressure reservoirs. Studies have shown that with arrangements of this type economic peak load operation of a nuclear power plant can be achieved for up to about 6 hours of peak load time. In so doing the reactor is operated with a constant load which is also important for operational reasons, for example to protect the fuel elements. With appropriate construction the system can moreover be operated within its design limits as a back up for the reactor. In summary, it can be stated that steam storage by means of recent PCP technology will be very important for all types of nuclear power plants and therefore represents a worthwhile development goal.

A. Stoll, Kraftwerk Union, Ltd., Erlangen:

Mr. Bitterlich, 10 years ago the public utility of Duisburg built a 150 MW block with a displacement reservoir. In your considerations have you included the experience gained there? It was decided there at that time to provide a cushion of steam above the water to ensure the reservoir agianst pump pressure among other things. One could have saved considerably more on safety devices than the additional charging and discharge pumps cost.

E. Bitterlich:

We did not make this profitability comparison. But I would like to make the following order-of-magnitude statement. If you recall, Dr. Stoll, the costs for the 8,000 cubic meter con- /499 were about 22 million German Marks. If you put a steam reservoir on the container and do not build an additional warm water reservoir, then 2 things must be distinguished. Either one uses the cushion of steam only for safety purposes -- then in each case readjustments must be made and we would have only just a safety device -- or you use the heat reservoir simultaneously as a compensation tank in order to allow for the various volumes as a function of the prevailing temperature. If you want to implement the latter, then instead of 8,000 cubic meters you need about 11,000 cubic meters of storage volume, and in my opinion you can build a good and safe regulating system for this.

R. Schach, Munich Public Utility:

Since 1972 we have been operating a storage system with a storage capacity of 4,500 cubic meters (15 containers 3 meters in diameter, about 33 meters high, nominal pressure 25 atmospheric excess pressure, 200°C). Hot water is stored for purposes of long-distance heating to cover night time demand. Here I would particularly like to point out the possible thermoelectric voltages connected with charging and discharging. Because of the thermoelectric voltages the material chosen for these containers was not distinctly fine-grained steel but rather an insensitive material with respect to the thermal voltages.

E. Bitterlich:

It coincides compeltely with my view with respect to the safety philosophy not to use steel containers but prestressed cast iron containers. It is certainly necessary to design and test steel containers with respect to their reliability in the face of alternating stresses. With case iron containers this is not necessary because cast iron is relatively insensitive to temperature. Therefore I believe that prestressed cast iron pressure containers here offer a solution to the problem.

G. Dietrich, KA Planning, Ltd., Heidelberg:

Mr. Bitterlich, what experiences does Siempelkamp have with prestressed cast iron containers?

E. Bitterlich:

With your permission I'll turn this question over to a Siempelkamp representative.

F.E. Schilling, Siempelkamp Foundry, Ltd., Krefeld:

Since 1968 we have been working on the development of prestressed cast iron containers, designing them primarily for gas cooled reactors. These containers are prestressed to 90 atmospheres above atmospheric pressure for a design of 60 atmospheres above atmospheric pressure. If for any reason these 90 atmospheres above atmospheric pressure would be reached, the cast iron parts in the bracing wires would float, the liner would break and the container would blow off steam. This so-called burst safety has been proved so far on a few similar containers, and to be sure prestressed concrete containers. The material of the pressure container is put under compressive stress, the cooled bracing cables are located outside the storage space so that the bracing steel takes up the internal pressure and the cast iron only serves for support. In addition to this come the good characteristics of cast iron with respect to thermoshock. So detailed relevant study results are available.

G. Volland, Kongsberg, Ltd., Neu-Isenburg:

Mr. Bitterlich, a little while ago you cited the following figures: 300 to 400 German Marks per kW and 3,200 to 3,400 kcal/kWh. For what block sizes do these values apply?

E. Bitterlich:

These values are valid for jet gas turbines, light gas turbines and units on the order of 60 MW.

A. Ziegler, Federal Ministry for Research and Technology, Bonn:

If I have understood you correctly, Mr. Bitterlich, then additional investments for storage systems are worthwhile when fuel costs are high. Therefore, from the standpoint of operational economy what do the proposals for nuclear power plants look like?

Another question: in case power plant operators and power companies do not form an economic unit, must a kind of divided power supply contract be negotiated for a pwer plant supplied with a storage system, according to which contract a portion of the output and work will be devoted to the conditions for medium load and the rest to the conditions for peak load? What problems does this create for the calculation of costs, since indeed a kind of compound production of medium and peak load exists?

E. Bitterlich:

As to you first question, my statements were with reference to conventional thermal power plants, but obviously such storage systems are also reasonable for nuclear power plants. You must install the base output of the reactor, and the bottleneck output must always be designed according to the peak value, that is, the total collective of existing power plants produce a bottleneck output, but on the basis of the systematic annual load curves the nuclear power plants move into the medium load range. Here then would lie the starting point, namely that the nuclear power plants could constantly be run at full load with the help of a storage system with the result that the peak load would not be covered by any newly installed power plant whatsoever, but by a combination of base power plant/nuclear power plant plus a storage system.

As for you second question, other gentlemen here are certainly more competent than I am to answer this question. But in responding to it I can say in general that each power company must obviously calculate a mixed price. They cannot assume that rates will be determined which, on the one hand, are related to peak load removal and on the other hand to base load removal, in any even only in special cases. Dr. Schoch, you can certainly say something more compelling on this point.

W. Schoch:

Naturally, you must make the output available in the form of base-medium and peak load. In any case, it is important that the total investment costs, or total expenditure, is not higher. If in so doing the heat economy can be improved, then this is yet another advantage to the consummer. Now just a few words on calculation. In our calculations we calculate the power production costs as a function of the production in question. If we sell night time power, we have produced the additionally produced kWh with an increased heat consumption which is significantly smaller than the average heat consumption. If we cannot sell any night time power we must shut down the system and then we have shutdown and startup losses. Thus we can precisely state that the additional heat consumption is about 1,600 kcal/kWh in comparison with the average heat consumption of 1,950 kcal per usable generated kWh. As a result, the power produced at night is accordingly valued as 63% of the power produced during the daytime.