SOME ASPECTS OF NAVAL TURBINE DESIGN

PART III

ROTORS

The requirement for high efficiency at partial loads has been seen to lead to a turbine with a high blade speed at full power, and that this blade speed should be attained by high revolutions, rather than large diameters, is also a requirement for efficiency and/or other reasons.

In the latest designs the limit of blade speed has been set by the acceptable rotor stresses ; lacking evidence to the contrary, it is believed that higher blade speeds still would be of advantage, particularly in the H.P. turbine.

In consideration of the latest designs in the preliminary stages it became apparent that fundamental changes from what had been for a long period an almost standard type of naval turbine rotor would have to be made. These were :—

(1) In view of the high stresses and high maximum temperatures, and considerable temperature swings, the conception of shrunk joints in the rotor could definitely not be entertained. The same applies to shrunk-on discs. Rotors for new designs would therefore have to be one-piece forgings.

(2) The stresses it was desired to work to, in combination with the temperatures to which the rotor would be exposed were such that a plain carbon steel, or a plain carbon molybdenum steel, would not be satisfactory.

Supposing it is eventually decided that the steam conditions of the *Daring* class are the most suitable having regard to all naval requirements in the broadest sense, and that no further advance is necessary, it is still extremely unlikely that any modification of (1) above could be accepted. It is, however, just possible that the results of researches now proceeding, together perhaps with a fundamentally different approach to the design problem, might allow the attainment of optimum efficiency with the employment of a plain carbon molybdenum steel rotor. Such a development would reduce costs and allow a more rapid increase of production in emergency, besides effecting some saving in alloying materials.

The present position, however, is that the rotor material we want is the one which will withstand the highest working stresses at temperatures varying from room temperature up to about 800° F. It is noted at this point that when deciding the highest working stress allowable other factors than the U.T.S. and proof stress must be taken into account.

The production of masses of steel suitable for forging into rotors weighing, in the finished state, 6 tons or so is a very different matter from the production of lesser quantities, and the good and uniform qualities expected, for example, in aero-engine connecting-rods or crankshafts cannot be reproduced in very large masses. Apart from the difficulty of obtaining clean steel in large melts, the mass effect during heat treatment is such that the required properties cannot be obtained throughout unless the hardenability of the steel is very good. (A steel is said to have good hardenability if the rate of cooling during a quench can be varied between fairly wide limits without adversely affecting the uniformity of hardening obtained.) It is clear that when a small mass is quenched the rate of cooling throughout will be reasonably uniform ; but when a mass of several tons is involved the ratio of $\frac{\text{surface area}}{\text{mass}}$ has become very small and little can be done to accelerate the flow of heat from the centre. The properties obtainable from the best forged and annealed (but otherwise un-heat-treated) carbon steels cannot be much improved upon by alloying unless a comprehensive heat treatment is resorted to. The major difference in the results obtainable from plain carbon and low alloy steel rotors lies in the fact that, because of the improved hardenability of the latter, heat treatment can be applied and a reasonable uniform result obtained throughout the thickness of the rotor.

The chief alloying elements employed are nickel or chrome—3 to $3\frac{1}{2}$% of one or other of these elements (with various minor additions of other alloying elements) improves the hardenability to such an extent that rotors of 6 tons or more can be quenched in oil (or in some cases by air) and subsequently tempered to give a great range of properties, with a surprising degree of uniformity throughout the mass.

At present (1948) although a large number of fully successful trial rotors have been produced in Great Britain and have been sectioned and tested in a most comprehensive way, the process of production is not yet as reliable as that for plain forged rotors ; the technique is one requiring experience as well as skill.

In the test rotors referred to specimens obtained from the cores (which are trepanned after the completion of heat treatment) and from exterior test rings (which are parted off) were pulled. Such specimens are obtainable from all production rotors, and constitute one of the checks made for uniformity between the production and the specimen rotors. The specimen rotors had axial, radial, and tangential test pieces removed from many positions so that a complete picture of the ability of the whole forging to resist stresses in any plane and at any position could be assessed.

The technique of producing alloy steel rotors is an involved one. The quenching treatment will clearly tend to leave locked-up stresses, which can be removed by soaking at a temperature a little below that employed when tempering ; but if the stresses have already led to cracks, there is of course no remedy.

Alloy steels, and particularly those containing nickel, have the power, when in a liquid state, of dissolving hydrogen (which comes either from the additions used to " kill " the steel, from furnace linings, moisture, or elsewhere). At a later stage in the solidifying of the steel the hydrogen is thrown out of solution and being able to escape only very slowly by percolation through the solid steel, produces immense inter-molecular pressure ; this gives rise to the small cavities known as " snow-flakes " and sometimes to hair-line cracks.

Immediately the cores are trepanned, specimens are removed and their hydrogen content determined ; there are certain limits for various types of steel and, if the hydrogen present is below these, the risk of defects from this cause is slight.

The path of escape for hydrogen from a trepanned core is, of course, a short one, and the hydrogen is evolved comparatively rapidly. The test is not reliable unless it is made within a short time of the removal of the core.

Steel rotors subjected to high temperatures are sometimes subject to a phenomenon known as heat distortion ; this takes the form of a bend and although it is small in amount it is large compared to the standard of axial concentricity required for smooth running of a high speed turbine. In some examples of this heat distortion the bend is permanent—that is, it persists when the rotor is cold. In this case the rotor can be made serviceable by re-machining. In other examples the bend disappears on cooling. Sometimes if the rotor is re-heated the bend does not re-occur, and the rotor is " cured " ; in other instances the bend takes place every time upon heating and disappears on cooling. In a rotor of this type the only alternatives are to scrap it or to arrange so that it is in balance in the hot and bent position—this latter would not be acceptable for naval work, but has been used in land practice. To avoid the possibility of waste of material and labour, all new construction rotors are subjected twice to a process known as " heat indication." The rotor is arranged in a simple furnace so that it can be rotated truly (to within fine limits) about its axis, and slowly and uniformly heated to just above its maximum working temperature and then slowly cooled. Indicating gear at three points along its length shows if any bend takes place during the process. Normally the run-out is well below the allowed eccentricity limits of $\pm .001''$ (*i.e.*, a dial gauge reading of $\pm .002$)—a figure probably little larger than the limits of accuracy of the apparatus.

The test is first carried out, after rough machining ; this is so that, if the rotor adopts a permanent set, correction is possible during the further machining, without finishing undersize. The test is repeated after finish machining as a final check, and because it is not yet known whether the distortion is caused by something to do with the machining process itself.

A comprehensive research is at present in hand to discover more about this phenomenon ; but it must be added that although there have been a fair number of reported cases in the United States, there have been very few in this country ; and none so far among rotors intended for naval turbines. Heat indication furnaces have been installed by some of the leading steelmakers and marine and land turbine manufacturers.

With the type of naval turbine which at present constitutes the latest practice, the rotor offers two definite major design limitations. One is the whirling speed ; and the other is the bore stress. At present it is considered that the maximum rotor speed in service should be such that there is a 25% or 30% margin on the whirling speed. In older types of turbine the maximum speed did not normally approach as close as this to the whirling speed ; in those ships the design allowed for " light-draught revolutions " (15% above the normal full-power revolutions) being obtained. This figure was seldom if ever obtained in service, and penalised some of the modern designs. It has now been reduced to 5% above normal full power revolutions.

It is important that the designed maximum revolutions of new construction turbines should not be exceeded as the limits are such that the most severe damage could be so caused, even to the point of endangering the ship.

In land practice the whirling speed limitation is not so onerous, as it is only necessary to ensure that the (constant) running speed is well clear of criticals ; with a well-balanced rotor, running through the criticals constitutes no hazard and indeed in many sets a rotor can be run on its critical without there being any indication of the fact by vibration or otherwise.

In marine practice, however, the chances of keeping a rotor in perfect balance are less ; when, for instance, it is necessary to get underway after the machinery has been shut down a few hours and is partially cooled it will be almost certain that small rotor distortions exist. In addition, of course, the rigidity of bed available in a power station is lacking. A rotor running quite satisfactorily

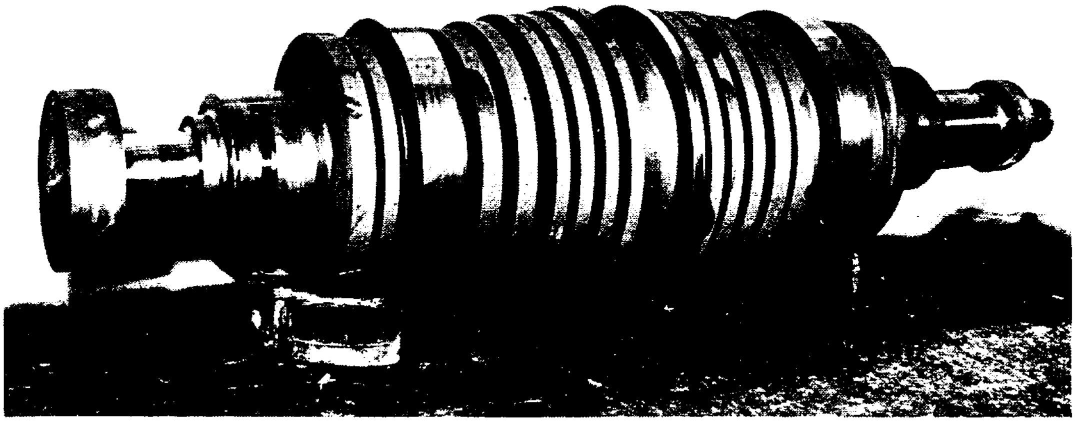


FIG. 1.—DOUBLE-FLOW L.P. ALL IMPULSE ROTOR OF GASHED CONSTRUCTION (ROUGH MACHINED)

at or near its critical could perhaps be thrown into a state of whirling by underwater shock or the ship's own gunfire. For all these reasons it seems unlikely that a turbine design in which a rotor ran near its critical at high speed could be accepted ; and that the present margin will probably not be reduced.

The running of a rotor at well over its critical speed is however a very different matter ; and one which has not, so far as is known, ever been very fully investigated for naval design. The deflection curve of a rotor—and particularly a drum-type reaction rotor—indicates that a very large portion of the deflection occurs close to the ends ; from this it might be supposed that in such a rotor the ratio of speeds at which the second and first criticals occur would be very much greater than for a uniform shaft, where the ratio is 4. It is possible that the criticals could be so spaced that the first occurred at a very low speed—5 or 6 knots—where it might be accepted or dealt with by avoiding this speed—and the second occurred out of the running range at the upper end. Such an arrangement, if it were possible, might give rise to a fundamentally different and improved type of turbine.

In calculating rotor whirling speeds an approximation is made by the use of rough methods ; this is sufficient to indicate whether a preliminary design is likely to be practicable from the whirling speed point of view.

Re-checking at a later stage is carried out making full allowance for blading loading, change of E with temperature, etc. This process is likely to take an experienced man three or four full working days.

The calculation of bore stress for a rotor having integral discs or wheels is a complicated matter, and is usually undertaken by the Hearle method. For a single wheel or disc by itself the assessment of the " equivalent wheel " in rectangles is reasonably simple ; but when the wheel is really a protuberance from a drum or hub, there is considerable doubt what hypothetical shape within the hub should be assumed as the " equivalent wheel."

Mathematical investigations made at Admiralty indicate that apparently the equivalent shape normally drawn in to suit the designer's judgment is much too long axially ; and the resulting calculated maximum stress is proportionally lower than it is in reality. In designs which are stressed to the limit, knowledge of this matter is of vital importance, and a research involving deliberate overspeeding of a rotor, at the same time measuring the extension of the bore hole and increase in external diameter, is at present in hand. The results of this research should clarify a number of doubts on the subject.

In the early " advanced steam condition " designs it was decided to design the rotors so that the maximum bore stress (which occurs under the Curtis wheel in the H.P.) should be related to the 0.2% proof stress of the material (at working temperature) by the ratio 1 to 1.5. In later designs this ratio has been reduced if the higher bore stress values given by the Admiralty methods of calculation, referred to above, are used. It is possible that at the 15% overspeed test some yielding at the bore may take place. If this happens, when the rotation stops, the material at the bore will be left in compression ; in fact, a type of auto-frettaging will have occurred. The reduction in bore stress caused by the yield is theoretically accompanied by an equivalent slight rise in stress radially outside the yielded zone ; and (theoretically again) if rotational speed is further increased sufficiently to the limit, the whole section will eventually adjust itself to an " integrated stress " constant throughout. Ideally, the stress will then proceed to rise with further speed increase until it reaches the ultimate, when the rotor will disintegrate with, incidentally, a tremendous dissipation of energy.

Arguing from this theory it has been suggested that a certain limited yielding at the bore can reasonably be permitted, providing that a yield in compression does not take place when rotation stops ; it being very undesirable to subject the material to a yield cycle which would rapidly fatigue it and result in cracks This theory seems to indicate that the value of the proof stress of the material is not of first importance ; but good ductility is required in order that re-distribution of the stresses can readily take place. The view is not infrequently held that the " factor of safety " to be applied should be that between the ultimate stress (at the working temperature) and the " integrated stress." A value of three for this is sometimes considered suitable. It will be seen that for the re-distribution of stresses to take place in a safe manner it is essential that the material of the rotor is of a homogeneous nature. Cracks or inclusions or any other form of discontinuity will clearly give rise to stress concentrations acting at the discontinuity. Such concentrations would constitute a considerable danger and could lead to cracking and ultimate failure of the whole forging ; it is therefore quite essential to take every possible means of ensuring that any rotors having flaws of any sort do not go into service in highly stressed designs.

Inspection of the bores (after trepanning and polishing) with optical apparatus, and magnetic and supersonic crack detection are necessary precautions. Small inclusions detected in the bores can sometimes be removed by local chamfering ; the extent to which the designer can accept an enlarged bore is established by consideration of the details of each case ; but whilst any blemish in the bore is perceptible the rotor cannot be accepted.

The maximum stress in the material is theoretically greatly increased (by something like twice) by the provision of a borehole. It is rather doubtful if this occurs in practice—or rather, it is doubtful whether the maximum stress in any particular rotor would have been halved if the borehole had been omitted. Any small discontinuity near the axis would serve as a stress raiser in the same way as a borehole does ; and with the present technique of rotor forging, inclusions are more likely to be present at the axis than elsewhere—and are likely to be not only exposed, when the core is taken out, but probably removed complete. British practice therefore is to remove the core by trepanning for these reasons ; it also provides valuable test data for individual rotors. In U.S. practice the core is often not removed, or removed only at the ends, leaving the rotor solid in way of the Curtis wheel or other most highly stressed position.

Overheating of naval turbines when running astern is a trouble which has arisen with increase of blade speeds and steam temperatures. It is caused fundamentally by churning and is undoubtedly a function of the density of the steam in the ahead stages. In an effort to prevent any steam from the last row of the astern turbine passing across the exhaust belt and entering the L.P. ahead stages, it is now usual to place a deflector to help to divert the flow towards the condenser. This deflector (which may or may not be of value—evidence is scanty) is sometimes stationary, and part of the casing, and sometimes is a protuberant collar on the rotor itself. In the latter case it can give rise to the highest bore stress throughout the rotor, particularly if the rotor is overspeeded in an unbladed condition.

Under present arrangements rotors are overspeeded in the turbine under steam by 15% above the highest revolutions to be attained in service. It has also been arranged for the rotors to be overspeeded in a test pit before assembly in the turbine. Some attempt has been made to increase the stress above that which will occur during the 15% overspeed mentioned above, as an additional test on the material. This, however, is very difficult to arrange, and it is not absolutely certain that it is desirable. It cannot conveniently be done after blading the rotor, as the power required to overspeed the bladed rotor in air would be very excessive, and also it is undesirable to subject the blade fixings to overstressing, as any yielding would inevitably result in slackness in service afterwards. Unbladed, the stress pattern in the revolving rotor is not the same as when the blade load is carried ; *e.g.*, in the L.P. rotor from giving a position of maximum bore stress under the last rows of blades it may well move to under the astern steam deflector when unbladed ; and in order to achieve the working stress in the unbladed rotor in the former position the revolutions would have to be high enough seriously to overstress the material in the latter.

Consequently, in general, the unbladed rotors are run fast enough to ensure that all parts of the rotor are stressed at least as much as they will be when the 15% overspeed is carried out in the bladed condition.

The rapid changes of power which naval turbines have to undergo involve rapid fluctuations of temperature of the steam surrounding the rotor. The shape of the rotor, and its mass, directly affect the speed with which steady temperature conditions are established in it after a change of power. The lower temperatures of the successive stages down the turbines tend to induce an axial heat flow in the rotor ; if the gland steam temperature is less than the steam in adjacent stages it will also have a cooling effect ; and some heat reaches the journals and is conducted away via the oil. Thus the rotor of a running turbine never reaches a uniform temperature even under steady running conditions ; it is always subject to complicated temperature gradients ; when changes of power occur the temperature gradients are altered ; and as the thermal inertia of the rotor causes it to lag behind the steam temperature, before steady gradients are again established a further system of transitory gradients is imposed upon the rotor with high steam temperatures ; both the steady and the transitory gradients may give rise to very high thermal stresses.

It is clear that an impulse type rotor, in which the discs present a large surface area containing a limited mass of metal, will follow changes of temperature more quickly than a drum type reaction rotor ; with the former type of rotor steady gradients may be established much more quickly than in the latter, after a change of power ; but the stresses induced may at the same time be much higher.

Even with the moderate steam temperatures used in the old type of Brown-

Curtis naval turbine, with shrunk-on discs, it was quite possible to loosen a wheel by clumsy operation of the bye-passes ; the wheel picked up an increased temperature much more quickly than the spindle and the relative expansion was such as to more than cancel the shrunk fit ; when steady conditions were reached the wheel normally tightened again.

With a solid gashed rotor a similar effect tries to occur, but the growth in diameter of the " hub " of the wheel is resisted by the laminae of material joining it to the spindle part of the rotor ; thus very high stresses are imposed which may be great enough to yield the material ; locked up stresses may thus be imposed which will materially affect the distribution and magnitude of the calculated centrifugal stresses. Also, if the yielding of the material is cyclic —that is, if a yield in the reversed sense is caused by a further train of events, and the cycle of reversal is repeated, cracking may occur, with considerable danger of rotor failure ; the amount of this sort of treatment the material will stand before failure occurs in a given case is dependent upon its ductility, and probably other more obscure qualities such as notch sensitivity.

Naval designs with heavy bye-passing inevitably are subject to large temperature swings, of perhaps three or four hundred degrees Fahrenheit or more in some cases ; the results of these swings in setting up thermal stresses are very difficult to assess, principally because little is known of the rates of heat transfer into bladed rotors revolving in steam. Research upon these matters is proceeding, and until results are known it is prudent to bear in mind that such stresses are undoubtedly set up, not only at the juncture of discs and spindle, but in many other positions, and that they may be additive to calculated centrifugal stresses. Careful treatment in service, and very close scrutiny when the chance of examination offers, may avert trouble. It is emphasised that as temperature swings are inevitable, and only limited alleviation is possible in " advanced " naval designs, the best insurance for the present is the employment of a rotor material which has good ductility characteristics throughout the whole range of operating temperature—from room temperature to the maximum. It must be borne in mind that many ferrous materials have a " trough " in the ductility/temperature curve, and that the bottom of this " trough " may be somewhere in the working range.

The designed life of naval turbines is dealt with later in these notes ; it is necessary here to deal with the effect of creep upon rotors. It is probable that only a small portion of the rotor's total life will be spent at high stress and high temperature, but this must be carefully checked to ensure that the actual life of the material under these combined onerous conditions is a suitably safe fraction of the known " stress to rupture " time for the material ; bearing in mind that different test specimens of the same material give great variation of results for this test, and considerable margins must be allowed.

Apart from the " stress to rupture " aspect, it is necessary to ensure that the actual rotor deformation due to creep is acceptable, having in mind the absorption of working clearances and loosening of the blades caused thereby. Consideration of the latter should be made in conjunction with that of the normal loosening at high speeds due to elastic stretch of the rim under centrifugal loading. (Referred to later under " Blading.")

The normal creep resistant properties of straight carbon steels are much improved by alloying cast molybdenum and other elements. Data from sufficiently long term creep tests is necessarily slow in forthcoming, but will be required if designs having long life requirements at high temperature *and* high stress materialise.

It is now considered prudent to avoid means of balancing which involve attached masses ; a better method being to provide strips (machined on suitable parts of the rotor) which can be ground away to effect the required alteration. In some cases metal can be removed by enlarging the steam balance holes in discs, but clearly this must be done with caution having regard to the high stresses which may not permit of safe increase.

It is sometimes queried how much unbalance is permissible ; no hard and fast answer can be made. If the unbalance is such that it produces a rotating force which can lift the rotor in its bearings it is clearly inadmissible ; but smaller degrees of unbalance may also be inadmissible depending upon the rigidity of the rotor, the bearing pedestals, the seatings and so on ; a great deal more data on this matter would be useful. Clearly more care must be taken in the balance of a high speed rotor, than a low speed one.

A rotor which ran true within very small limits has sometimes been found to have bent permanently after a " touch " has occurred. It might be thought that such a rotor, if it touched stationary parts at all, would touch all round ; and this is frequently the case ; but not always. It is probable that slight unbalance causes a bend at high speed, and the " high " spot then touches, such a " touch " may generate enough heat in the rotor to cause a further distortion in the same direction—*i.e.*, it will increase the bend, and this cumulative effect can be sufficient to distort the rotor permanently. Careful examination of turbines which have fouled will often enable what actually occurred to be deduced.

An initially bent rotor, even if it is in balance, always runs the risk of being further bent in the same direction if contact occurs.

Rotors which are badly bent by shock or some other cause can often be " heat straightened " by experts. In this process a hot spot is made on the " convex " side of the rotor opposite the point of maximum bend, by using an oxy-propane or other suitable torch. The hot metal expands and is hot enough under the torch to yield, on cooling a tensile stress is set up which somewhat straightens the rotor ; the process is repeated carefully until the eccentricity of the rotor is within acceptable limits. This method was used quite extensively during the war ; it was not necessary to de-blade the rotors.

It is not yet known whether it can be used on alloy steel rotors with safety ; investigation is proceeding.

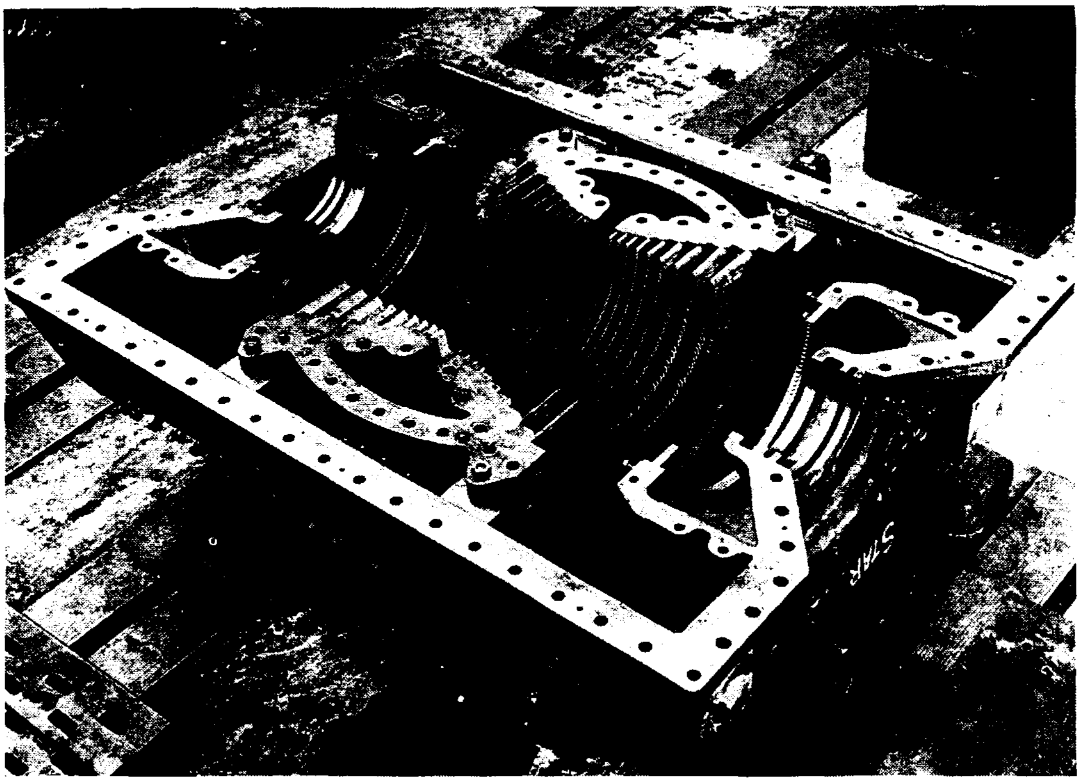
Certain cases of bent rotors in the past have been traced to the use of wide white-metal oil seals fitted each side of the adjusting block, in conjunction with turbine foot distortion. At high power the latter caused the oil seal to rise, and its area was sufficient to act as a bearing, lifting the rotor from the main bearing, without failure of the whitemetal of the seal. The unsupported length of the rotor in this condition was so increased that it whirled at its running speed, with the result that the rotor was permanently bent.

In modern design although pedestal distortion has been guarded against, where whitemetal seals are fitted they are turned in the form of a labyrinth with narrow fins which would collapse under the weight of the rotor.

CASINGS

To say that success of a modern naval turbine depends to a great degree upon the experience and skill of the casing designer is probably an understatement ; if the turbine has a bad casing it will be a bad turbine. Bad casings are the most likely source of turbine failures now that the major problems of vibration are understood.

Casing design is rendered more difficult because it is somewhat intangible ;



Double-Flow L.P. Reaction Casing

there is comparatively little that can be calculated about a turbine casing ; it has to be based upon past experience and an understanding of many general principles and likelihoods. Design can be checked only by full scale trial ; and such trials are so lengthy and expensive as to be almost out of the question ; a sort of compromise can be struck by making " prototype design " ; but the tendency is for major alterations to be avoided as far as possible.

The two major functions of a conventional type of casing are to support the fixed blades and other parts so that the designed clearances relative to the moving parts are maintained, and to retain the steam so that it is constrained to flow through the designed passages ; the second of these functions is inimical to the first, because in flowing the steam falls in pressure and temperature and sets up stress gradients that distort the whole.

The major problem of the designer is to reduce these casing distortions, or to limit them in magnitude and position so that leakages do not occur except through designed clearances, and that these latter should be as small as possible.

The natural tendency of a naval designer is to attempt to separate the two functions referred to above ; floating nozzle boxes and loose cones in the dual flow L.P. turbines are the results of such separation ; double-case turbines, not yet generally adopted in large sizes, are an extension of the idea, but very difficult to apply to naval design, which has the greatest need of them. Land turbine designs can largely avoid the bye-passing arrangements which complicate the naval machines, and can be assured of more tender treatment in warming through and changing power ; while space and other considerations permit three-cylinder sets with correspondingly lower temperature gradients in any one turbine.

If turbine casings could be so constructed that every transverse section was a circular annulus little distortion would be expected ; but unfortunately there are attached to the casings appendages of every sort—heavy flanges, supports, steam belts, bye-pass passages, nozzle belts, nozzle valves, eduction branches, condensers, pipe connections, and so on. Not only do all these parts acquire different temperatures under steady running conditions, but they are subject to swings of temperature, often violent, with changes of power.

The designer trying to assess the best arrangements is further handicapped by having to plan something which can be made ; the fact that a casing can be cast is hardly sufficient, because steel castings only too frequently require repair by welding before they are suitable for use ; and important parts should be capable of being examined radiographically and be accessible for welding if there is to be reasonable security against " wasters."

The rapid progress of welding during the war has led to the introduction of much fabrication by this method in the designs of L.P. turbines, but for 650 p.s.i. and 850°F. steam conditions all naval H.P. turbine designs under production in this country have fully cast casings. Production difficulties are, however, considerable and a change to casings fabricated by welding from smaller castings, or from castings and forged or rolled sections, is likely.

It is unlikely that naval designs will have more than two cylinders for some time ; and it is convenient to consider the problems associated with H.P. and L.P. turbine casings separately.

H.P. Turbine Casings

When considering casing designs the effect of differences in temperature of the parts, and changes in temperature must always be held in mind. With total steam temperature of 400°F. or so, little trouble was experienced ; and most of what there was could have been avoided by modern methods of operation ; but in such turbines it is probable that temperature swings in any part rarely exceeded 100°F. or so, and in spite of their comparatively large sizes distortions were not great. With steam temperatures of 850°F., however, matters are very different ; sudden increases in power may produce swings, in some designs, of four or five hundred degrees Fahr. ; and although H.P. turbines are comparatively small overall the general scantlings are heavy and large distortions and great stresses can be produced.

For reasons dealt with elsewhere modern H.P. turbines tend to have the nozzle and bye-pass valves cast integrally with the turbine cover ; and the sequential opening of these valves flood various parts of the turbine, which may have been at comparatively low temperatures, with steam at 850°F. Consider a passage 2 feet long cast along the top of a turbine leading from a valve to a bye-pass belt ; at low power the average temperature of the casing in this neighbourhood may be perhaps 300°F. Opening the bye-pass will cause a rise of perhaps 500°F. corresponding to an extension in length of about one-sixteenth of an inch—sufficient to cause plastic flow if the expansion is fully restrained. The large force set up by such an expansion, applied along the top of the casing, will tend to make the whole casing hog, with the absorption perhaps of clearances under the rotor. The admission of hot steam into a circumferential belt will have, in the first place, a tendency to cause large compressive forces in the inside layer of metal and possibly a tendency for the U-section of the belt to open out rather like a Bowdon tube.

Such examples abound in the modern naval H.P. turbine ; casings of the present types must distort ; the designers cannot avoid it ; what they can strive for, however, is to prevent heat stresses yielding the metal ; and to arrange so that the small working clearances are as far removed as possible from the places where maximum distortions are to be expected.

From this point of view the designer of turbines of the impulse type has a comparatively happy time compared to designers of reaction H.P. turbines ; a consideration of where the danger points lie in each type will show this.

The most dangerous point in a reaction H.P. turbine is the dummy piston and cylinder ; this is dealt with elsewhere.

The horizontal flange joint of a high pressure and high temperature turbine assumes a formidable thickness ; but trouble with such joints should not be experienced if they are designed upon sound principles. This great thickness may cause casting difficulties ; but apart from its value as a beam in keeping the joint tight, it is necessary in order that the bolts can be kept tucked in close to the casing. It is generally considered desirable to avoid joggling the joint around bye-pass belts to avoid distortion and possible leakage due to heat stresses when the belt is thrown into, or out of, use. Straight fore and aft flanges are aimed at and everything possible is done to reduce the width of the flange and keep the bolts in as close as possible. In some cases the bolts are heat-tightened ; that is, they are made hollow and heated by an inserted electric heating element ; the nut can then be screwed up, without flogging, an amount which will leave a pre-determined stress in the bolt after cooling has taken place. This method cannot be used for fitted bolts, which would not be free to expand diametrically during the heating and would thus seize in their holes with possible damage to the flange.

The number of fitted bolts used has now been drastically reduced and four well spaced ones are often considered sufficient. In order to try to facilitate withdrawal of fitted bolts after some service, the actual bolt is sometimes reduced so that the fitting section is about one-third of the flange thickness in each flange ; the bolt is relieved for the remainder of its length.

In some turbines, in order to allow relief to heat stresses in heavy flanges, saw-cuts are made out from some of the bolt holes to the edge of the flanges, allowing some amount of elastic deformation in a fore and aft direction.

Even with moderate steam conditions, considerable troubles have been experienced in the past particularly at the hot end of the turbines with the combined bearing pedestal and turbine foot cast integrally with the casing. The rigid attachment of such a pedestal is necessary to maintain alignments and to give sufficient mechanical strength for supporting the turbine against shock loadings ; and the integral casting, well webbed, provided a rigid, comparatively cold, attachment which resisted the expansion of the hottest portion to which it was attached. Some of the heat conducted to the turbine end of the pedestal further distorted this, causing " cocking." In all the arrangement was a potent source of distortion and overstressing under modern steam conditions.

The modern arrangement in H.P. turbines is to provide separate pedestals. At the forward end the pedestal contains the turbine bearing and adjusting block, and is rigidly bolted down to a beam which supports the whole turbine and is structurally separate from it. The forward end of the turbine casing has two palms which rest upon lands on each side of the pedestal at the level of the rotor axis, and are bolted down in such a way that they have complete radial freedom, whilst axial movement is prevented and alignment maintained. The bottom of the casing is also constrained to the pedestal by a vertical key which does not in any way interfere with the radial freedom.

At the after end the cooler conditions have permitted the bearing to be supported in an integral extension of the turbine casing, but the cylinder is supported by two palm supports bolted on to lands on the pedestal at the level of the turbine axis, and constrained by keys so that both radial and axial freedom is permitted to the casing, without loss of alignment. The pedestal is rigidly bolted to the beam mentioned above.

These arrangements, besides allowing considerable freedom of expansion, also offer a resistance to heat flow from the turbine to the supporting arrangements, reducing both the distortion of the latter and the fire risk.

Under the most extreme conditions of temperature difference between rotor and casing the relative expansions axially between the two may approach $\frac{1}{4}''$. While this figure is not likely to be reached in practice it is necessary to study each design and to try to decide what is likely to be the amount of differential expansion that must be allowed for at the various important points ; the efficiency of the turbine will depend upon not making the clearances unnecessarily large ; its safety upon not making them too small. The lag of the rotor temperature behind that of the casing, or *vice-versa*, when changes take place, varies with the type of rotor ; a gashed impulse rotor owing to its greater surface area and smaller mass, will acquire new temperature conditions more quickly than a drum type one.

The strength of H.P. casings against shock loadings is not a very readily calculable quantity ; but a general consideration of the forces which come into play when accelerations are applied to the pedestals enable a fair estimate to be made of the stresses which will occur.

For " advanced " steam conditions (850°F.) cast steel containing not more than 0.25% carbon and 0.5% molybdenum is used. This material is weldable and possesses adequate creep resistance. Except for nozzle boxes, some further advances in temperature could be made without having to seek a new material ; there are already available cast steels containing chrome and vanadium whose properties are likely to be adequate for the main bodies of casings at any temperatures at present contemplated. In this connection it has to be borne in mind that under cruising conditions the highest temperatures are confined to a comparatively small part of the turbine ; and they do not extend much past the bye-pass belts at full power. The highest temperatures would, therefore, probably result in composite designs so that the use of special heat resisting alloys could be confined to the places where it was essential.

The thick-walled steam pipes which have resulted from high temperatures and pressures are capable of exerting very harmful thrusts upon turbines unless adequate flexibility is provided, either by corrugated pipes, bends, or other devices. It is important that the turbine designer watches his interests in this matter.

Gland pockets are almost invariably arranged integrally with the casings, to avoid joint and alignment troubles. Large pipes are usually required for connection to leak-off pockets, and in the case of reaction turbines dummy cylinder balance pipes of large proportions are required to connect the back of the dummy piston to the exhaust end of the turbine, as the new solid designs of rotors no longer permit the dummy steam to be passed through them. In this connection it is of interest to note that certain cases of H.P. turbine seizure which have taken place under stand-by conditions after a period of steaming in the past have been attributed to the cooling effect of saturated gland steam passing through the rotor and causing it to contract more quickly than the casing ; these cases occurred when a high vacuum was maintained.

L.P. Casings

The design of L.P. Casings is freed from the bye-passes and very hot steam which complicate the H.P. ; but the proximity of the underslung condenser, the larger dimensions, the astern turbines, and the need for allowing for considerable heating taking place during prolonged running astern, all complicate the problem.

The actual temperature swings during ahead running are not very great—in the *Darings* the temperature of the steam at inlet may vary perhaps from 240°F. to, say, 420°F. Under prolonged astern conditions higher temperatures are to be expected, due to churning effects ; whether this temperature will become constant at an acceptable figure and thus (at any rate from this point of view) allow astern running at high power for an indefinite time, or whether it will set a limit to the permissible maximum time for high power astern running will depend upon features of the design ; particularly upon blade speed. The effect is that clearances must be those necessary to ensure safety under the conditions varying from the whole turbine being at steady room temperature to those at which the astern turbine or turbines are at full power and the churned steam in the L.P. ahead stages is at a predetermined figure, say 700°F. Although these, however, may be the final steady astern conditions the critical temperature differences between the various parts of the turbine that will fix the necessary room temperature clearances may be transitory and occur before steady conditions are reached. A scientific approach to the estimation of the correct clearances for any particular design is not yet possible ; a combination of experience and estimation is the present method. Various researches will, however, soon add to our knowledge in this matter ; meanwhile the designer has two aims unlikely to be altered by further data—firstly, to design so that thermal expansions of the rotor and stator are as far as possible in the same sense ; and secondly, so that if a " touch " takes place, it will do a minimum of damage.

A considerable time ago the old " stepped " cones in turbines were replaced by " smooth " cones ; it was hoped that this would provide a steam flow more free from eddying ; the result, however, was that radial blade clearances could be reduced or absorbed by relative axial movements ; and in reaction turbines with this type of cone this is a matter which must be considered. If in a " smooth " cone design due to loss of radial clearance an unshrouded blade touches at the tip the results can be expected to be worse if the turbine is running ahead than if it is running astern at the time. The reason for this is that the touch will induce the blade to bend slightly ; and the bending will not be circumferential, but in the direction in which it is less stiff, *i.e.*, across the chord of the blade section ; and if a diagram is drawn it will be seen that when running ahead such bending will become progressive because the blade will be diverted towards the smaller end of the cone. While running astern the bend would be towards the longer end of the cone, with the result that it will tend to clear itself. This fact is worth bearing in mind when testing a turbine for freedom after suspected seizure.

In normal dual flow L.Ps. the risk of absorbing axial clearances is usually greater in one cone than in the other ; and this should be borne in mind when deciding clearances or in endeavouring to find the most suitable compromise for the rotor position in a turbine in which due to damage or wear, or bad workmanship, the designed clearances cannot be achieved throughout.

So far the absorption of clearances due to symmetrical expansions of L.P. turbines only has been considered ; trouble more often occurs from unsymmetrical expansions, or, more bluntly, casing distortions. Rotors should not bend a significant amount given satisfactory operation ; that is if they are initially straight and the warming through and shutting down techniques are satisfactory ; casing distortions are, however, inevitable ; the limitation of their extent and effect is a criterion of good design.

Typical L.P. turbines with underslung condensers have an inherent tendency to hog, because the top of the casing is almost certainly hotter than the bottom under almost all running and standing by conditions. In order to try to keep the blade cones concentric with the rotor axis various palliatives have been adopted with some success ; but the inherent tendency is there.

Apart from the probability of absorbing radial clearances such hogging can set up severe stresses which may put the turbine out of line in other directions and also cause cracking of the materials at points where local stiffness leads to stress concentrations. In an effort to avoid some of these evils the " free-cone " design was introduced and is still adhered to. In this type of design the pair of blade cones form an integral casting with the steam inlet belt ; and this casting is supported in main turbine structure so that it is free to expand axially and radially and not subject to any stresses transmitted from the remainder of the casing, etc.

Although it adds some complication this arrangement is in the main good ; but analysis of what may happen to axial clearances under certain conditions shows it is by no means perfect.

In order to reduce the effects of the adjacent cold condenser lagging of a water-resistant type has been applied in some cases to the lower side of the cones ; but whether this is of real assistance has yet to be definitely established.

The scantlings of the main L.P. structure are now decided by shock strength considerations ; the structure broadly takes the form of a massive double beam of fabricated steel, the blade cones being positioned between its two fore and aft members and the bearing supports bridging the ends. The need for separate floating astern nozzle boxes has been very amply demonstrated by troublesome failures which have been experienced with the integral type, and also with their externally piped connections across the horizontal joint ; the floating astern nozzle boxes now fitted are supported at the ends of the main structure ; the upper casing is fabricated from plate.

The condenser is supported from the lower side of the main structure ; and additional support for the condenser by means of springs underneath is no longer considered necessary or desirable.

Cast iron has been completely eliminated and cast steel covers and lower halves are now virtually obsolete ; steel castings for bearing supports are, however, retained, and at present nozzle boxes are cast, with inserted nozzle plates.

The material from which the fabrications are made has in general been mild steel ; but it has now been found that with a reasonably simple technique no difficulty is experienced in using " D " quality plate and this should allow some reductions in weight or equivalent advantages in new construction.

The blade cones have normally been of cast steel ; and although the casting is a simple one and should give no trouble faulty foundry technique in many cases has led to the need for considerable repair by welding before use. Apart from this difficulty, which should not recur, there are reasons why rolled plate sections welded together might be preferable from the production aspect, and this form of manufacture may become general in future.

With loose blade cones a flexible joint of some sort between the L.P. inlet branch (which is integral with cones) and the casing is required ; a comparatively simple arrangement using the flexibility of their mild steel plates is easy to devise.

With twin astern turbines it is usual not to have any valves after the bifurcation of the steam pipe ; if any are to be fitted it is necessary to examine the extent of the unbalanced thrusts which may arise if the supply to one only of the turbines is shut.

BLADING

Material

There are numerous blade materials available to the designer of modern steam turbines ; but the qualities required are also numerous and so diverse that no one material is known which fulfils them all. Selecting the best material for blades in each part of the turbine can result in the employment of a large number of materials in one machine ; and while this has been done in some designs it is obviously a far from ideal arrangement and is one to avoid if possible.

But for one weakness stainless iron is the best all-round material for modern advanced conditions. This weakness is its tendency to a form of decay at present known as "chloride attack." The incidence of this disease has led to the substitution of stainless steel or materials in other ways less favourable, either in certain parts of turbines, or in some cases throughout. Out of the large number of H.M. Ships fitted with stainless iron blading (exceeding two hundred) less than a dozen cases of chloride attack have been reported, and nearly all in destroyers. In U.S. warships stainless iron is very largely used, and the attack is practically unknown. Although in the British Navy the incidence of attack is quite low (serious cases amounting to perhaps 5% of ships fitted) the cost in money and non-availability of having to re-blade where this has been necessary has been sufficient to preclude the use of stainless iron in parts of turbines where experience has shown attack to be most likely.

Research is at present proceeding to try to establish the cause and prevention of the attack, but the matter is a complicated one as there are many variables and not much actual data available. It is not yet even certain that the attack is caused by chlorides ; or that if it is, the chlorides originate in the steam rather than from some process during manufacture (e.g., pickling or brazing).

The parts of the turbine where stainless iron has proved most subject to attack are those where the steam is wet, but not very wet ; the early stages of the H.P. and the final ones of the L.P. have generally proved relatively immune, and in some modern turbines stainless iron has been used in these positions, monel or A.T.V. being used in the last stages of the H.P. and early stages of the L.P.

For the very highly stressed L.P. last row blades various high tensile steels, protected by chromium plating, have also been considered suitable.

Among the more important properties which must be considered when choosing a material are—

Ease of manufacture

Given good modern machine tools, all the blading materials in general use in steam turbines are satisfactorily machinable ; but the machining cost and time vary considerably. Stainless iron, for example, is very much more readily and quickly machined than Hecla A.T.V. The latter material has in the past been rejected because of machining difficulties which were very real with the type of machines still in use in some marine blading shops.

Mechanical Properties—Specific Strength

High blade speeds and long blades both lead to high root stresses ; steam bending stresses can also be considerable ; the higher the specific strength (the ratio strength/density) the higher the blade speeds for a given diameter can be, as far as this limitation is concerned. The effect of blade load on rotor stresses is also considerable and the actual mass of the row of blades, not the specific weight of the material, is the important factor from this point of view.

High mechanical properties at room temperature are of importance in the later stages of the L.P. turbine where the highest stresses are likely to occur. Running astern these blades may get very hot, but as the astern revolutions are not likely to exceed about two-thirds of the ahead full speed the stresses will probably not exceed one-third of the full speed ahead running stress and therefore the retention of high mechanical properties at elevated temperatures is not important provided that any reduction of properties with temperature rise is not permanent. At the hot end of the turbine, strength at room temperatures is not of great importance (provided the material is not brittle under shock). Here the high strength at high temperature and possibly creep resistance are the important factor.

Where brazing is to be carried out on the blades the strength of the material after this treatment is of importance ; for example, the yield point of monel is relatively high in the cold-worked condition ; but falls after the annealing treatment which it receives during brazing operations.

Ability to withstand cold work

This is of importance where rivetting of tenons is required. Adequate ductility during and after riveting are necessary to avoid cracks.

Ability to be brazed

Nearly all blading materials encountered in steam practice can be silver soldered and brazed ; but they do differ in their amenability to these processes. With the austenitic steels there is possibly less certainty than with some other materials ; but it has to be borne in mind that the finding of a satisfactory technique for the process when operating on almost any material is like so many other matters, probably only a question of applying sufficient research effort and control. All normal steam blading materials are weldable.

Co-efficient of expansion

It is desirable that material with a suitable co-efficient of thermal expansion should be used if possible ; but it is not quite straightforward knowing what is the most suitable co-efficient ; it has to be borne in mind that when the steam temperature in any stage alters the blading will tend to lead the rotor in picking up the new conditions.

Erosion resistance

In general, the harder the material the greater its resistance to erosion by water and particles ; but this is not invariable. The need for erosion resistance is greater at the wet end of the turbine.

Inherent damping

Not very much is known about what part variations in this factor play in preventing vibration failures. Clearly, however, a material with high inherent damping properties is preferable to one without.

Costs and Availability

Whilst first cost is not a factor of major importance for the more general materials in use, if rising temperatures forced the use of materials now used in jet engines, the cost would be very considerable ; such materials, together with others containing significant quantities of the rarer metals may be expected to be in short supply in future wars, and their use on a large scale in naval steam turbines would require considerable justification.

Fatigue properties

It is probable that more turbine blades fail from fatigue (as a result of vibration) than from any other cause. Consequently the ability of the material to resist fatigue is important ; and more knowledge than we have at present is required of the fatigue-at-temperature of the materials available.

It is generally (but by no means universally) considered that such fatigue tests should be carried out on actual blades ; the complexity of the effects of discontinuities, section changes and notch sensitivity being insufficiently understood to enable satisfactory conclusions to be drawn from simple tests on standard specimens of materials.

Segmental blading

This type of reaction blading, which has given such good service (in conjunction with the side-locking system) in the past is probably likely to be used decreasingly in turbines subject to large steam temperature swings ; with this type of fixing the blade can be considered as a fully encastal beam ; thermal expansions of the shrouding due to the direct impingement of steam during temperature swings may be very rapid and the corresponding bending stresses induced in the blades can be very considerable and lead to failure. Where blades are individually fitted it is likely that even the very small movements they can make relative to each other and to the rotor will greatly reduce these stresses. In either case it is to be expected that the stresses will be more severe if the shroud band is brazed to the blades. The magnitude of these stresses is dependent upon, among other factors, the length of each section of shroud ; in general the number of blades covered by a single section should be limited to a figure of perhaps 6 or 8 ; but the length, section and type of fixing of the blades, and their position in the turbine together with certain aspects of vibration problems all affect the choice.

Pot brazing techniques for segmental blading have been worked out and standardised to a large extent ; but close supervision of the operation is still necessary to avoid causes of failure. Detailed inspection of the parts, the assembly of the packs and of the baths, in fact of the whole process down to the finished product is essential to avoid failures.

Individual blading

The various types of root fixings—T-root, serrated rhubarb section, fir-tree root, double straddle, riveted straddle, axially inverted fir-tree root, and so on all have their applications. There is no object in choosing a more expensive type of fixing than is necessary.

In all the types which enter circumferential grooves through a gate, the method of securing the closing blade or blades is usually a critical matter, and in highly stressed designs frequently presents difficulty. In extreme cases it is sometimes necessary to leave a gap by omitting the closing blade, it being found not possible to devise a closing fixing which can support the pull of a blade. In such cases a small loss of efficiency has to be accepted (it might amount to $\frac{1}{2}\%$ if all the rows were so treated). Where this is done in adjacent rows the closing pieces should be spaced 180° apart, for considerations of balance, if this is possible.

In any particular case it is likely that research will yield detail improvements of considerable value ; small alterations in proportion may show disproportionate results. Photo-elastic methods may be of great help ; but it must be remembered that in order to fail other than by fatigue the blade will have to pass well out of the elastic range and photo-elastic analysis alone may be very misleading in seeking the right answer. Actual pull tests on full-scale models of the correct materials should always be used as a check where results are critical ; and great care is necessary to ensure that the conditions of these tests are really realistic. Extension curves of such tests should always be taken, and it is of value to stop the test temporarily when the equivalent running or over-speed loads have been reached in order to gauge the " permanent set " which takes place during the initial loading.

The effect of various types of creep upon rotor stresses, not only at the rim, but at the bore may vary considerably ; with double straddle roots, particularly in small sizes, the weight of the actual blade section may be only a very small fraction of the weight of the complete blade.

Shrouding and tenons

The shroud band, apart from any duties it may have in directing steam flow and preventing leakage, has important functions in preventing blade vibration ; to do this, and avoid the imposition of severe initial stresses on the blades, the shroud must be accurately marked out and fitted ; it is seldom satisfactory for the holes to be made at the theoretically correct spacing ; marking out from the actual tenons after blading is nearly always desirable. Punching the tenon holes is regarded with disfavour as it is thought that the process may leave the metal in a condition of stress favourable to the initiation of cracks, but punching out a section between drilled holes for oval tenons is often allowed. If tenons of odd sections are necessary, punching may have to be accepted.

Correct rivetting of the tenons requires a high degree of skill, and it is usual to insist that a light hammer, with perhaps a half-pound head, only should be used.

If the tenons are too short, an inadequate rivet head will be formed, and the shrouding may become detached in service ; if they are too long there is danger that radial splits will form in the rivet head due to having to put too much work into the material to close the rivet ; or the tenon may form a sort of bulge below the shroud, which will later be flattened into a fold which can form the starting place for a crack. This last trouble can also occur if the closing process is started by applying the hammer squarely to the tenon ; care should be taken to work down the edges of the tenon first. The use of too heavy a hammer is likely to result in damage to the blade fixing and initial looseness, particularly in that type of blade which after being positioned in the groove is held radially out on its lands by a small packing piece forced under it.

The centrifugal stresses in shrouds in high speed turbines are often considerable, and careful design is necessary or the edges and corners of the band at the ends of the sections may turn out radially in service. Various devices in the way of making the gaps curved, levelling off corners, and so on are employed to obviate this. The calculation methods available on this detail are not satisfactory and research is in hand to facilitate the design of this part.

In order to take advantage of available metal in the blade section, tenons may have to be of shapes other than circular ; from the points of view of avoiding stress concentrations and care of forming the shroud holes circular tenons are preferable. Where, however, they cannot be used the tenons must be shaped so that the rivet gives the best support to the shroud band with the least chance of overworking the blade material, at the same time avoiding shapes and sizes of shroud holes which could for one reason or another be a source of weakness. In some cases the tenons may be bifurcated.

All tenons must have a generous radius at their point of juncture with the blade, and here, as in every other part of a highly stressed blade, dimensional accuracy and excellence of finish are vital.

The shroud should also have the tenon holes well radiused on both edges.

In some cases shrouding of individual blading is brazed on. Experience of welding shroud bands is unsatisfactory.

Lacing

The lacing of blading is now usually a purely anti-vibration measure. (Exception to this is the brazed-in wires used in long reaction blades.) The mutual support afforded between the blades by the lacing wire prevents independent vibration, that is, any vibration which takes place must be with all the laced blades in phase, a state of affairs which is unlikely as the major disturbing forces tending to cause vibration are applied to the blades successively. The lacing wire is only useful, of course, in suppressing nodes of vibration in which the nodes are remote from the laced point, and which would involve a phase difference in the vibration of adjacent blades. There are mechanised methods of securing lacing wires ; but brazing or silver soldering probably offer the best support provided that the temperatures of the process do not cause deterioration of the materials.

Circular bands

With all types of root which fit into or round circumferential rotor grooving, it is clear that, if the corresponding bands on the blade roots are flat, contact will occur only at the ends of the root. This effect is of importance in highly-stressed small diameter naval turbines ; and for this work it is now insisted that the bands on the blade roots should be machined to a circular profile to match the grooving in which they are to mate. If this is not done yielding of the bearing surfaces and concentrated loads on the highly stressed disc head may lead to trouble. The circular bands can be formed by milling (except in certain cases where interference of cutters does not allow it) or (in all cases) by circular broaching. The latter process produces excellent results but calls for more expensive equipment.

Fit of blades

Very accurately formed grooves and blade roots are essential to reliability and long life in highly stressed designs. Strict control by tolerance and gauge ensure this necessary accuracy ; but considerable skill is necessary, particularly in the more complicated root forms, to produce a design in which each surface bears its allotted portion of the load, yet in which the tolerances on wheel rim and blade root are not too fine to be commercially practicable.

In considering blade fixing designs (and when testing specimens by static pull) it is necessary to bear in mind the circumstances which will exist under centrifugal loading ; the actual circumferential length of the wheel rim will be elastically increased to a quite substantial amount, allowing some spacing of the blades ; fixings which under static conditions fitted with an interference may have clearances ; and so on. This aspect of the problem is of particular importance in the consideration of blade vibration problems—for example a blade which when stationary behaves as an encastal cantilever may at full speed behave as though it were pin-jointed to the rotor.

Axially inverted blades in gas turbine practice are sometimes fitted " loose." The grooves and four or five band " fir-tree " roots are held to very close tolerances so that, when cold and stationary, the top of the blade can be cocked circumferentially a few thousandths of an inch—within specified limits. If sudden heating of the turbine produces a powerful compressive stress in the disc rim, this arrangement may prevent damage ; and the elastic stretch of the rim at full speed would in any case annul the effect of an initial interference fit of the blade roots had this been attempted.

The challenge of the gas turbine may be reflected in " twisted " blades being fitted in more stages in steam turbines that has hitherto been the case ; such blades help to maintain control of the steam even at the larger e/d ratios. On account of the complicated machining operations required to produce them, they are, however, expensive.

There does not at present seem to be a field for precision cast blades in steam turbines, the superior properties and reliability of forged and rolled materials do not seem so far to have been seriously challenged.

On small highly-stressed rotors with short blades there are good reasons for manufacture by machining from the solid, provided that materials are available, which, with or without protective plating, are suitable for rotor and blades. A rotor with blades machined from the rim may be actually cheaper to produce than one with inserted blades.

GLANDS AND DUMMIES

The glands of all modern naval turbines are of the labyrinth type. The formerly used carbon packed type, although it had certain advantages (such as a possible saving in rotor length), led to much maintenance work, even when the segments were correctly fitted, which was by no means always the case. Chromium plating of the spindles in way of the gland (where this could conveniently be applied) certainly did much to improve the carbon type, but troubles still persisted and it is unlikely that a gland of this nature will be fitted in preference to a labyrinth one until research or invention show a way to overcome fundamental difficulties.

In the labyrinth type, naval practice is now to confine the packing fins to the stationary part of the gland, although suitable steps or ridges are sometimes turned out of the solid spindle forgings to provide what is considered to be the path of greatest resistance to the passage of steam, depending upon the shape of the packing fins, and whether radial or axial clearances (or both) are provided. The practice of caulking in the packing fin material has in some instances been abandoned in favour of providing a positive lock, the packing being introduced at the horizontal joint and slid or driven round the grooves.

The shape of the fins, and the shape of the expansion spaces between the fins, and the relative position of the successive restrictions vary with every maker ; in practice the difference in results between most types has not been found to be very great.

The number of restrictions provided is in practice somewhat arbitrary. The leakage to be expected from a given arrangement is usually calculated from data given in paper by Adolf Egli ; but it is not usually assumed that the designed clearances will be indefinitely maintained, and supply and leak-off pipe areas (based on calculated flows) are usually multiplied by at least two, in order that the system may continue to operate successfully should a " rub " occur at some time in service.

At moderate steam temperature—up to perhaps 600°F.—soft brass strip has proved to be a satisfactory gland packing material, as it is easy to work, retains its properties quite well, and is not apt to damage the shaft should light rubs occur. It is also capable of being " dressed up " with suitable roller tools so that it is frequently possible to make a good job of re-fitting it without actual replacement.

Brass has not, however, been found to stand up very satisfactorily to higher temperatures ; it loses mechanical strength, and works out of its grooves ; this is probably partly due to its comparatively high coefficient of thermal expansion.

Other materials which are suitable for the higher temperatures are stainless iron, nickel, and soft monel. It is likely that all these will have more tendency to damage a spindle if contact occurs than brass has. Some makers for this reason, and for ease of fitting instead of using rolled or extended finned sections, use a ribbon—perhaps 20 or 30 thousandths thick, fixed in its groove by caulking pieces. When this is done it is said that the division of the packing into short (one inch or so) strips with gaps between each is unnecessary.

A material which retains its form and strength when heated and rubbed is dangerous ; the heat generated by the first touch causes expansion which forces the parts into closer contact and the trouble tends to become cumulative ; the bad qualities of such a material are accentuated if it is also a bad conductor of heat as the expansion and distortion will be localized and concentrated.

A good gland packing material, therefore, should be a good conductor of heat, able to resist working steam temperatures without deterioration, but having little mechanical strength at the temperatures it will attain if contact occurs. Its coefficient of expansion should, if it is to be used for inserted type of packing, be appropriate to its purpose ; and it should have absolutely no tendency to weld onto the material of the turbine spindle, or to cut the spindle. It must also be readily machinable and non-corroding in steam, water and air.

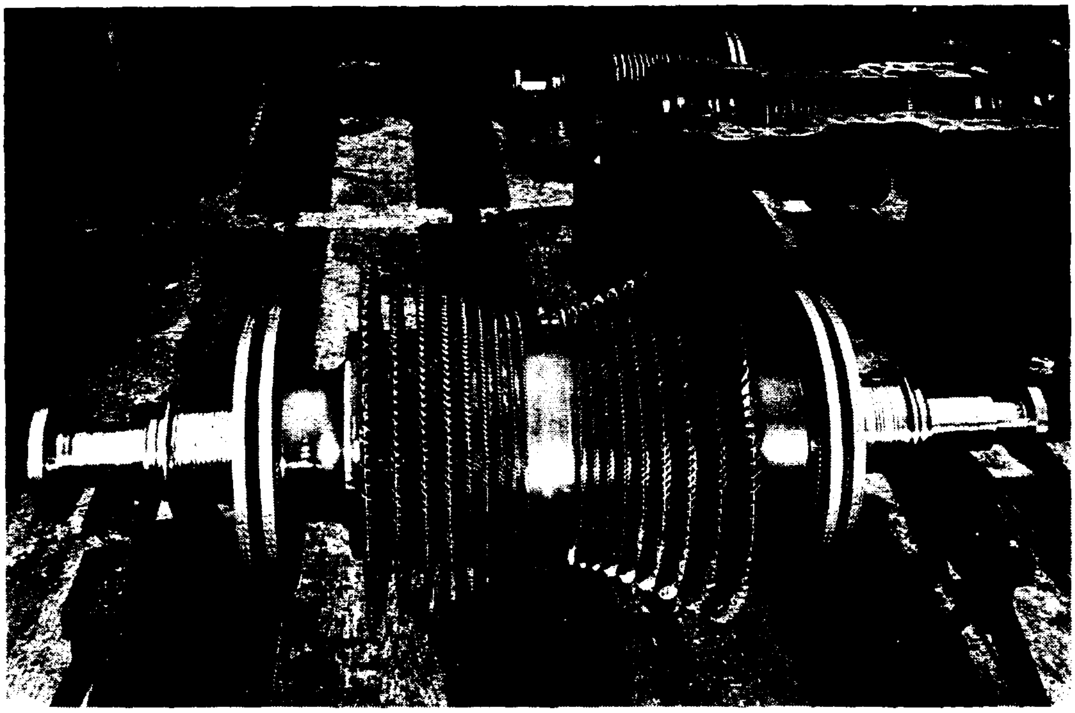
Some makers use solid packing sections each with a number of circumferential fins turned on it. These sections are machined from a cast proprietary material usually with a nickel-bronze base ; the material has the special property of rubbing away to powder without the formation of much heat if contact with the revolving shaft occurs, thus avoiding damage to the shaft.

A research is in hand covering all the aspects of gland design and material ; this is aimed to determine how glands can be shortened, thus allowing shorter rotors, or more stages ; and also to find the most suitable materials.

If a turbine shaft that is initially running very nearly true lightly touches a gland, it is probable that little damage will be done ; but if the shaft is perceptibly out of true the " high " part will of course rub first and a local hot spot may be formed. This hot spot will tend to cause the rotor to bend further out of truth and the effect may become cumulative. The temperature attained at the " hot spot " of the shaft may be such that the bend becomes permanent.

All the above remarks, apart from the first paragraph, apply in some measure to dummies. The rubbing speeds, should contact occur, are higher, and more damage is likely to be done. Cases have occurred in which the dummy piston and cylinder have rapidly become so hot that the steel has become plastic, and spun out into a funnel shape ; a striking example of the cumulative action referred to above.

In both glands and dummies the designer can choose whether he arranges the clearances axially or radially ; and if the former, whether they shall be absorbed by movement of the rotor forward relative to the casing, or aft. In deciding such matters, it is important to consider all the possible conditions, through which a turbine may pass, including warming up, during increase and



Double-Flow L.P. Reaction Rotor

decrease of power, prolonged running at various powers, cooling off, and re-warming from a partially cooled condition.

The way in which the dummy piston and cylinder are attached to the rotor and casing respectively is also of importance ; matters can often be arranged so that (in the design stage) alteration of the anchorage from one end to the middle, or the other end, allows an overall improvement by making expansion of individual parts cancel each other. The exposure or shielding of the dummy cylinder to steam flows, etc., also may admit of some control of rate of change of temperature. The general configuration of the casing at the inlet end of the turbine will determine how much distortion, under varying conditions mentioned above, will be communicated to the dummy cylinder ; it will be the aim of the designer to so arrange matters that no operating condition can so distort the dummy cylinder that the working clearances are absorbed.

LIFE OF TURBINES

The increase in operating temperatures has made necessary the consideration of creep in the hot parts ; and as creep in any material is a function of time and stress, the required life at the operating temperature and high stress becomes of importance. With most applications of most materials creep will not be a limiting factor except under the most highly stressed conditions—*i.e.*, at the highest powers ; even if the full temperature is maintained or somewhat increased at reduced powers, creep will probably not become significant. The life required at full power may therefore become a determining factor of the design.

Normal merchant marine plants will have a probable full power life of 100,000 hours or more ; such a requirement applied to warship machinery would severely penalize the design if very high temperature steam is to be used ; and would be unnecessary for most classes of ship.

Data upon the full power life required is at present scanty, and assessment of the matter from war experience is not easy as any future war may be fought under very different conditions ; and also, the majority of our ships seldom attained full designed power revolutions due to carrying over " heavy " propellers and to increase in displacement due to added equipment.

It seems likely, however, that a full stress—full temperature turbine life of 1,000 hours would be quite adequate in nearly all classes of vessel, and half this figure might be worked to if considerable advantages accrued thereby.

If vessels are required to have longer full power lives than this, and the matter is critical from a design point of view, a way out may be to make the parts of the turbine which take the initial " sting " of the high temperature readily replaceable ; for example, by providing an initial impulse stage with a readily replaceable rotor in its own casing. Only a very small portion of the whole turbine is affected by very high temperature steam, except where external by-passing is used.