SOME ASPECTS OF NAVAL TURBINE DESIGN

PART II

BY-PASSING

In any multi-stage marine turbine in which high efficiency is required to be maintained at partial loads, ways must be found to keep up, as far as possible, the velocity ratios at the lower outputs at any rate in the early stages. As one means to this end the pressure in these early stages must be " held up " so that the heat drops here are not excessive. If at these partial loads special precautions are not taken to prevent low pressures in the early stages, large heat drops will occur with consequent high steam speeds which, in combination with the reduced blade speeds, will give most unsatisfactory velocity ratios ; the heat energy will have been expanded inefficiently and only a small portion of the loss will be recoverable in the later turbine stages.

With control only of the first stage nozzles the only possible way of holding up the pressures in the early stages is by reducing their flow areas, and, while this serves excellently at partial loads, the same reduced areas will be insufficient to pass the steam required for full power.

For these reasons many naval turbines are fitted with by-passes. The by-passed stages can then be designed for optimum efficiency at partial loads ; and, when it is necessary to take more steam than these early stages can pass, this extra steam, by means of the by-passes, is admitted at a later stage in the turbine where the flow areas have been proportioned to receive it. The stages before the point of entry of the by-passed steam will then be " backed up " and will probably ultimately become overspeeded. The nearer the stage pressure at the point of entry to that of the by-passed steam the less will be the loss due to throttling or shock and the higher the efficiency ; it is desirable therefore from the point of view of efficiency at higher powers to introduce the by-passed steam at the earliest stage of the turbine where it is possible to do so, but this, of course, militates against designing the maximum number of early stages for small steam flow to secure good low load efficiency.

In practice more than one by-pass is sometimes provided ; additional ones are opened successively as the load increases ; always, however, care must be taken that no stages are so " backed up " that dangerous overheating occurs.

By-passes can be of two main types—internal and external. These terms do not refer to the situation of the passages with regard to the turbine, and to this extent are misleading. The internal by-pass is one which takes steam which has passed the first one or more stages and by-passes one or more following stages. The normal example of this is an impulse or impulse-reaction turbine in which steam is drawn from the Curtis wheelcase and by-passes two or three stages which have been designed to run full at partial loads.

The external by-pass simply introduces live boiler steam into later stages of the turbine. Where this type is used it is frequently arranged so that the live steam is introduced at one or more successive points down the turbine as the required power increases.

Thermodynamically, and in general, there is probably not a great deal to choose between the two types ; in any particular turbine it would be necessary to make a close analysis of both systems, having regard to other theoretical and practical features, to discover which is the better.

Where the internal by-pass is fitted, and the by-passed steam all goes through the Curtis wheel at full power, it follows that if this wheel is really overspeeded the inefficiency introduced will be greater than if only a portion of the steam passes it. If it is not really overspeeded at full power, its important function of maintaining part load efficiently will be prejudiced.

Regarding the external by-pass the introduction of live steam at successive points tends to greater shock or throttling losses ; and there is also a practical disadvantage which affects the thermodynamic aspect—temperatures approaching the full steam temperature are applied directly to the rotor when the by-passes are open—a point avoided in the internal type of by-pass. When designing the rotor, having to take this point into consideration may result in accepting a lower blade speed throughout the power range, in order to proportion the full power stresses to the reduced mechanical properties of the rotor material at the full steam temperature. Where, however, creep at this temperature, rather than maximum stress, is the critical factor, the point may not be significant, as the designed full-power life of the turbine is probably such that a creep rate may be worked to which would be quite unacceptable for the total life of the turbine.

The external by-pass, in contradistinction to the internal, allows the flow through the Curtis wheel at full power to be reduced to the small quantity required for safety, and avoids a loss of efficiency due to " fanning-up " an unnecessarily large flow of steam.

Practical arguments tend to have a more decisive effect than theoretical ones in deciding which type is selected. It is usually found that if an internal by-pass is selected (with all the full power steam passing through the Curtis wheel) that full admission to the Curtis wheel is necessary. In the interests of heating the hot end of the H.P. turbine symmetrically this is sometimes thought to be good, although it must be realized that the heating will be confined to arcs of the circle, except at full power when all the nozzle groups are open. In present naval arrangements it is particularly difficult to take steam direct to the bottom half of the turbine, and the alternative methods of getting it there are also troublesome. Either the steam can be led through the casing joint in a cast-in belt, which (as will be shown under " Casings ") is objectionable, or it has to be taken from upper to lower casing by external pipes, again a very awkward matter on account of the difficulty of providing sufficient flexibility in the pipes to ensure trouble-free joints and pipes without the space required becoming prohibitive. Sometimes there is literally no space available for such pipes either outboard or inboard of the H.P. turbine. In this connection it is worth noting that new habitability standards require five or six inches of lagging on such a pipe, bringing the total diameter up to 15 ins or 18 ins—a bulk out of proportion to the size of the H.P. turbine.

Where an internal by-pass is fitted the specific volume of the steam to be by-passed is greater than that of live steam, and the problem is complicated by having to provide a way out of the turbine as well as a way in. In either case a by-pass belt extending round the turbine will probably be necessary, and practical difficulties of finding a satisfactory way of passing this round the horizontal joint are met again ; the smaller the volume of the steam, the less the difficulty.

The entering by-passed steam should, as far as possible, be directed axially so as to mingle with the exhaust from the previous stage rather than enter radially and cause a confused flow and losses. It is sometimes not possible to arrange for a satisfactory entry without absorbing a little valuable rotor length—*i.e.*, opening the spacing of the stages a little at the point of entry.

NOZZLING, NOZZLES, NOZZLE-BOXES AND NOZZLE CONTROL

At partial loads, the advantage of reducing the steam flow by adjusting the number of nozzles in use, rather than by throttling the steam, is well understood ; the process does, of course, require that the turbine should have initially some type of impulse stage.

The older type of control, providing a moderate number of nozzle groups and a separate throttle, had thermodynamical and practical disadvantages ; under normal conditions a fair amount of throttling had to be used to adjust the power within the available " steps " provided by various combinations of nozzle groups, and all the steam passing to the turbine was, of course, subject to this throttling.

Under war conditions the ever-present chance of a call for a rapid increase of speed without warning frequently led to a nozzle group additional to the minimum number required at any speed being left open, especially in destroyers where engine room watches did not provide sufficient hands to open nozzles on both engines at the same time in swift emergency.

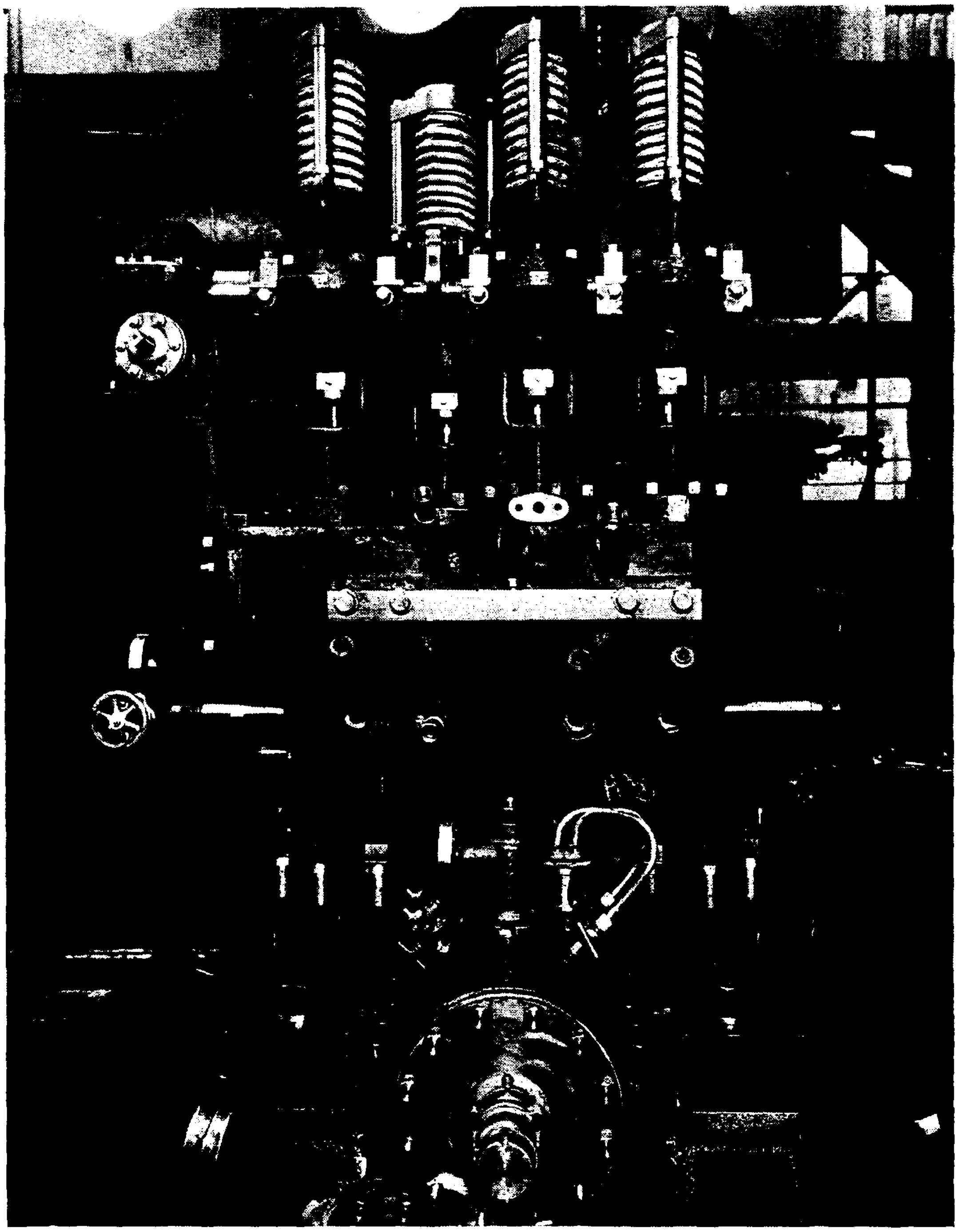
The new system of sequential opening overcomes both these disadvantages. The single handwheel control avoids entirely the delay of the older individual nozzle group control, at the same time releasing any available watchkeepers for making necessary adjustments to auxiliaries, sending messages to boiler rooms, or carrying out other such duties consequent upon sudden changes in power.

It remains for experience to show whether these advantages may be slightly offset by a certain amount of increased upkeep of valves.

With regard to the first stage nozzles themselves, there is some choice of materials of which they can be made ; many of the qualities required for blading materials apply equally to nozzles ; in the case of the first stage nozzles it is probable that neither the mechanical strength nor resistance to what is at present known as chloride attack need be so high as for blading ; nor is the inherent damping an important property here. (See under " Blading.")

The older methods of manufacture by casing shaped vanes into nozzle plates, or by using a series of cast blocks which when assembled in a frame provided nozzle-shaped passages, will not normally be found suitable for modern steam conditions ; the accuracy of the passages, steam-tightness at the joints, and ability to stand rapid temperature fluctuations lead to a preference for the machined-from-the-solid, built-up types used in high-class land turbines.

Each leading firm has its own methods of manufacture ; in general, a start is made with rectangular billets of selected material (stainless iron, Heclo A.T.V., etc.), which are milled in a series of jigs or fixtures, to very fine limits. Probably a score or more of machining operations are performed, in sequence, upon each block, and the finished articles are accurate to certain very fine limits, and ready to secure in the nozzle box or nozzle plate without hand fitting. They are often secured by riveting, with or without a seal weld at the joints. The geometry of the blocks is complicated ; control of the steam in both planes is provided and the areas are frequently held to within 1 or 2% of the designed figure.



H.P. TURBINE—NOZZLE CONTROL ARRANGEMENT
(*Courtesy of English Electric Co.*)

Manufacture by these methods is expensive, and has a minor disadvantage also, inasmuch as principal firms have a selection of cutters suitable to cover a large range of standard nozzles ; these cutters are individually costly and as the range contains probably several thousand, there is a disinclination to add to it to produce special sections.

Some thought and effort has been given to production of nozzles by assembling rather simpler components and securing the whole by controlled-atmosphere furnace brazing. So far this has not been entirely successful, one trouble being that the varying sections of the components lead to distortion and opening of the clearances under the heat. Research is still proceeding.

Another suggested method of making nozzles is the use of precision casting (the " lost wax " process). The number of alloys that can be handled by this process is somewhat limited ; the " as cast " structure does not give the same mechanical strength as a forged one ; and there are other disadvantages such as the large number of " wasters " sometimes produced by the process, which is perhaps more suitable for applications where larger numbers of one type of part are required than in this case. But, nevertheless, the process may prove to have applications, and is being studied.

The traditional form of construction, in which the nozzle chests and the passages leading to them are cast integrally with the turbine casing, is tending to become obsolescent in naval designs due to the effect of rising steam temperatures. The latest designs embody this method of construction in high-pressure turbines ; but for the astern turbines it has been discarded.

The sudden admission of high temperature steam into a comparatively cool chamber, such as a nozzle chest, unavoidably produces in the walls of the chamber considerable heat stresses. The stresses will, of course, vary with the shape and dimensions of the chamber, and the conductivity and coefficient of thermal expansion of the material, as well as with other secondary factors. In general, however, these primary heat stresses may be expected to be high, and even approach the yield point of the material. If the chest as a whole is constrained by being securely attached to surrounding structures, there will be added to the heat stresses, referred to above, very severe direct expansion stresses. In one class of vessel, it has been calculated that admission of steam into the (cold) astern nozzle belt would cause an expansion of a quarter of an inch on the diameter, if it were free to expand ; it is not, however, free to expand, but is restrained to a large extent by the surrounding cast structures. The result is that both the belt and structure are distorted, and various major troubles arise, especially in the lower half of the casing, where the gland housings and bearings are affected. Every time this tug-of-war takes place, some of the metal yields, and, when steam is shut off and the nozzle belt cools, it yields again. It is thus passing through a yield fatigue cycle, and apart from the alignment troubles, cracking is to be expected in due course.

To avoid such troubles it is necessary to allow the parts in direct contact with the steam freedom to move independently of the surrounding structure. There are two ways of achieving this, although fundamentally there is not much difference between them. The first is the " inserting nozzle group " method. Here, the nozzles are built-up on the inner end of a more or less radial passage supported only at its outer end by riveting to the casing, where it may form the exit from a nozzle control valve ; the essential feature of such an arrangement, to be effective, is that the actual steam passage can expand independently of the casing proper (particularly in those directions where the maximum expansion takes place) while maintaining the actual nozzles in a close approximation to their designed position relative to the moving blading. Radial movement is of less importance than axial.

The other type is the floating nozzle box ; here the chest is in the form of a complete ring, or half ring, which " floats " on keys designed to allow it the greatest possible freedom of movement while retaining the geometric centre of the ring fixed relative to the casing, and having provision for taking the torque re-action. In its simplest form this constraint would consist of three radial pins attached to the periphery of the ring and sliding in radial holes in the casing. Admission of steam to the ring or semi-ring is accomplished through a branch fitted with piston rings which slide in what amounts to an extension of the supply pipe, secured inside the casing or by some other suitable method.

The actual nozzles are mounted in plates bolted over suitable apertures in the sides of such rings, or arranged directly in dove-tailed slots ; the heat and pressure stresses acting on the transverse section of such a ring need to be studied to ensure that the inevitable distortions are sufficiently small to ensure that fatigue of the material or unacceptable leakage round the nozzles do not occur.

Present policy is towards the reduction or elimination of controlled nozzling for astern turbines ; and other considerations usually lead to the desirability of all-round admission ; hence the floating nozzle chest type is more suitable than the inserted type for astern turbines. Another point is that after some service the piston ring type of sliding steam joint, if adopted, will probably leak a little. Such leakage will be, of course, inside the casing, and probably harmless except for a slight loss of efficiency which will be quite acceptable when going astern, but might become important if it persisted all the time the engines were running ahead.

Where controlled nozzling is required, the floating type is clearly difficult to arrange. Either type is likely to take up more room than the older integral pattern.

It is more than possible that any further increase in steam temperature over 850°F., or even a search for increased robustness and general flexibility in operation at this temperature, may result in the adoption of separate free nozzle chests in H.P. turbines.

Single handwheel sequential operation of nozzles and by-passes demands in practice that the controlling valves shall be situated reasonably close together, so that the number of camshafts, rockers, bevels, etc., can be kept to the minimum most desirable for satisfactory operation ; and also so that expansion and distortions of casings of structures do not affect the freedom of " timing " of the gear. (Certain special precautions to prevent jambing will in any case have to be made.)

The two reasonable positions for the group of valves are first upon the top of the H.P. turbine, where the boxes can be cast integrally with, or welded to the turbine casing, with direct passages to the nozzles and by-passes ; or second upon a bulkhead or some adjacent part of the ship's structure, connected to nozzle groups and by-pass inlets by pipes.

In theory, the second method has much to recommend it ; it avoids the distortion and fatigue cracking which may be caused to the top half casing by the intermittent heating and cooling of integral passages ; if flanges and access can be provided to the bottom half, steam can be led there directly ; avoiding the bugbear of belts passing the horizontal joints ; it simplifies to some extent the incorporation of inserted or floating nozzle chests ; it also simplifies the casting or fabrication of the already complicated high-pressure end.

In practice, a factor arises which probably more than outweighs all these advantages ; that is, the complexity of the pipe work. The pipes must be designed to withstand the full temperature for their designed life, and at modern steam temperatures, in the creep range, this means low steam stresses and consequently thick walls ; thick walls mean stiffness, and in order to limit bending stresses and large end loads (which it is most undesirable to apply to the turbine, apart from considerations of keeping joints tight), large radius bends are necessary. The pipes are necessarily attached to the turbine at a variety of angles. In one modern destroyer set there are five such pipes (varying up to 12 ins diameter over the lagging), passing to the H.P. turbine. This particular turbine has an internal by-pass, or there would possibly be more. This by-pass valve is on the turbine top with an external pipe, and its valve is geared to the main control spindle. In the very restricted space between the control chest on the bulkhead and the various points on the turbine, sufficiently generous bends have to be fitted in to ensure adequate flexibility in three dimensions, each pipe avoiding not only all the others, but the eduction bend, the pipes to the twin astern turbines, the by-pass valve and gearing, and all the other pipes normally found overhead in an engine room. The resulting complexity and congestion is difficult to describe adequately. The gear to be cleared away before a turbine can be lifted can be imagined ; this probably becomes the major part of the job.

In direct contrast is the alternative type having one steam pipe only going to the nozzle chest on the turbine. If it proves in practice with rising steam conditions and increasing size of units that casing distortions or other trouble are of serious proportions with this position for the control valve bore, the tendency will almost certainly be to try to overcome them by design and research rather than accept the pipework problem of the remote control chest.

It is of interest to note that if the control chest is not integral with the turbine, it must be placed sufficiently far away to allow the pipework adequate flexibility ; it is probably not possible to have it separate from, but close to, the turbine.

In either method, the actual valves are of much the same type ; they are sufficiently steam balanced to enable them to be closed by powerful springs ; and they are operated by pilot valves seating in the main valves and actuated by a camshaft which gives the correct sequential opening ; adjustments may be provided to ensure that valve openings are such that the pressure drop across all stages throughout the power range is always sufficient to avoid the risk of overheating.

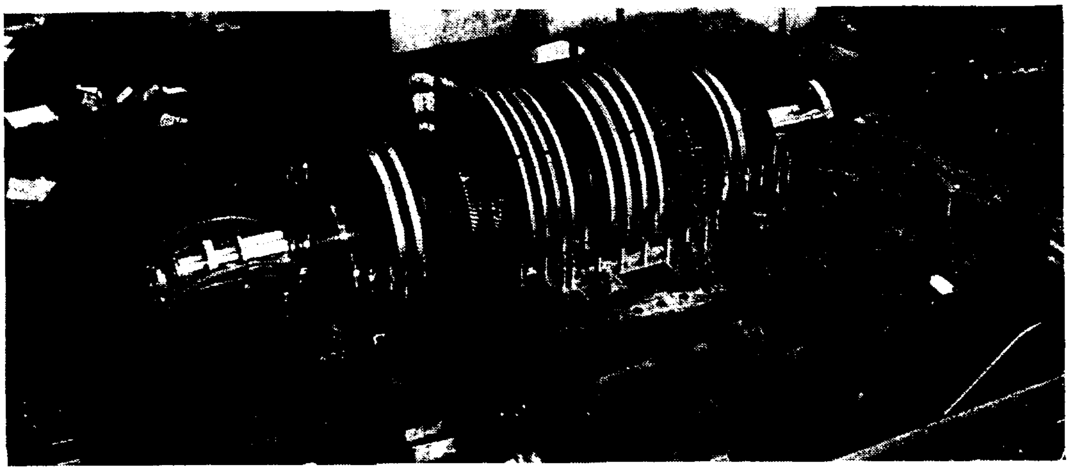
The detailed design of the valves is complex and requires specialized experience if satisfactory operation is to be obtained. Special materials are used for all the vital parts, with seats of stellite or other material suitable for this arduous duty. The manufacture of most of the wearing parts is outside the scope of ship's equipment ; and repair, if required, will necessarily be by replacement in most cases.

Nozzle boxes and valve boxes are cast in steel containing 0.5% molybdenum, and preferably not more than .25% of carbon. If the carbon content exceeds this figure, welding the material presents difficulties. In this connection it must be remembered that any complicated steel casting is likely to have casting defects which need to be made good by welding before it is put into service.

DIAPHRAGMS

Rises in initial steam pressures, together with the greater heat drop per stage (which higher blade speeds now permit), have increased the pressure differences across the interstage diaphragms of impulse turbines. On the other hand high rotational speeds have permitted smaller diameters at the high pressure end of the turbine.

Modern naval impulse rotors are invariably solid forgings, so that diaphragms are inevitably split or halved.



L.P. IMPULSE TURBINE—SHOWING ASTERN STAGES AT EACH END
(Courtesy of English Electric Company)

The design of the diaphragm is divided broadly into firstly, planning of the steam passage so that the expansion and increase in velocity of the steam follow the designer's requirements, and secondly, securing the required overall strength of the diaphragm.

The nozzle shape may be complex to avoid radial flow of the steam, and in the later stages to provide the necessary differences in steam velocity between the minimum and maximum diameters of any nozzle ring, so that the leaving velocity at any radius is correctly related to the speed of that portion of the blade the steam will meet.

The machining of the nozzle segments is a complicated matter of many processes. As for the first stage nozzles, the old form in which shaped vanes were cast into a matrix or plate is seldom met except in the last few stages of the L.P. turbine, and (also as for the first stage nozzles) although other methods of manufacture are under investigation, all modern high class turbines have, with the possible exception noted above, nozzle segments machined from blank billets. The complication of the form of the individual sections is such that a prolonged study of the drawings is frequently necessary to obtain a clear idea of how they are arrived at. In spite of this the leading firms work to extremely fine limits—achieving accuracies of within 2% of designed areas for individual nozzles, and closer still for a group or complete diaphragm.

The loading on diaphragms with a considerable pressure drop across them is, of course, considerable ; but it is frequently not realized that such loading will produce a quite significant deflection. A medium sized diaphragm—say perhaps 30 ins diameter—may well have a maximum working diaphragm deflection of $\frac{1}{16}$ in or more.

The deflection of a uniformly loaded circular plate is ascertainable mathematically ; but it is a far cry from this to a diaphragm comprised of an outer annulus joined to an inner annulus by a composite structure of nozzle segment the whole being split across a diameter.

Most large firms have a standard form of nozzle segment, and a standard method of uniting the various parts which form the complete diaphragm ; the same limits of tolerances (which, of course, materially affect the strength and deflection under load of the finished article) are also always worked to.

Typical diaphragms are tested under pressure and their deflections determined experimentally. A mass of data is thus built up about the design adopted, enabling the designer to predict closely what deflection he must expect from diaphragms in new designs. Such data is continually checked and supplemented by practical test.

In the same way maximum stress, obtained from strain gauge data from experimental diaphragms, or by other methods, can be predicted. In a specific design the stress must of course be held down to a safe figure, having regard to the working temperature at the stage under consideration.

In the matter of deflection there is some room for compromise. To the axial thickness of a diaphragm must be added its maximum working deflection when considering the space it takes up. In the interests of shortening the turbine as much as possible (with a view to increasing K one way or another) the diaphragm thickness can be so chosen that this figure plus the deflection are a minimum, provided there is no overstressing.

The axial clearance between any diaphragm and adjacent rotor discs must, of course, allow not only for diaphragm deflection but also for the differential expansion of the rotor and casing at this point.

A sound design of the interlocking parts of the diaphragm is of great importance ; there is probably a fair amount of progress to be made by careful research in this direction.

In all cases, of course, the calculation must be based upon the most onerous conditions which occur within the power range—which may well be at low power for the early stage, if these are by-passed at the higher powers.

The mechanical strength of the materials chosen is of importance ; in general the properties required are the same as those for blading, except that as centrifugal forces are absent the density of the material is not significant. The diametral clearances of diaphragms must be so adjusted that they are not absorbed under the worst condition ; in the L.P., and even in the H.P., the maximum temperatures may well occur when going astern, and this must be borne in mind when diaphragm expansion is considered. The two halves of each diaphragm are usually arranged with keys at the horizontal joint, and at top and bottom of the casing, so that, although free to expand, the diaphragm as a whole is maintained concentric with the casing. Top and bottom halves are keyed or scarfed together at the horizontal joint.

The casing recesses into which diaphragms fit normally also provide a large axial clearance ; the diaphragm bears upon the low pressure side of the recess, an axial movement is prevented by pegs fitted on the other side. This arrangement serves to prevent seizure and facilitate removal of the diaphragms after prolonged service.

The interstage gland packing normally follows the practice employed for the spindle glands, which is discussed elsewhere.

PARTIAL ADMISSION

It has been seen that to retain high efficiency at reduced loads nozzling (and consequently, partial admission to the first stage) is a necessity. Partial admission however has certain disadvantages which cannot be overlooked.

(1) When steam is supplied to a wheel through a sector of nozzles, it is likely that whilst well within this sector the rotor blades will " run full " in accordance with the design. At any particular instance, however, one or more blades which are just entering the steam jet, and one or more blades which are just leaving it, will probably be only partly " filled."

In these blades the flow will not take place in the required manner, and some inefficiency will be expected. Clearly, the longer the sector over which nozzles are in operation, the lower will be the proportionate result of this effect, which does not occur at all with full admission. It follows that from the point of view of avoiding this effect nozzle groups should be arranged so that whatever the number of nozzles in use there should be no gap between the jets ; and also that discontinuities in the steam flow caused by the horizontal joint and other such features should be avoided as far as possible.

(2) Where a group of steam jets is in operation, research has shown that, although the main body of the steam delivered by the inner jets follows the designed path fairly well, the outer jets tend to turn away slightly, giving a different angle of attack on the moving blades—hence a further reason for reducing the number of " gaps " in the jets to a minimum at all powers.

(3) In full admission stages following one having partial admission, there is likely to be some circumferential steam flow before an orderly full admission flow is established. This in itself will produce a minor loss coupled with a repetition of the losses described above.

(4) The effect of partial admission is to cause the whole of the work of a stage at any instance to be performed by only a proportion of the moving blades, which are consequently more highly stressed than if all were sharing the load. In any particular design, the fewer the nozzles open the lower is likely to be the stage pressure, and the larger the heat drop to be absorbed as work. Consequently blades are often most highly stressed and most trouble to vibration troubles when at cruising powers ; and in astern turbines full admission may be essential to avoid unacceptable blade stresses and risk of blade vibration.

(5) With full admission the many steam jets coalesce to a large extent but the change in thrust which a blade receives as it enters or leaves a group of jets causes a shock loading which may lead to vibration, the fact that the frequency of this disturbing force is usually much lower than the natural frequency of the blade is something of a saving factor here.

(6) Whilst a turbine wheel has all its blades running full, the windage losses are not very severe ; when, however, only a few blades are full and the remainder churn around in stagnant or confused steam the windage losses are likely to assume significant proportion particularly where blade speeds are high and (as in the early stages) the steam is comparatively dense.

The sum of these disadvantages is by no means sufficient to outweigh the advantages of nozzling at reduced powers ; but the extension of partial admission beyond the first stage is to be avoided if possible. A situation which drives designers to it is met when by-passing is carried out to such an extent that the quantity of steam flowing through the by-passed stages (even when the by-passes are shut) is so small that it involves accepting either extremely short blades or partial admission. The former alternative introduces losses which probably may be the greater evil.