BROWN BOVERI

The 1160 MW Turbine for "Donald C. Cook" Nuclear Power Plant of AEP

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Following some introductory comments on the reasons for building half-speed machines, the turbine for "Donald C. Cook" nuclear power plant is described. In dealing with some elements, the author goes into details in explaining the basic ideas which governed the designs adopted. Some notes on the tests performed and on special safety considerations round off the article.

About ten years ago nuclear power plants emerged from the experimental stage into the everyday industrial field. The reactors used today may be divided into three main groups:

- Gas-cooled reactors (e.g. AGR or THTR) which, up to now, have only made headway in Britain; more recent developments will confirm whether they are economically competitive.
- Pressurized-water reactors (PWR), representing the "light-water" line of reactors, which today are being built by a number of manufacturers and are in use throughout the world.
- Boiling-water reactors (BWR), to which the same applies.

When the success of the light-water reactors began to become apparent, some years ago, it was soon seen to affect two aspects of steam turbine design:

- Light-water reactors generally provide saturated steam at a pressure of 40 to 80 bar.
Consequently the heat drop that is available is only about 65% of that used by modern reheat turbines. The specific steam consumption can therefore be 60 to 90% higher than in conventional plants, depending on the specific conditions.
- The corresponding nuclear power plants can only be justified economically if unit ratings are made very high.

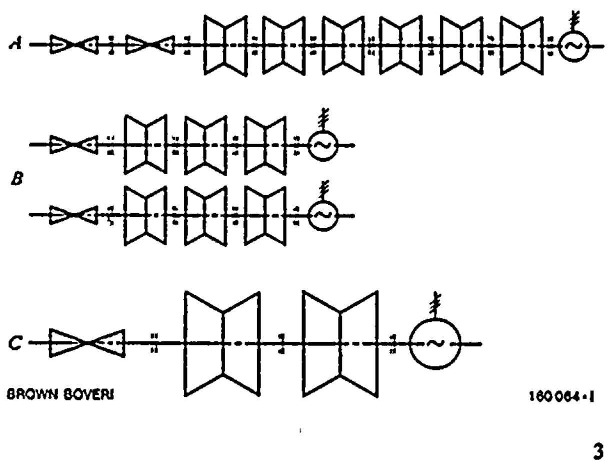
These factors led to the problem of handling very large steam volumes, especially at the low-pressure end of the turbine and this induced Brown Boveri to reconsider the construction of "half-speed" turbines (running at 1500 or 1800 rev/min instead of 3000 or 3600 rev/min) after a break of some 40 years. It was assumed that, having regard to the specific conditions, the configuration of a machine running at the normal 3000 rev/min would, for example, comprise a four-flow high-pressure section and a twelve to sixteen-flow low-pressure section. Considering the overall planning, the construction of such a machine in one line (tandem compound) would become somewhat questionable, even if the design problems (e.g. differential expansion) could be solved without great difficulty. Breaking the unit down into two machines is usually uneconomical, so that the next obvious solution was to revert to "half-speed" machines (see Fig. 1).

The preliminary design work was therefore put in hand, in order that the answers to fundamental questions could be found before enquiries were received. In this process the design principles that have proved so successful in the past were adopted, as they not only offer numerous advantages, they can also be extrapolated with remarkable accuracy. Nevertheless the new dimensions did pose some major problems which had to be solved first and made additional tests and experiments necessary.

Having closely examined the detailed proposals regarding design, production and operation of half-speed machines, the American Electric Power System (AEP) placed an order with Brown Boveri early in 1968 for a machine rated 1160 MW (53 bar, 268 °C saturated steam, back pressure 0·051 bar), comprising turbine and generator, destined for 'Donald C. Cook" nuclear power plant.

Fig. 1 – Comparison of the size and capacity of full-speed and half-speed machines

A = 1 turbine, 3000 rev/min, 100% output
B = 2 turbines, 3000 rev/min, each 50% output
C = 1 turbine, 1500 rev/min, 100% output



"Donald C. Cook" Nuclear Power Plant

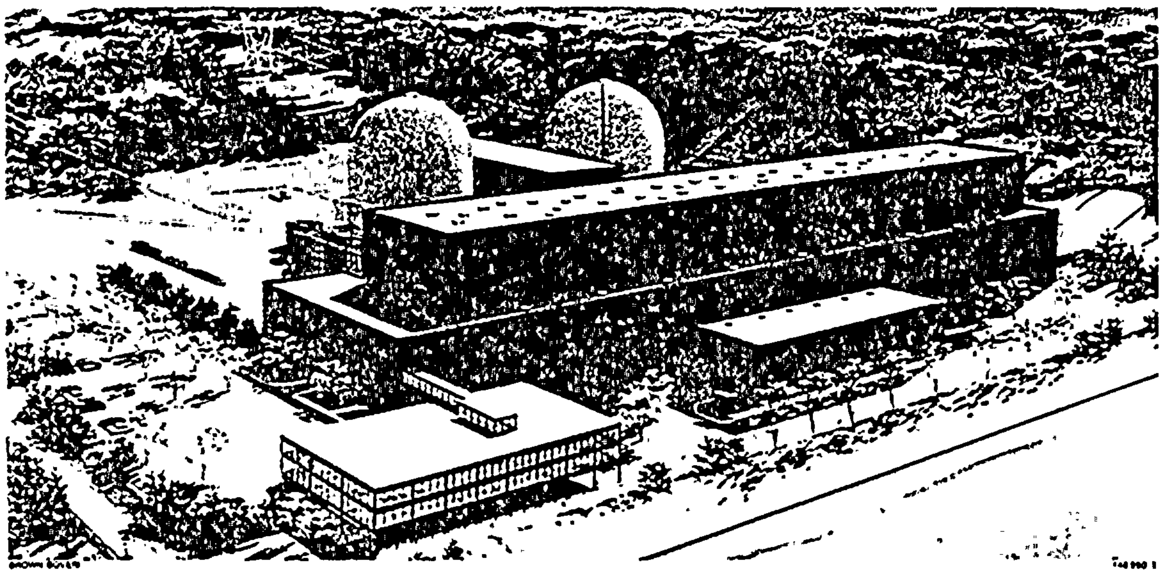
The plant is located on the east bank of Lake Michigan in St. Joseph's County and is therefore directly accessible by ship from Europe through the St. Lawrence Seaway. This is important in view of the considerable transport problems. Fig. 2 shows an artist's impression of the plant which will contain two units. Each turbine will be supplied with steam from a Westinghouse pressurized-water reactor. The first turboset is being provided by an American manufacturer, while set No. 2 is being supplied by Brown Boveri. The self-explanatory schematic layout can be seen in Fig. 3.
The two feed pumps, each of 50% capacity, are to be driven by steam turbines [3].

The Turboset

Layout

The turbine consists of a double-flow h.p. section and three double-flow l.p. sections driving a four-pole alternator. On either side of the h.p. cylinder there is a pair of combined stop and control (throttle) valves. The general arrangement of the set is illustrated in Fig. 4, 5 and 6. The enormous size of the combined water separators/reheaters between the h.p. and l.p. sections of the turbine can be seen at a glance.

Fig. 2 – View of a model of "Donald C. Cook" nuclear power plant of AEP on the east bank of Lake Michigan



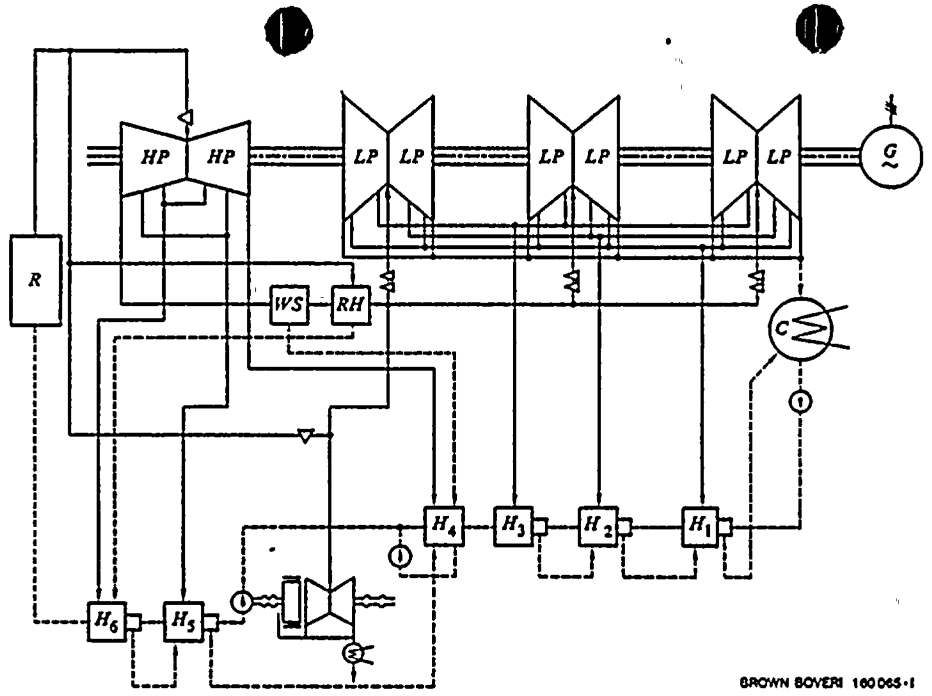


Fig. 3 – Schematic layout of the "Donald C. Cook" plant

R = Reactor
HP = High-pressure turbine
LP = Low-pressure turbine
G = Generator
C = Condenser
H = Feed-heaters
WS = Water separator
RH = Reheater
——— = Steam
– – – = Water

Inlet Valves

The saturated steam, at 53 bar and 268 °C, from the reactor enters the turbine through four live-steam lines to the four combined valves (Fig. 7) which are equipped with steam strainers to prevent solid matter entering the turbine and also to stabilize the flow. In their dimensions and design pressure these valves resemble the interceptor valves supplied for the 1300 MW reheat turbine for Cumberland power plant of TVA [1]. However, the much lower temperature at "Cook" allows the use of ordinary, low-alloy cast steel. Fig. 8 gives some idea of the proportions of these huge inlet valves. From them four pipes carry the steam into the h.p. cylinder.

High-Pressure Section

The h.p. section is of double-flow design; as the turbine is intended for base-load duty, a regulating stage can be dispensed with, the steam flowing directly through the reaction blading.
The casing is of low-alloy cast steel. The size and weight of its two halves made it necessary to adopt a composite assembly, each half of the casing being made of six sections which were afterwards welded together (Fig. 9, 10, 11).
When these large castings were ordered—each half weighs about 100 t—it was found that the risk of rejection and, consequently, of not being able to fulfil deadlines, was relatively high. Therefore, for the next pair of similar turbines that are on hand for TVA, as well as for a 1200 MW set for Jersey Central, a modified design was developed in which the outer casing is a welded fabrication (Fig. 12).
The cast h.p. casing of the "Cook" turbine is a single-shell design and features blade carriers. The latter are not attached to the casing itself, but form an integral casting together with the casing. In this way the risk of erosion due to leakage in the region of the attachment points was completely avoided. The critical parts of the flanges were faced with high-alloy material, the blade carriers being additionally bolted together, so as to prevent leakage. Due allowance had to be made for accessibility to these bolts from outside. To minimize distortion of the large end faces under the internal pressure, tensioners were incorporated. This is particularly important as it prevents any displacement and distortion of the gland sections, the whole casing being mounted direct on the foundations at the sides, on account of the very large torque, and not supported in the usual manner by feet on the end faces and pedestal bearings.
The advanced welded design used for TVA and Jersey Central is based on similar considerations. Two solid rings in the outer casing absorb the torque exerted on the stationary part and transfer the forces direct to the foundations through feet. The end faces are similarly fixed by means of tensioners. Of course, the points at which

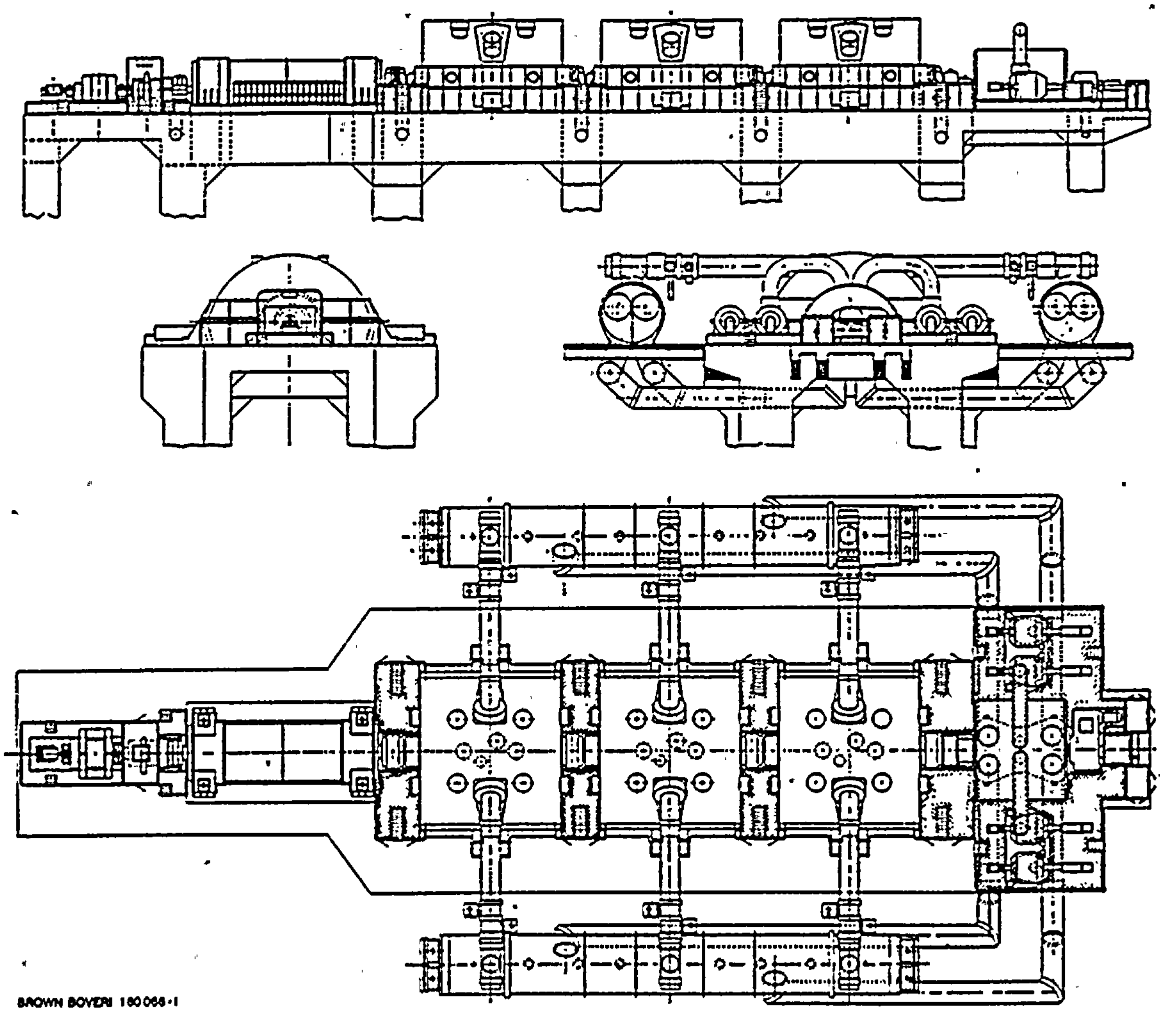
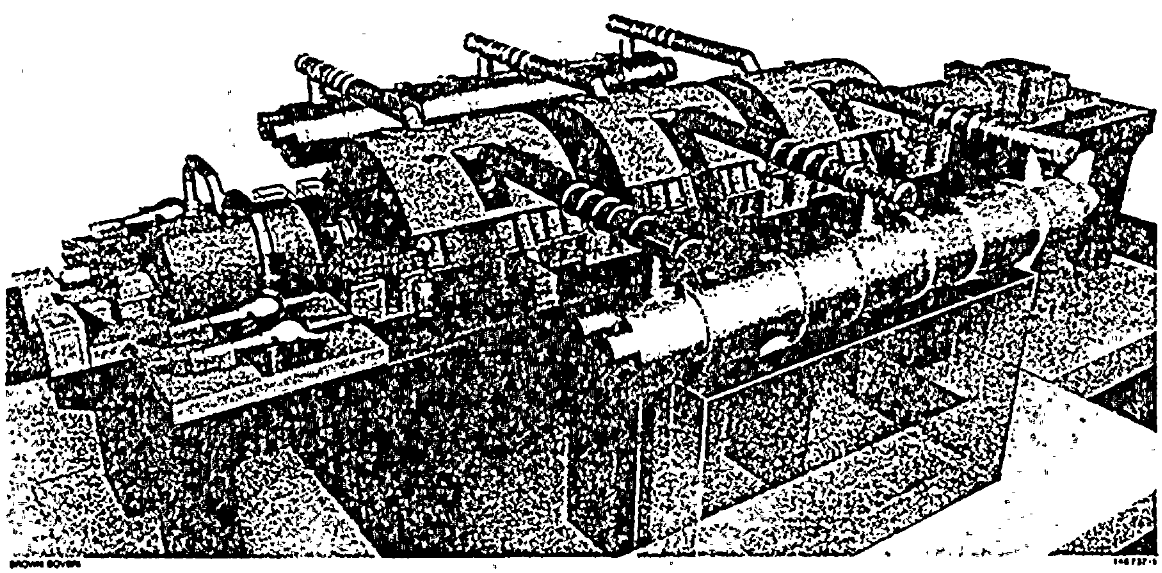


Fig. 4 – Layout of the "Cook" turbine, rated 1160 MW, 53 bar, 268 °C saturated steam

Fig. 5 – Model of the "Cook" turboset, used for working out the piping layout



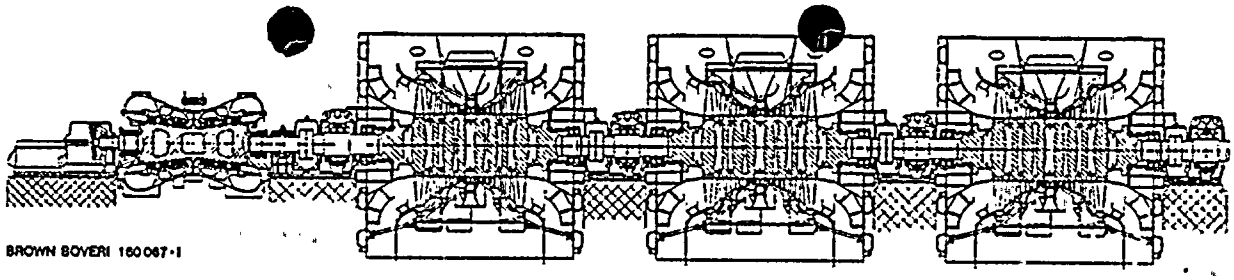


Fig. 6 – Longitudinal section through the "Cook" turbine

there might be some risk of leakage (blade carrier attachments, flange joint, etc.) are faced with high-alloy material. If necessary, the blade carriers can be made of high-alloy material for instance, should there be any risk of erosion.
For some time now it has been possible to calculate the highly complex shapes of these casings with a high degree of accuracy. Numerical methods, using finite elements, for modern large computers have been developed to such an extent that they enable these problems to be solved.

Crossover Pipes, Water Separators/Reheaters, Interceptor Valves

From the h.p. section the steam passes through four lines into the combined water separators/reheaters (Fig. 13). There the steam is first dried in mats of wire mesh, following which it is superheated by flowing through nests of tubes heated with live steam.
The reheating part can be designed in two stages, the lower stage being heated by bled steam from the h.p. cylinder

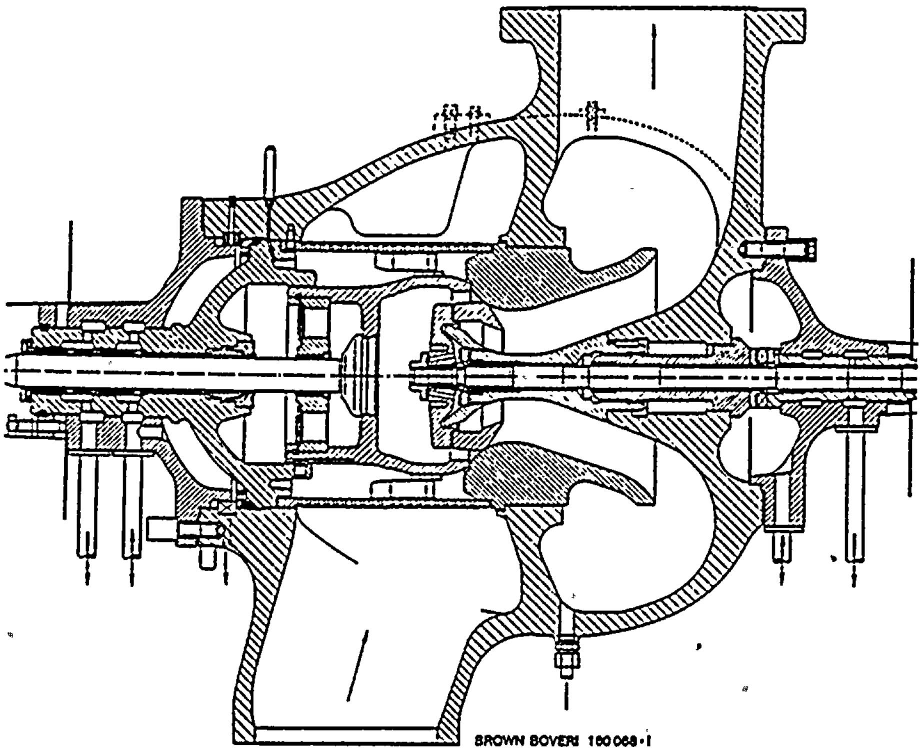
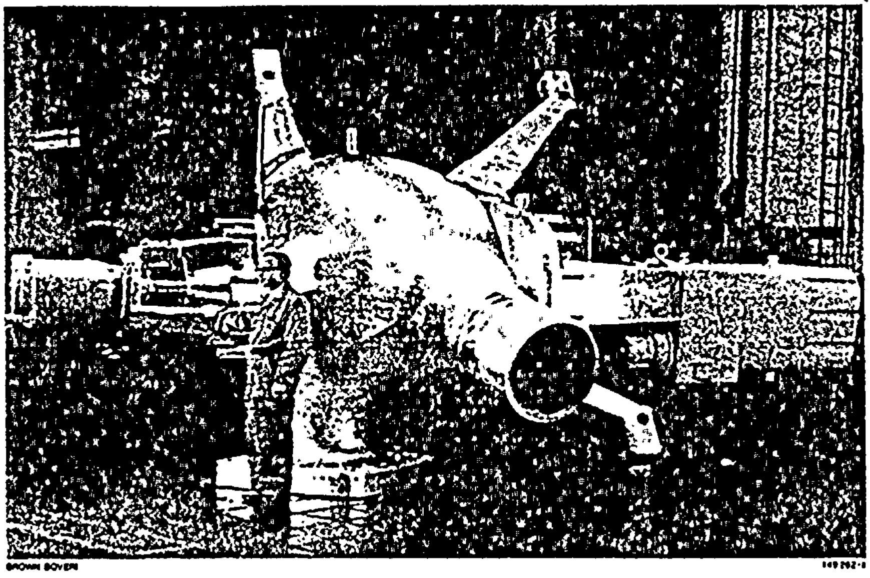


Fig. 7 – Section through a combined stop and control valve

Fig. 8 – Combined stop and control valve, assembled

Left: Servomotor of the stop valve
Right: Servomotor of the control valve
Middle: Valve housing with steam pipes and supporting arms



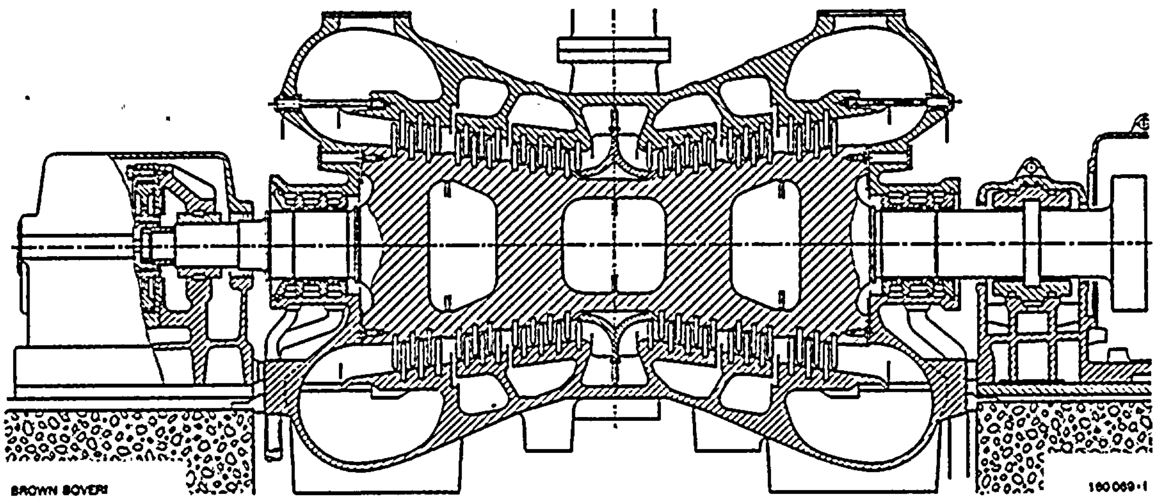
and the upper by live steam. The decision as to whether a single or two-stage design should be adopted is largely dependent on the result of an economic calculation. From the tanks housing the separators/reheaters the steam flows to the l.p. sections. Each of the two reheaters has three outlets, so that each l.p. section is fed through a pair of symmetrical lines (see Fig. 14).

Reheat stop and interceptor valves are incorporated in these crossover lines, their task in the event of a shutdown being to block the large amount of energy in the steam stored in the separator/reheater tanks and thus to prevent the turbine from overspeeding. An overspeed calculation confirmed by measurement is needed to determine the number of valves required. Depending on the result, either no valve at all is provided, or one valve controlled by the steam regulating system; it may even be necessary to provide two such valves, one of which is controlled, as before, by the steam regulating system, the other being actuated by the trip system. These valves are well-tried components (Fig. 14, 15), having already been used in a number of district-heating turbines for control duties.

Low-Pressure Section

The enormous dimensions compared to a full-speed machine of similar output in a fossil plant are still more obvious in the l.p. sections (compare with the height of the man in Fig. 5). Here, too, the established design has been adapted to meet the requirements of the enlarged dimensions.

Fig. 9 – Longitudinal section through the high-pressure section (cast casing) of the "Cook" turbine



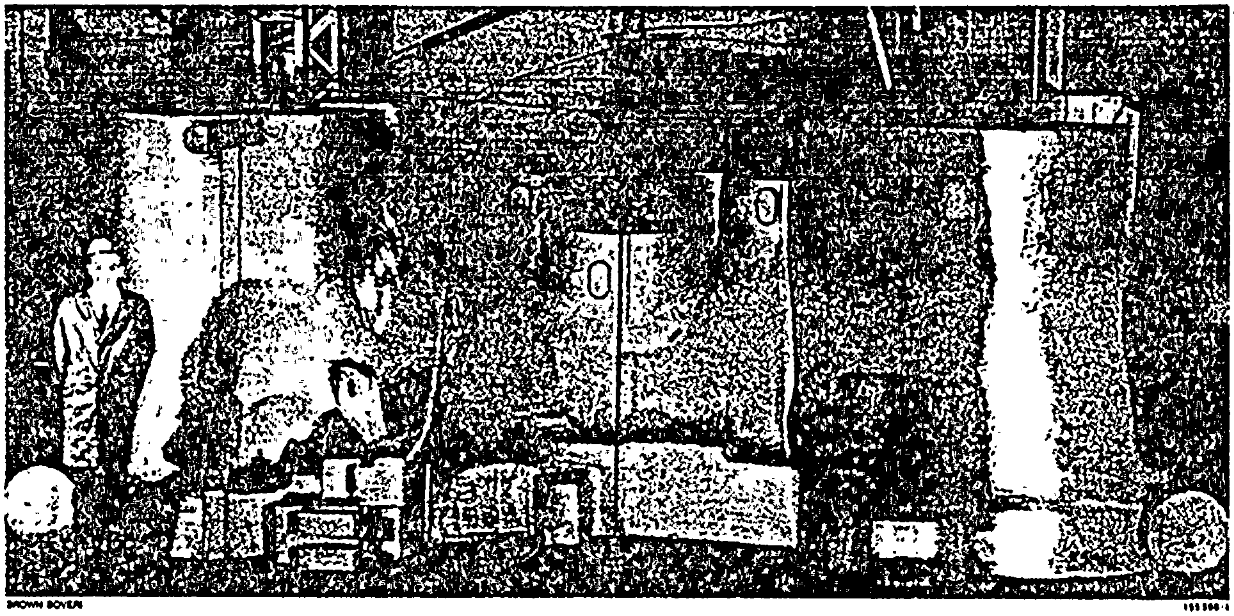


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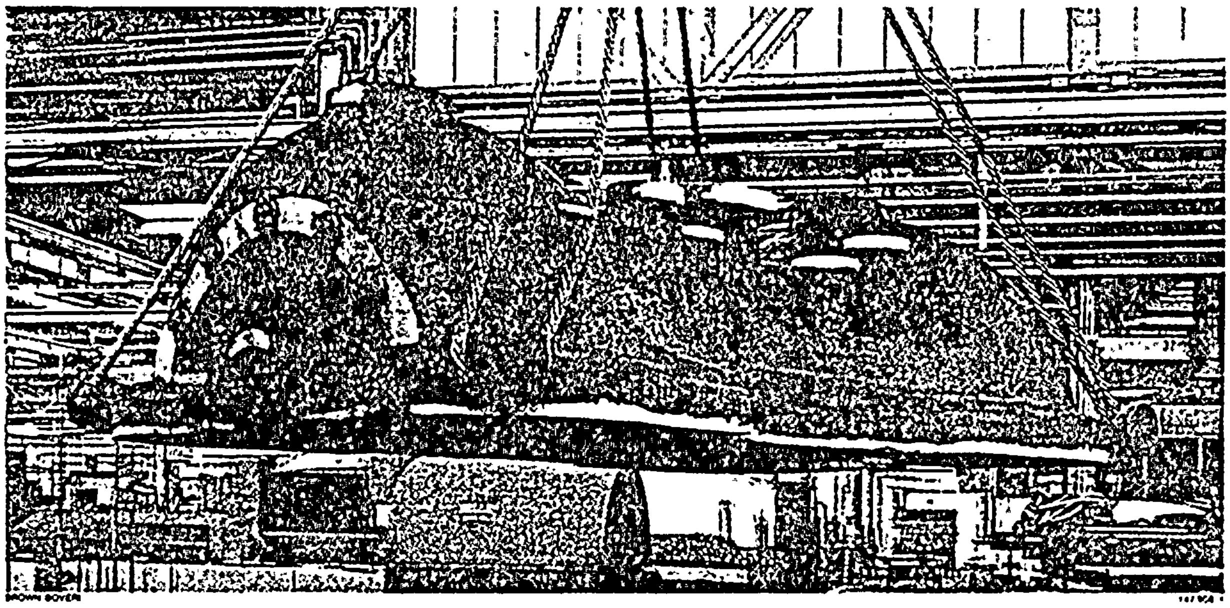
Fig. 10 – Half the casing of a h.p. cylinder, showing the various castings of wh.ch it is composed

Fig. 11 – Finished half of the h.p. casing (weight approx. 100 t)



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A consistent distinction between the various functions has been observed. The outer casing serves only to confine the steam and to absorb the forces of external pressure. The blade carriers are supported by cantilever beams fastened direct to the foundations. The glands are attached to the bearing pedestals and also joined to the outer casing through flexible elements rather like expansion joints.
In this way it is possible to prevent the inevitable elastic distortion of such a large outer casing from having a negative effect on the rotating parts (e.g. rubbing due to reduction of clearances, fouling, etc.).
The problems connected with production and transport were solved by designing the l.p. section in several parts. The hood and the sides of the lower part can, if necessary, be welded together on site after they have been assembled. Special precautions have been taken in the design to prevent distortion due to welding at critical points, e.g. at the horizontal flange joint.

Since these casings are exposed to an external pressure, due allowance has to be made for unstable implosion in addition to the normal stresses. The procedure adopted for the hood is that it is assumed that a state of stress as in a membrane is present (i.e. tension and compression, but no bending stress). As with Euler's bending equation, plausible deformation is assumed (longitudinal or peripheral waves), as known from observations. The resultant additional stresses in the case of instability are then larger than the opposing forces due to resilience. Since the hoods of such l.p. casings are, in principle, cylindrical shells, the problem has to be tackled by means of partial differential equations, the solutions of which yield two types of bending characteristics in the longitudinal and peripheral directions. The combination which is able to withstand the minimum loading—usually it leads to roughly square indentations—is decisive. Fig. 16 shows such indentations in a model casing. It is worth noting that measurements

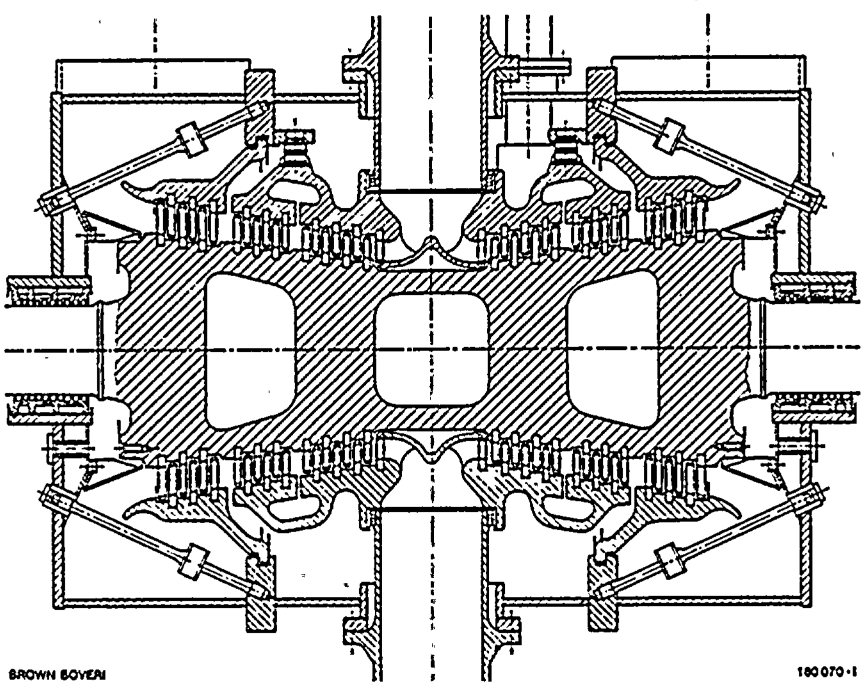


Fig. 12 – Longitudinal section through the h.p. section of a half-speed, saturated steam turbine with welded casing
(Jersey Central, TVA)

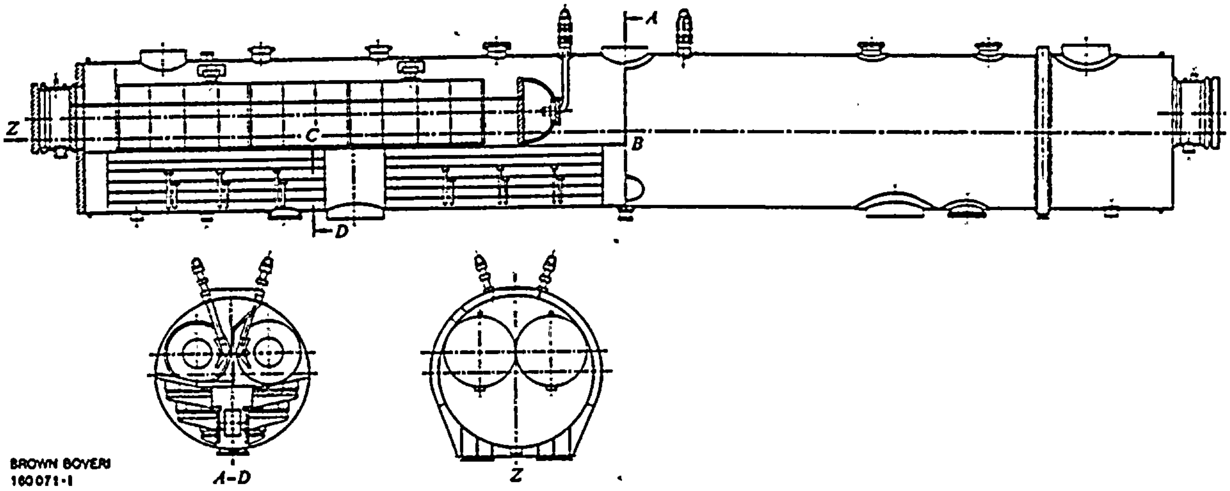


Fig. 13 – Sections through a combined water separator/reheater (Balcke)

Fig. 14 – Section through the reheat intercept butterfly valve in the cross-over pipe

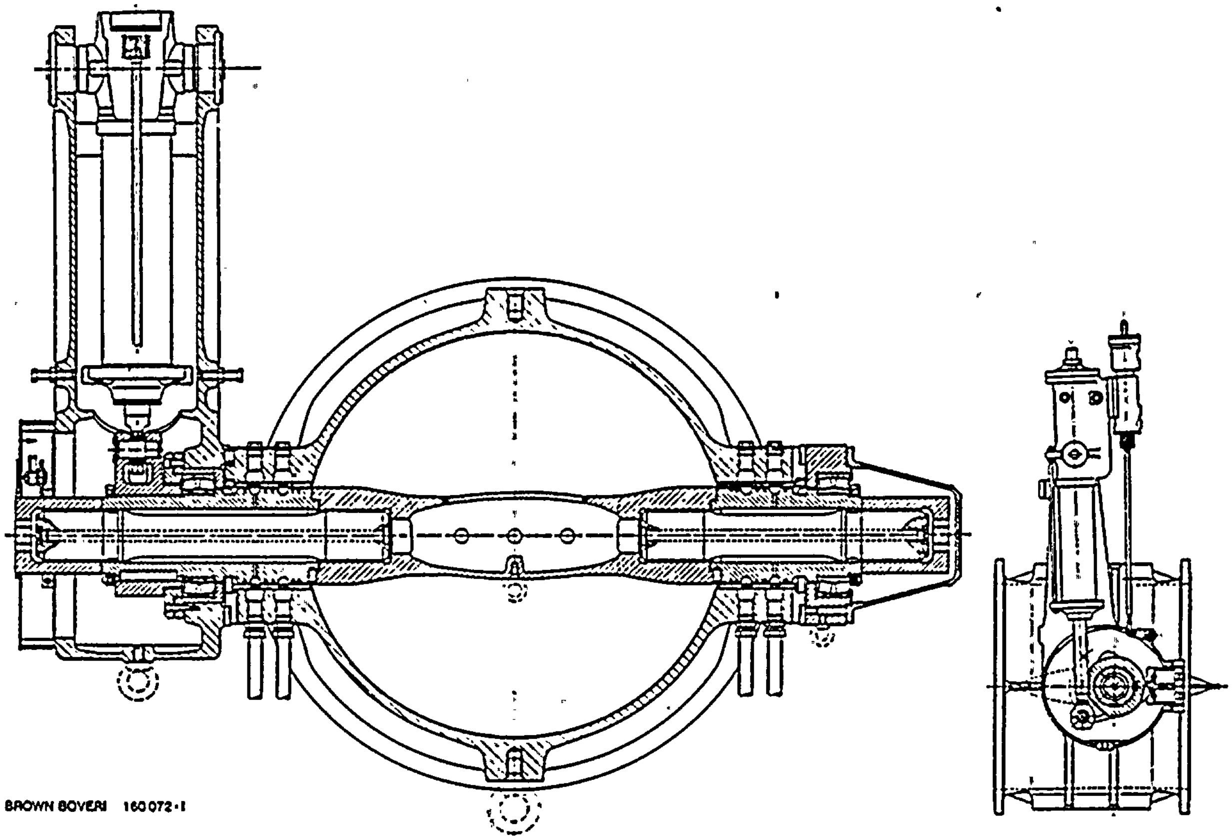


Fig. 15 – Assembled butterfly valve

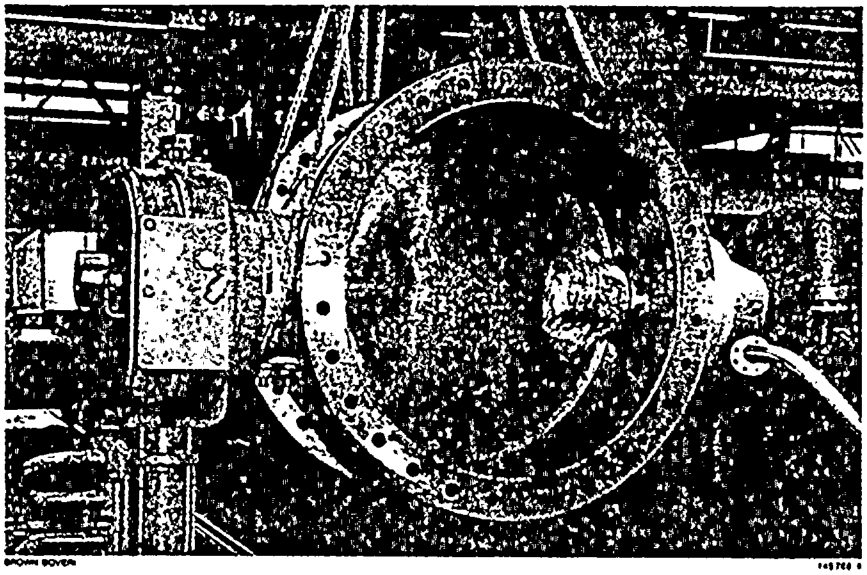
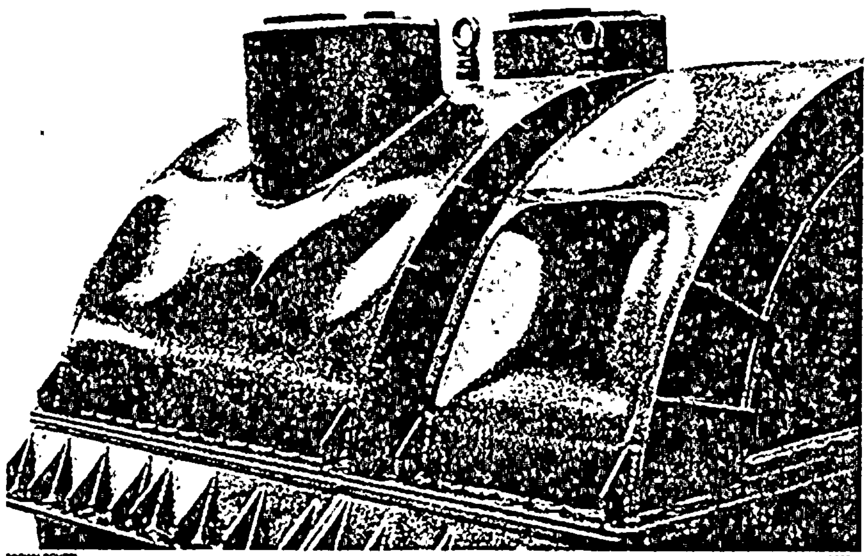


Fig. 16 – Model of l.p. casing after implosion tests



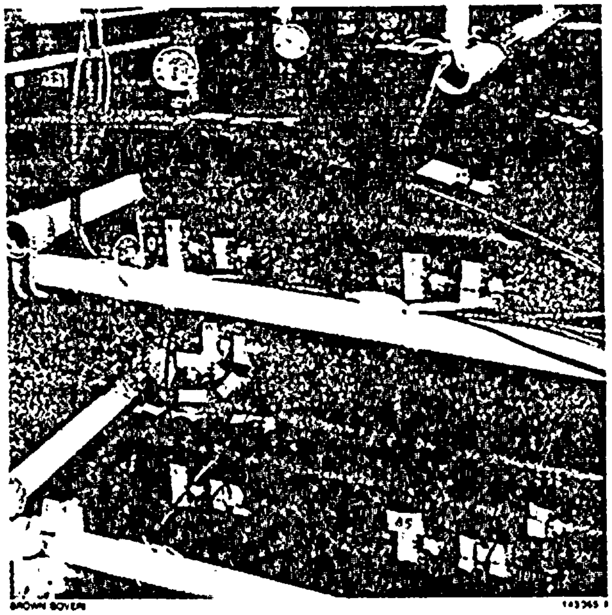
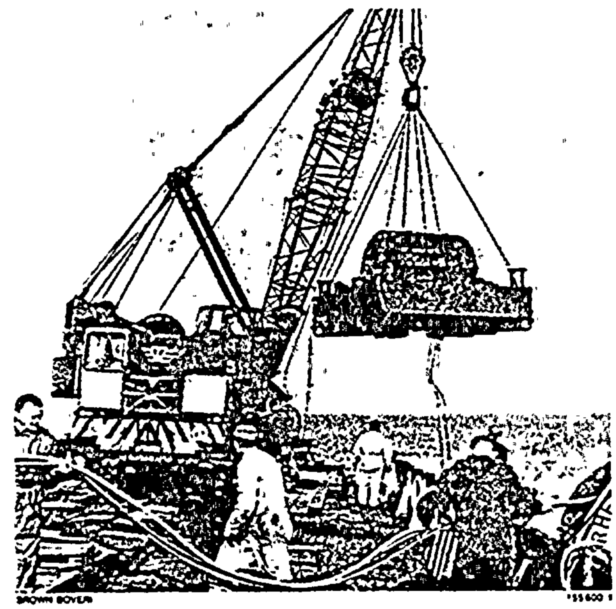


Fig. 17 – Tests on a model of the l.p. casing of the "Cook" turbine

Using dial gauges and strain gauges the deformation and stresses on the evacuated casing were measured.

Fig. 18 – Test to destruction on the model casing of the "Cook" turbine

The necessary external pressure was obtained by lowering the model, internally at atmospheric pressure, into Lake Constance until a depth of over 65 m was reached.



agree very well with the calculated values. Also, it may be pointed out that the model casing had no internal struts whatsoever.

To establish the degree of safety with respect to implosion allowance must naturally be made for additional boundary conditions, such as pre-shaping for production reasons, and the like, which reduce the implosion limit.

Exhaustive tests on models (Fig. 17) provided ample proof that the calculated values were correct. For the l.p. casings of half-speed machines, however, the need to be strictly true to scale (e.g. welds) makes it necessary to use such large models that a most unconventional method had to be adopted for the pressure test to destruction.

Determination of the safety with respect to implosion is naturally somewhat uncertain. In order to be sure of the results the model casing of the l.p. section of the "Cook" turbine was lowered to a depth of 65 m in Lake Constance (Fig. 18), at which depth it was subjected to an external pressure which caused it to buckle inwards.

With this casing the safety factor with respect to implosion was found to be more than 6. The method of calculation was calibrated against the results of this test, so that it is now possible to interpolate and extrapolate the calculations.

The inner casings are welded fabrications and, like the cast blade carriers, are only noteworthy for their large dimensions (Fig. 19, 20). The rotor blades of the final l.p. stage (Fig. 21), which in the "Cook" machine are 52 inches long (1320 mm), were derived by means of model laws from those normally made for, and currently in service in, machines for 3000/3600 rev/min. In this way it was possible to utilize the wealth of experience gained hitherto and so ensure enhanced reliability (Fig. 22).

Rotors

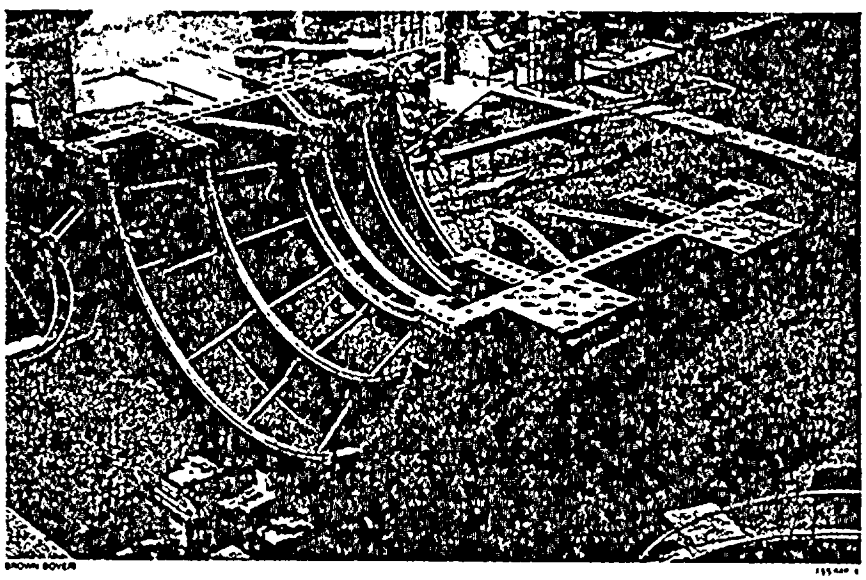
The welded sectional design of the rotors [2], though demanding comprehensive experience gained over many years, offers so many advantages that its use is likely to increase. The ever-growing unit sizes, especially those of turbines for 1500/1800 rev/min, makes this design almost inevitable. One l.p. rotor of the 1800 rev/min "Cook" turbine weighs almost 200 t without its blading. In view of the quality requirements that have to be satisfied, it is impossible to obtain a suitable one-piece forging anywhere in the world at the present time. This problem is neatly solved by the welded sectional design.

The various aspects which favour the adoption of this system will therefore be briefly recapitulated.

The sections can be designed so that they come very close to the ideal, uniformly stressed disc. It is possible to construct rotors of almost unlimited size, as the size of the

individual disc sections is small compared with that of the rotor as a whole. On account of their relatively small cross-sectional area, the sections can be annealed right through with comparative ease; consequently the quality of the material at the centre of the disc is first-class.
Material samples for destructive testing are taken from the most highly stressed region, close to the centre of the discs. Owing to the ease with which such sections can also be non-destructively tested there is no need for a central hole, which would give rise to double, local stresses. In designs with shrunk-on sections it is even possible for some of the disc material to become plastic (Fig. 23). This could affect the shrink fit to such an extent that the smooth running properties would be adversely affected. This cannot occur with welded rotor assemblies.
Constructing the rotor of several sections eliminates thermal instability. Owing to the ease with which sections can be replaced at short notice, it is possible to be much stricter as regards rejection, without the risk of exceeding delivery deadlines; in other words, still better quality.
The ratio of the weight of such rotors to their moment of inertia is extremely good. Owing to the specific stress in l.p. rotors being low, they can be made with much larger diameters; the Brown Boveri steam turbines have the highest ratio of shaft diameter to blade length. Each l.p. rotor of the "Cook" turbine is composed of ten sections (the h.p. rotors of four). The weight of the heaviest section is not more than 30 t, which is well within the power of most steelworks, and enables them to produce flawless forgings of excellent quality.
Of course, the necessary production and testing facilities had to be provided. The requirements of future turbines were duly taken into account. Finally, the cranes and lifting gear had to be dimensioned accordingly (Fig. 24).
To enable these rotors to be transported, the last two rows of blades have to be removed. With the fir-tree root method of fixing, this does not present any particular problems when these blades are inserted on site.
Special containers were made to protect the rotors with the rest of their blading during shipment.

Fig. 19 – One half of the inner l.p. casing during production



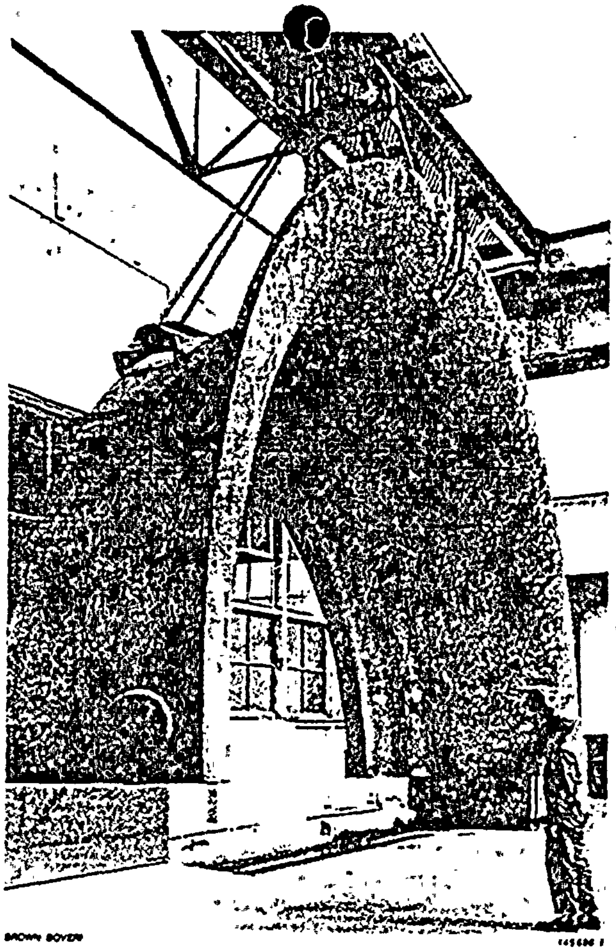


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Fig. 20 – Blade carrier of the l.p. section before machining

Bearings

Together with the constantly growing unit ratings, the size of these important components have also increased. For a long time it was possible to extrapolate existing bearing designs which have rendered good service, without encountering any unexpected problems. In the meantime, however, the necessary dimensions have become so large that, owing to the increased Reynolds number, flow in the lubricating gap has become turbulent. As a result of this, the losses and the temperature rise of the oil increase much more rapidly than would be expected from simple extrapolation. A possible way of avoiding these difficulties is to use pivoted segmental bearings.

During the development of these bearings exhaustive trials had to be carried out on the test-bed in order to determine the most favourable design, as well as the maximum load capacity and the loss power. During the past five years considerable experience has been gained with this kind of bearing, so that there was nothing to prevent their use in the "Cook" turbine.

Fig. 21 – Blades of the final rotating stage (52 in. long)

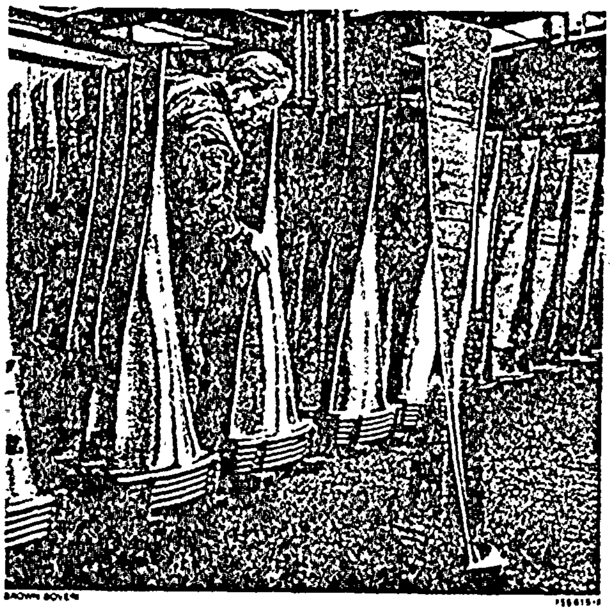

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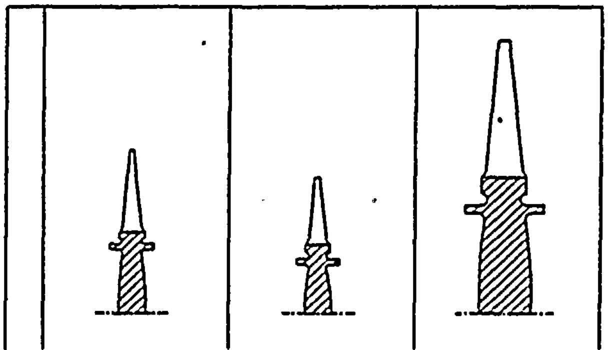
Fig. 22 – Relationships with similar last-stage l.p. blades

n = Speed in rev/min
D = Mean diameter (mm; inch)
c = Tip velocity (m/s; ft/s)
l = Length of blade (mm; inch)



n	3000		×1,2	3600		×0,5	1800	
D	2376	93,5	×0,83	1980	78	×2	3960	156
c	498	1634	×1	498	1634	×1	498	1634
l	792	31,2	×0,83	660	26	×2	1320	52
D/l	3			3			3	

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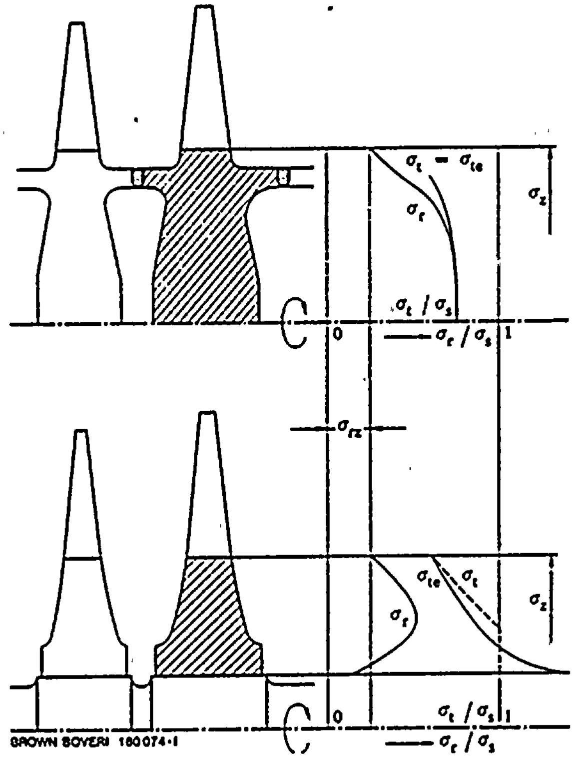


Fig. 23 – Comparison between a welded rotor design and a shaft with shrunk-on discs

σ_r = Radial stress
σ_t = Tangential stress after plastic yield
σ_{te} = Tangential stress (elastic)
σ_s = Yield point
σ_z = Blading tension
σ_{rz} = Radial stress due to blading

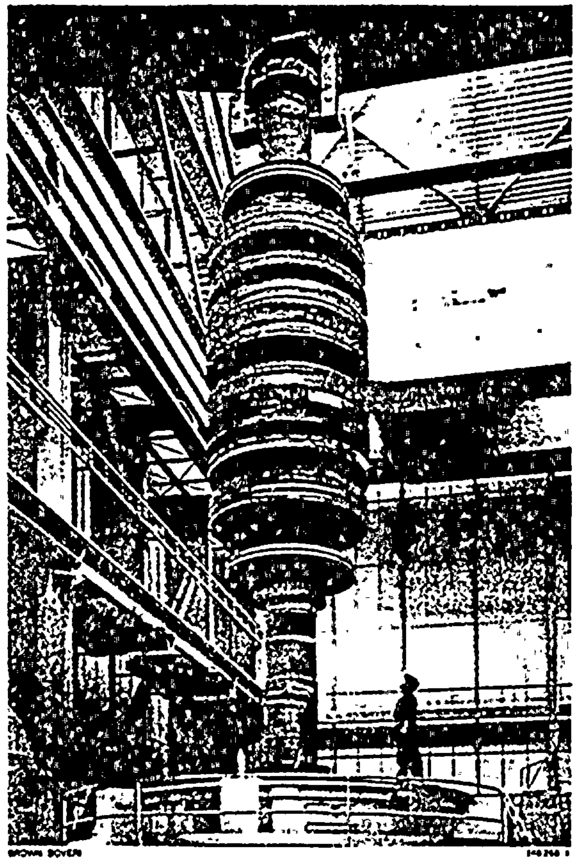


Fig. 24 – Low-pressure rotor of the "Cook" turbine (weight approx. 200 t) being removed from the furnace after being welded and stress relieved

Bearing Arrangement

For the assembly of the shaft line the neatest and also the technically most consistent solution was adopted, with only one bearing between two turbine casings and between the turbine and the generator.
This arrangement offers the following advantages:

- Alignment of the turboset is simple
- The critical speed is clearly defined (no uncertain bearing loads during assembly or in operation due to the bearing pedestal heating up unevenly)
- Insensitivity to deformation of the foundations
- The bearing load is relatively high, therefore the tendency for oil whip is minimized

On the other hand, this single-bearing design must pay particular attention to the following points:

- Different methods of assembly (though not more difficult)
- Designing the coupling as an auxiliary bearing
- Auxiliary stub shaft, needed for overspeed test on the individual shaft, and for assembly

This system has been employed on large turbines for over twenty years. The excellent results obtained prove that the principle adopted was correct.

Draining, Protection against Erosion

In the h.p. section the expansion of the steam continues well into the wet-steam region. To protect it against erosion caused by the film of water that condenses inside the turbine casing, the inner surface is lined with stainless steel (Fig. 25); in the final stage of the blading, slots ensure that this film is drained off.
The blades of the last l.p. stage are protected against erosion by having their leading edge hardened by an induction process.
In the l.p. section the same criteria apply as to conventional machines because, with the arrangement adopted, the expansion line yields the same steam conditions as in reheat turbines. As additional safeguards, special draining facilities are incorporated in the crossover lines to the l.p. sections which, in the event of failure of the reheaters, remove the film of condensate that forms on the walls of the pipes and thus prevent the formation of dangerous water streaks at the inlet to the l.p. blading.

Overspeed

Saturated steam turbines in nuclear power plants are particularly prone to overspeeding in the event of a shutdown, because the large amounts of steam trapped in piping and vessels (water separators/reheaters) still contain a considerable amount of energy and because the film of condensate on the walls of all casings and pipes flashes due to the sudden drop in pressure and, when it subsequently expands, also produces a large amount of energy.
However, in contrast to earlier assumptions, this energy is released relatively slowly. Therefore, the rise in speed is fairly steep to begin with, i.e. at the customary rate, and then after about one second, it reaches the level known for conventional plants. Due to the residual energy in the slowly evaporating films and deposits of moisture, there follows a second, though slower rise in speed, which does not reach its considerably higher culminating point for about 30 to 40 s. This "creeping" rise in speed is countered by incorporating valves in the crossover pipes. This is shown by the test results reproduced in Fig. 26.
By comparing the results of measurements and calculations, the assumptions originally made, for instance regarding the thickness of the film of water, the rate of evaporation, efficiency of residual expansion, etc., can be corrected to more realistic values.
Now that it is possible to carry out accurate calculations, the overspeed situation to be expected can now be predicted reasonably well for new turbines still in the design stage.
If the calculation indicates that the machine is liable to reach a dangerous overspeed (without valves), two valves in series are provided, controlled by independent systems (the one by the steam regulating system, the other by the tripping system). In this way the turbine and generator are reliably protected, even if one of the systems should fail.
For the "Cook" turbine described, the calculation proved the necessity of providing two butterfly valves, clearly recognizable in Fig. 4 and 5.
If the speed rise were sufficient to cause the overspeed trip to operate, though still below the danger limit (assuming no valves), it would be sufficient to incorporate only one valve. If the overspeed trip were not actuated, the interceptor valves can be dispensed with altogether.

Fig. 25 – Protection of the wall of the h.p. casing by rings of stainless steel (A)

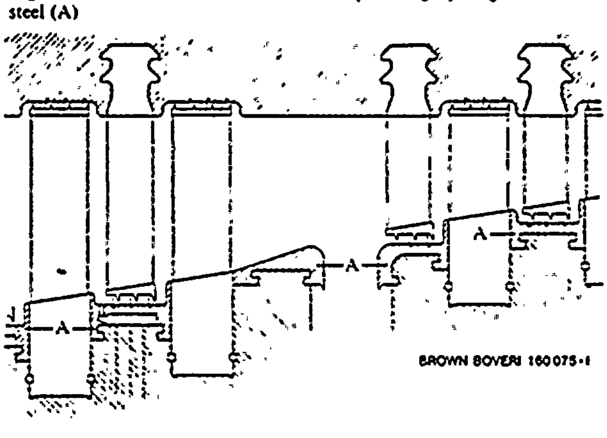
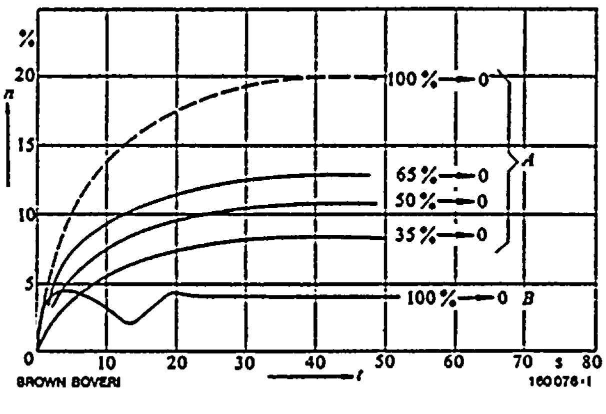


Fig. 26 – Shutdown tests on turbines in a PWR plant

n = Relative increase in speed (%)
t = Time (s)
A = Interceptor valves blocked in open position
B = Interceptor valve in operation
——— = Test results
– – – – = Extrapolated values



Safety Analysis

The special conditions under which turbines in nuclear power plants operate necessitates a special safety analysis being undertaken, in which the most improbable incidents have to be taken into account. The Atomic Energy Commission (USA) therefore stipulates a twofold analysis of the plant. All components are examined, firstly in respect of their own inherent safety and secondly with regard to the results of a possible incident.
The corresponding examination of the turbine covers the design, production and testing, in so far as the safety is concerned (control and safety systems, safety factors, design principles, manufacturing procedures, and so on).
Finally the conditions applying in the event of runaway were investigated. This situation is extremely unlikely, though, as it can only arise when all safeguards fail. Above a certain speed which is only slightly below the theoretical runaway speed of 200% of rated, isolated components begin to fail: plastic deformation of blade fixings and at the generator end-bells, fouling of the rotor, explosion of the rotor (especially disc sections, which are deliberately designed to burst first).
Next it is necessary to investigate whether and with what residual energy debris can be expelled from the machine.
If debris does penetrate the turbine casing, the residual energy must be so small that there is no risk of the containment being penetrated if it is struck.
Owing to the high degree of safety inherent in Brown Boveri turbine designs, the construction permit for "Cook" plant was obtained on presentation of the results of the various investigations. The operating permit review is in progress at the time of writing.

Prospects

The extensive preparations enabled us to present a mature design to AEP at the end of 1967, which can be used for the most part in the execution of other orders.
Certain problems in production and in the procurement of materials were recognized in good time and the appropriate conclusions drawn for future machines of this class.
With all the data worked out, we are now in a position to proceed to still larger unit capacities (over 2000 MW) without difficulty, provided certain prerequisite conditions are fulfilled.

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