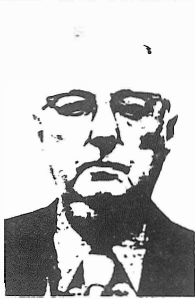


REPAIR TECHNIQUES FOR ROTOR AND CASE DAMAGE

by

Harry Erb

Consultant, Elliot Co.
Greensburg, Pennsylvania



Mr. Harry E. Erb is a consultant for Elliot Company. He has been working in the field of engineering for the past 50 years. In 1928 he received a Bachelor Degree in Electrical Engineering from Cornell University.

Mr. Erb has been associated with Elliot in many capacities since 1959. He was the chief engineer and works manager before he retired in 1962

when he became their consultant, a position he still holds. His wealth of experience in compressor design and service has earned for him a reputation throughout the industry.

INTRODUCTION

To properly install, profitably operate, and economically maintain high speed rotating machinery requires considerable skill, judgment, and experience. Excellent engineering references covering the mechanical design and the basic principles as applied to this class of machinery can be found in many textbooks. Very few textbooks are available, however, which cover the engineering aspects as applied to installation, operating, and maintenance of this class of machinery.

This collection of engineering notes, recording the combined skill and thinking of many people, has been assembled for the general guidance and training of men engaged in this class of work. It is hoped that this may be of interest and use to properly develop men who are called upon to install, operate, and maintain this class of machinery.

This class of machinery, properly designed and built, and with proper installation, and given reasonable attention and care, should give little trouble over long periods of time. Many outstanding records, made over the past years, amply demonstrate this fact. However, because of its ruggedness and reliability, this machinery is sometimes improperly installed, and sometimes gets little attention and care until serious trouble develops, or a failure causes a plant shutdown and focuses attention on the trouble or failure rather than on the underlying causes therefor.

All machinery requires proper installation and reasonable attention and care if these troubles and failures are to be avoided. It is often observed that some installations are practically "trouble free" whereas identical machinery in other installations is continually giving trouble. Although it is obvious that some troubles or failures are purely accidental and do not reflect on installation, operation, and maintenance, it is equally obvious that "trouble free" installation are not accidental but are the end result of skill, judgement, and experience of those

charged with installation, operation, and maintenance. Unsatisfactory performance, therefore, cannot always be attributed to "hard luck."

Skillful installation, operation, and maintenance may be defined as the activity of extending the effective, useful life of machinery at the minimum cost. Cost as used herein must include not only the direct labor and material costs for this activity, but also the production losses resulting from either too long or unnecessary scheduled shutdowns and, particularly, unscheduled shutdowns. Only machinery in effective use can create profits. Idle or ineffective use of machinery can only absorb profits.

Today's machinery can be characterized by rapid increase in range and complexity, as well as greater refinements and exactness in manufacture. These factors, together with advancing automation, today demand a far greater versatility of the people charged with and responsible for these activities. In the past, an occasional malfunction of machinery resulting from any unusual condition (operating or otherwise) could perhaps be considered acceptable as an operator was probably available to quickly get the machine back into normal operation. In the largely automatic plant today, **SUCH MALFUNCTIONING OF MACHINERY IS INTOLERABLE!** Even though many skilled operators perform these activities almost instinctively, aided and abetted by experience or repetition, both terms must be defined. "Experience" has been defined as learning by doing and/or observing by our senses as contrasted to learning by thinking. "Repetition" means repeating the same experience. For example, we all know many men who are credited with, say, twenty years' experience when in reality they have one month's experience repeated two hundred and forty times. These are the people who have had plenty of experiences but have not profited by them. The point is that no one can learn by experience alone; we must think out the experience; otherwise, we only repeat. More simply, experience is often negative—finding out how not to do. Thinking is always positive—thinking out how to do. Positive experience after thinking out the problem and then taking action gives confidence to the individual; repeating the action gives skill.

As these particular notes do not deal with the design aspects of this class of machinery, we will primarily devote our attention to those aspects which contribute toward a "trouble free" installation—at the same time pointing out those factors which may result in unsatisfactory performance but which are not attributable to faulty design or workmanship in the design and building of the machinery itself. **WE WILL, THEREFORE, START WITH THE ASSUMPTION THAT THE MACHINERY ITSELF HAS BEEN PROPERLY AND CAREFULLY DESIGNED AND BUILT.**

It is to be noted that considerable emphasis has been placed on proper installation. As used herein, the installation includes plant layouts, piping layouts, and

foundations, together with the basic field erection and assembly of the principal machinery, piping, and necessary auxiliaries. This is the starting point for a "trouble free" installation as conditions vitally affecting installation, operation, and maintenance are thereby firmly established: and in many cases cannot easily be rectified when once established.

Although this paper is entitled "Repair Techniques of Rotor and Case Damage," it should be self-evident that our primary emphasis should be directed toward preventative repairs rather than on what we will call "random repairs" which frequently rely on "expediency" in making the repair. It is for this reason that **WE MUST OUTLINE THE BASIC ITEMS WHICH WILL ASSURE THAT THE MACHINERY ITSELF IS ALSO PROPERLY AND CAREFULLY ERECTED AND STARTED UP. THIS IS A FACTOR WE CANNOT ASSUME.**

As stated above, even with identical machinery we often observe wide differences in reliability. This reliability is reflected in frequent unscheduled shutdowns, frequent bearing replacements, frequent seal replacement, coupling problems, erratic vibration, etc.

This comparison of relative total costs of maintenance between units may sometimes be made by comparisons of maintenance costs of units in a given plant or by comparison with other plants utilizing the same or closely similar process and machinery.

If we find that our total maintenance costs for a particular unit are in the lower range of such costs, we could proceed with repairs with few, if any, further reservations.

If, however, we find that our total maintenance costs appear to be way out of line, we should first attempt to isolate the reasons therefor before proceeding with any repair.

The possible variable factors in a comparison of total maintenance cost between identical machinery in closely similar processes are plant layout, foundations, and piping layout. We, therefore, should examine and compare these possible variable factors in order to assess whether or not these variable factors may contribute to the high total maintenance costs before any repair is attempted. In my experience, there is usually general correlation between these variable factors and high total maintenance costs.

To assist in assessing these factors, we outline below general criteria for plant layouts, foundations, and piping layouts. Too often, too little attention is focused on these items until serious trouble develops.

GENERAL

Proper installation is the first and most important requisite for satisfactory operation of high speed rotating machinery—and this fact cannot be over-emphasized. The rugged and simple construction of this class of machinery permits its operation under adverse and unfavorable conditions, but it is of primary interest to the purchaser to provide the best conditions possible in order that maximum service at minimum cost can be obtained.

PLANT LAYOUT

The principal machinery foundations, piping, wiring, and the necessary auxiliaries must be carefully located in

the plant layout. Even where space is limited, skillful locating of the various pieces of equipment with an eye to future installation, operation, and maintenance is a far more effective way to provide for ease and convenience in installation, operation, and maintenance than anything the erector, the operator, and the maintenance men can do with a faulty plant layout. It naturally follows that machinery which is easy to install, operate, and maintain will generally be well-operated and well-maintained. Conversely, machinery which is difficult to install, operate, and maintain—because of a faulty plant layout—will generally be poorly operated and maintained.

FOUNDATIONS

Foundations for high speed rotating machinery need not be as massive as foundations for reciprocating machinery; however, the foundation as a unit must be rigid to prevent relative distortion so as to permanently maintain the close shaft alignment necessary for satisfactory operation. To illustrate this point, it must be kept in mind that foundation loadings for solid bedrock may be upwards of 200 tons per square foot; but for wet sand, the calculated loading should be reduced to approximately 0.5 to 1.0 ton per square foot.

Where the foundation rests entirely on solid bedrock, the loading may be high; and little relative distortion of the foundation is likely to occur. However, where the foundation rests on either firm clay or well-packed sand, it is obvious that differences in water level under portions of the support can easily result in relative foundation distortion—throwing the unit out of alignment.

The foundation must, therefore, provide a permanently rigid, non-warping support for the unit. To attain this, all conditions surrounding the foundation should be uniform insofar as possible. The foundation should rest entirely on natural rock or entirely on solid earth. A foundation resting part on one and part on the other may warp due to settling of part of the foundation support, or may be distorted by unequal pressures due to the differences in ground water level. Foundations supported on piling should have a rigid continuous cap over the piling on which the foundation rests. A foundation resting on a non-continuous or flexible cap may warp due to settling of one part of the support with respect to the others, or the cap may become warped due to differences in ground water level.

One case is known where a unit with a non-continuous piling cap had sufficient relative movement between the various sections of the piling caps to distort the foundation $\frac{3}{8}$ ". It should also be noted that no perceptible cracking of the foundation superstructure could be detected even with this distortion, even though warpage of upwards of $\frac{1}{8}$ " occurred overnight!

The temperatures surrounding the foundation should likewise be uniform to avoid unequal temperature distortion. A case is known where a concrete foundation distorted sufficiently to cause .060" misalignment, the result of uneven basement heating!

The foundation should be sufficiently massive so that it will absorb, to a large extent, vibration of the units installed on it. Likewise, it preferably should be isolated from all other structures and arranged so that outside vibrations are not transmitted to it.

Some foundations, especially fabricated steel structures, may contain component parts having a natural period of vibration which closely matches the operating speed of the units and contributes in magnifying any vibration present. The best correction in these cases is to stiffen the structure so as to change the natural period of vibration.

PIPING LAYOUT

On most high speed rotating machinery, the piping connections are large compared to the size of the machinery with the result that piping forces of very large magnitude can easily be imposed on the machinery. With an adequate foundation, these are the only external forces which can disturb a proper shaft alignment—when once made; therefore, the importance of a proper piping layout and the proper installation of the piping cannot be over-emphasized.

Piping for high speed rotating machinery should in general be as short and direct as possible in order to minimize cost, radiation, and pressure losses; but at the same time must be laid out and designed so that no substantial forces will be imposed on the machinery casings due to expansion and contraction, by the weight, or by internal pressure reactions of the piping. Many times compromises, which in effect extend the piping runs, may have to be made to minimize the resultant piping forces on the machinery casings, or to provide for ease and convenience in installation of the piping, or to provide for ease and convenience in installation, operation, and maintenance of the machinery.

It should be noted that a proper piping layout is a far more effective way of accomplishing the objective of preventing the piping—under any condition of operation—from imposing severe strains on the equipment than anything the erector can do with a faulty piping layout. Careful workmanship can prevent initial piping strains being imposed on the machinery, but any subsequent movement or warpage of the piping can easily defeat the best efforts of the erector.

PIPING

As the piping for high speed rotating machinery is large compared to the size of the unit, the piping must be carefully aligned with the unit; otherwise, residual forces of sufficient magnitude and direction may be imposed on the unit thereby forcing it out of alignment. This particularly is true if the residual forces are transverse to the unit, or if they impose twisting moments on the unit. Resultant residual vertical forces symmetrical with the shaft centerline, or resultant residual horizontal forces concentric with the shaft centerline, are generally less likely to cause alignment difficulties. However, the resultant residual forces should always be investigated with respect to the casing anchorages—due to differences in design between various units.

The piping on high speed rotating machinery should be aligned and supported so that, at operating temperature, the connecting flanges between the unit and the piping should be parallel within .010" with the flange bolting removed and concentric with the bolt holes matched, so that the flange bolts can freely be inserted or removed by hand with no additional forces on the piping to bring the flanges square and concentric, or to bring the flanges together or to push them apart.

Where stress consideration will not permit "walking the pipe" by heat or otherwise, a thin transition piece may be incorporated between the flanges and machined to get the flanges square within the limit given above. In making up the piping, always begin at the header and make the last connection to the unit flange.

INITIAL PREPARATION AND PLANNING

Having assumed that the machinery is properly designed and carefully built, and assured of a proper and careful erection and startup, we will now outline the major repair techniques to take care of repairs to both the rotor and the stator. As indicated earlier, we want to consider repairs during a planned "turnaround"—not "random" repairs which are frequently done on an "emergency" basis and where techniques are sometimes used which are questionable and should only be used in emergencies. These will be covered later in these notes.

To plan for a "turnaround," one must be guided by the operating history of the given plant and, if it is the first "turnaround," by conditions found in other plants utilizing the same or closely similar process and machinery. This is how the time between subsequent "turnarounds" has been extended to three years or more in many instances.

By utilizing the operating history and inspections at previous "turnarounds" at this or similar installations, one can get a fair idea of what parts are most likely to be found deteriorated and, therefore, must be replaced and/or repaired, and what other work should be done to the unit while it is down. It should be pointed out that, with modern turbomachinery, items such as bearings, seals, etc., which are precision made, are seldom if ever repaired except in an emergency; such items are replaced with new parts.

This means that parts must be ordered in advance of the "turnaround" and other work must be planned for so that the whole operation will proceed smoothly—and without holdups which could have been foreseen. This usually means close collaboration with the manufacturer or his service shop representative so that handling facilities, service men, parts, cleaning facilities, inspection facilities, chrome plating and/or metalizing facilities, balancing facilities, etc., are available—and will be open for production at the proper time required. This is the planning which must be done in detail before the shutdown with sufficient lead time available in order to have replacement parts available at the job site.

DISASSEMBLY OF THE UNIT

A starting point in major repair operations is, of course, disassembly of the unit; and this gives us a rational starting point.

Hopefully, proper overhead cranes and laydown space have been provided. To this we must add ancillary equipment such as lifting rigs with at least three hand-operated chain hoists or equivalent so that the top half can be properly leveled. As most of you know, the clearances on turbomachinery are as small as possible so fairly precise leveling is a must. Secondly, the crane should be geared for very slow and steady hoisting or lowering; and this precludes the use of "long boom" mobile cranes although they are frequently used but are certainly not recommended by the writer. The hazards

of serious damage to the machinery using long boom mobile cranes are, in my judgment, just too great.

As the top half of the unit is being raised, the gaps between top and bottom flange faces should be periodically checked to assure that the top half is indeed coming up square. Guide studs are generally recommended to assure a straight up lift after the top half is free from the dowels. Once the top half is free from the rotor, it can be lowered to nail-free cribbing and prepared to roll over.

To roll over such a unit, assuming that the length is greater than the width, it is preferable to use a crane with two hoists and roll over parallel to the axis of the crane using the main hoist and a single looped cable so attached to the casing that it cannot slip off as the top half rolls over center and starts downward. A similar looped cable should be attached to the other end and using the auxiliary hoist slowly lift the down end and, either by operation of the auxiliary hoist or by operation of the main hoist, approximately level and set the inverted top half on cribbing so that it can be conveniently worked on.

Depending on the internal conditions as found, the diaphragm labyrinth or other packing should be removed and, if it shows no appreciable wear, cleaned up, inspected, and stored in marked packages in a floor area reserved for the parts.

Diaphragms should also be removed, cleaned up, inspected, and stored for reassembly. This same procedure applies to all other parts from both halves. Inspection should be visual, dimensional, and, if any cracks are "suspected" in the diaphragms, magnaflux-inspected as well.

After the casing seals have been removed, the rotor is ready to be lifted from the casing. A lifting rig is helpful here, but otherwise one end can be attached directly to the main hoist and the other end to the main hoist also but through a manual hoist to assure leveling as the unit is raised. Again the lift must also be square and a careful watch made as the rotor lifts off the bottom half bearings to assure that it is indeed coming up straight and square. The rotors in most cases are not so heavy as the other assembled stator parts and, consequently, can be guided by hand.

Horses or equivalents should be available for lowering the rotor onto. The rotor should rest on the bearing journals which must be protected by soft packing or equivalent to avoid any marring of the journals.

If the rotor is reasonably clean, it is ready for visual inspection. The things to look for are journal scoring, packing rubs, wheel rubs, etc. If these appear to be very light, the rotor is ready for indication using a device as shown in Figure 1, and using a ball axial locating device, i.e. a spring, say 5-10# spring scale, lightly compressed to hold the ball up against a ground flat surface such as a $\frac{3}{4}$ " x $\frac{3}{4}$ " lathe tool bit. The parts to be indicated are wheel wobble and wheel roundness at the packing surfaces and thrust collar run-out. The rotor shaft should be indicated at about the middle of the rotor and should run true about .002" to .004" T.I.R. Most manufacturers have established standards and have limits for these run-outs. These should be followed and, if any readings are questionable, the manufacturer should be consulted.

If the shaft does indeed have a permanent bow in excess of the manufacturer's limit or if there is evidence of wheel distress, the rotor must be disassembled. Similarly, if the journals or seal surfaces on the shaft are badly scored, disassembly in most cases is indicated.

ASSEMBLY AND DISASSEMBLY OF TURBOMACHINERY ROTORS

A rotor assembly should be made so that the centerlines of both the wheels and shaft will remain wholly and exactly coincident at all speeds within the possible range of operation. To accomplish this, heavy uniform shrinks are used and this alone requires a heating and/or cooling process or sometimes in extreme cases a combination process. Assembly by hydraulic and/or mechanical processes is usually impracticable although it is sometimes used for couplings and overhung wheels.

In any heating and cooling process, if done uniformly, the metal will be distorted without imposing any appreciable thermal stresses. It is self-evident that high thermal stresses can be imposed if the heating and cooling processes are not uniform to any marked degree. A case is known where a turbine wheel of about normal proportions with a 6" bore had the bore permanently *reduced* in diameter about .060". This resulted from attempting to heat the wheel in a blacksmith forge in which case the center was over-heated while the rim was cool. Although this method of reducing bores is sometimes utilized, it is obvious that it sets up stresses beyond the elastic limit and is only mentioned to point this out.

Even under the best controlled conditions, the heating and cooling will not be uniform to a degree. The basic solution to successfully assemble and disassemble rotors is, therefore, to keep all conditions as uniform as is possible. And it must be kept in mind that even so, some permanent deformation can generally be expected which will result in a rotor which is not wholly true. To obtain usable rotors, this deformation must be kept to a minimum and this points to the following.

On any units where the axial length of the wheel is large compared to the shaft bore, say, on L/D ratio of 0.20 or larger, the rotor should always be placed with the shaft in a true vertical position for either assembly and/or disassembly. As a matter of fact, most rotors are usually placed in this position for disassembly anyway for the simple reason that the rotor can be rotated while heat is applied to the wheel, thus insuring more uniform heat distribution through the wheel, and so that the wheel will automatically drop off when the fit is reduced by heat.

It is to be noted that the basic solution to successful assembly of rotors is to keep all conditions as uniform as is possible. We will point out those conditions where this uniformity must be checked before assembly is started:

1. The key must be tried in keyways in the shaft and the wheel, and must be a reasonably line-to-line fit in the shaft keyway and slightly loose in the wheel keyway. Tight keys in the shaft keyway of themselves can cause shaft bending. The key should be slightly loose at the top as here again a tight key can cause bending.
2. The keyway must be straight with the shaft both in length and in depth. If two or more keys are used

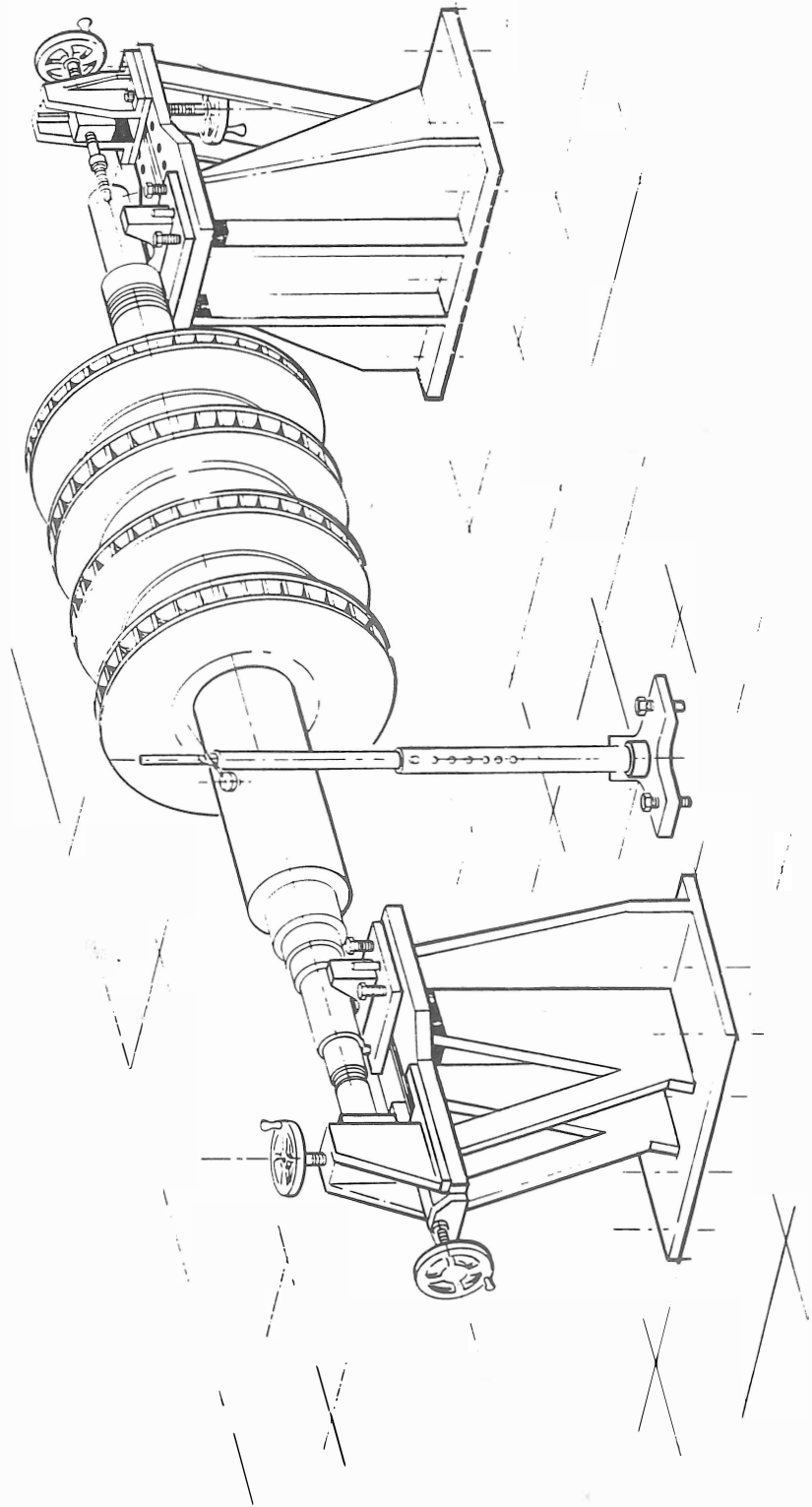


Figure 1. Rotor Testing Fixture.

in each wheel, then all of the above precautions must be taken and, in addition, the keyway spacing for both the wheels and the shaft must exactly match. Here again, differences in matching as little as .001" can result in shaft distortion.

3. No lubricant or anti-galling compound should be used on the shaft during assembly for the reason that this may interfere with the heat transfer from the wheel to the shaft and result in unequal heating and or cooling. To prevent burrs and galling of the shaft and wheels, all sharp corners should be radiused smooth before attempting any assembly. Any burrs raised by previously assembled wheels should be carefully removed and the surfaces smoothed out.

4. A pin gauge made to a micrometer measurement of about .001" per inch larger than the shaft diameter at the wheel fit should be available for checking the wheel bore before any assembly shrinking is attempted. To this allowance, it is well to add an additional allowance to compensate possible cooling while moving the wheel from the furnace to the Assembly and Disassembly Rig (see Figures 2, 3, and 4).

5. The preferable method of heating the wheel for assembly is in a horizontal furnace where the temperature can be carefully controlled. Under such conditions, the usual geometry of both compressor and turbine wheels is such that they will generally be heated so that the rim will expand slightly ahead of the hub section and tend to lift the hub section outward. Where we have long and heavy hub sections, extreme care must be taken to not attempt too rapid a rate of heating because under such conditions the bore of the hub can heat up ahead of the hub section and result in a permanent inward growth of the bore as explained above. Anyone who has permanently "shrunk in" the bores of couplings is aware of how easy this can be done. The basic solution here is uniform and slow heat rates, especially where heavy hub sections are encountered.

6. An alternate method of heating wheels is by use of a gas ring which should, in general, be made a diameter which will be equal to the mass center of the wheel only. Here again, the rate of heating must be carefully controlled for the reasons as given above.

7. For assembly, temperatures in the wheel bore hub and rim section can easily be monitored. The important thing to keep in mind is that the bore temperature must not get ahead of the hub or rim temperature by more than 10-15°F. Temperatures around the shaft centerline of the wheel must be kept within 10°F at any radius, but some stratification along this centerline is permissible, provided it does not exceed 30°F. For large wheels, this points toward horizontal furnaces; but vertical furnaces can be used but generally should be equipped with a turning device to keep all temperatures at any radius from the shaft centerline within the limits given above.

The equipment necessary to do this work is fairly simple but must be carefully designed so that when a shaft is supported from the crane or hoist, it will be truly vertical. When extremely large turbine wheels are placed on the equalizing springs, the wheel must be truly horizontal, etc.

8. For long shafts, a pit should be available for ease in assembly; and for extremely large turbine wheels,

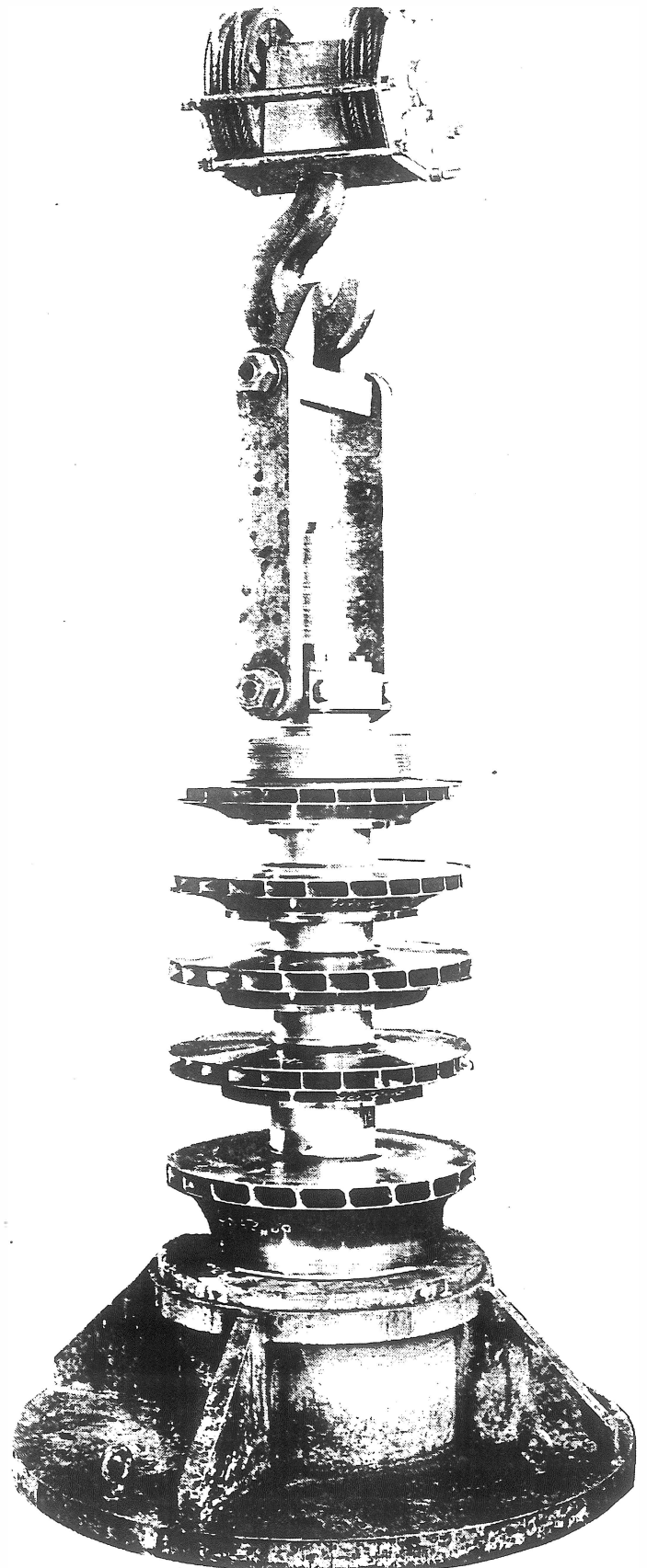


Figure 2. Assembly and Disassembly Rig.

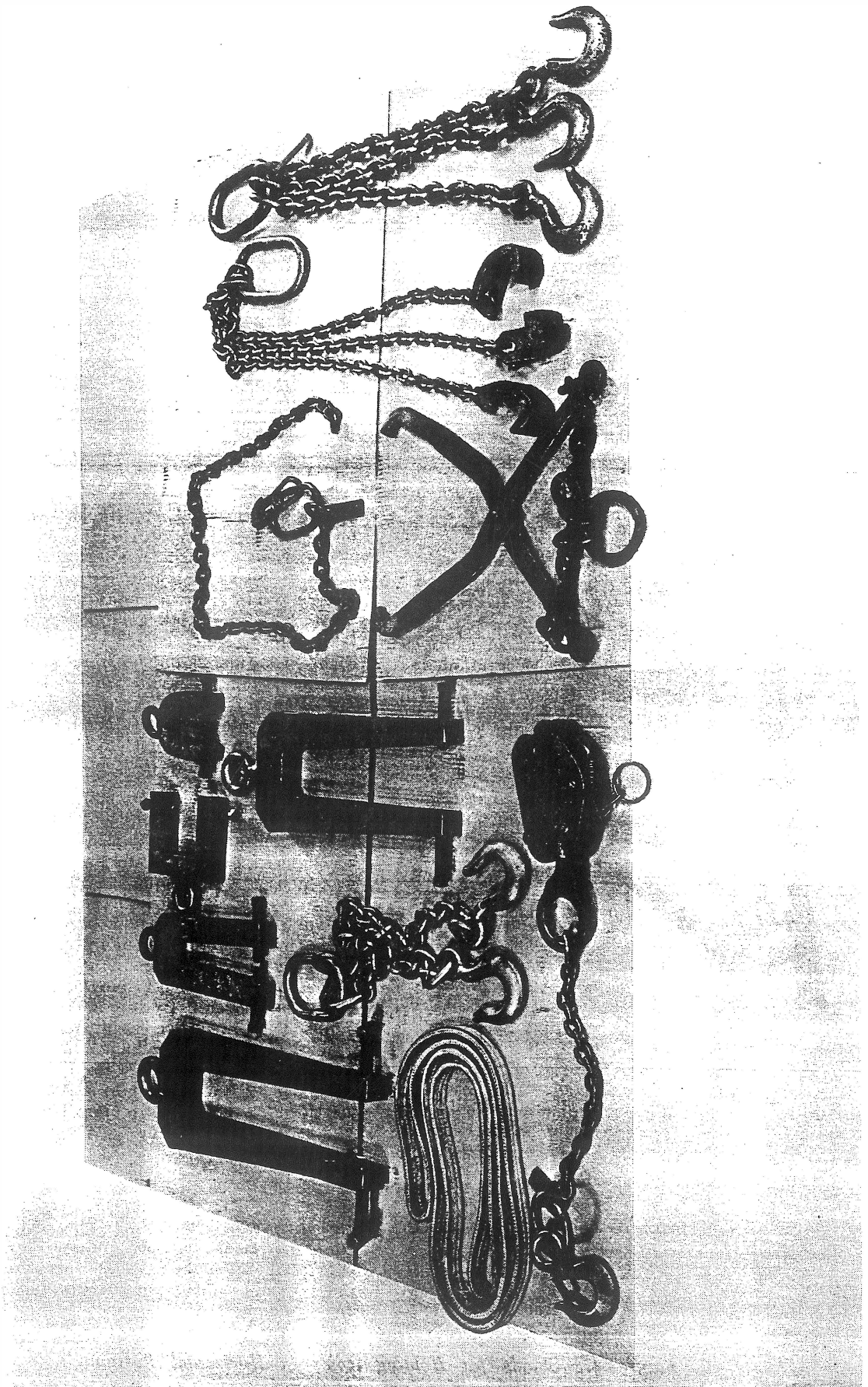


Figure 3. Display of Fixtures Necessary for Assembly and Disassembly.

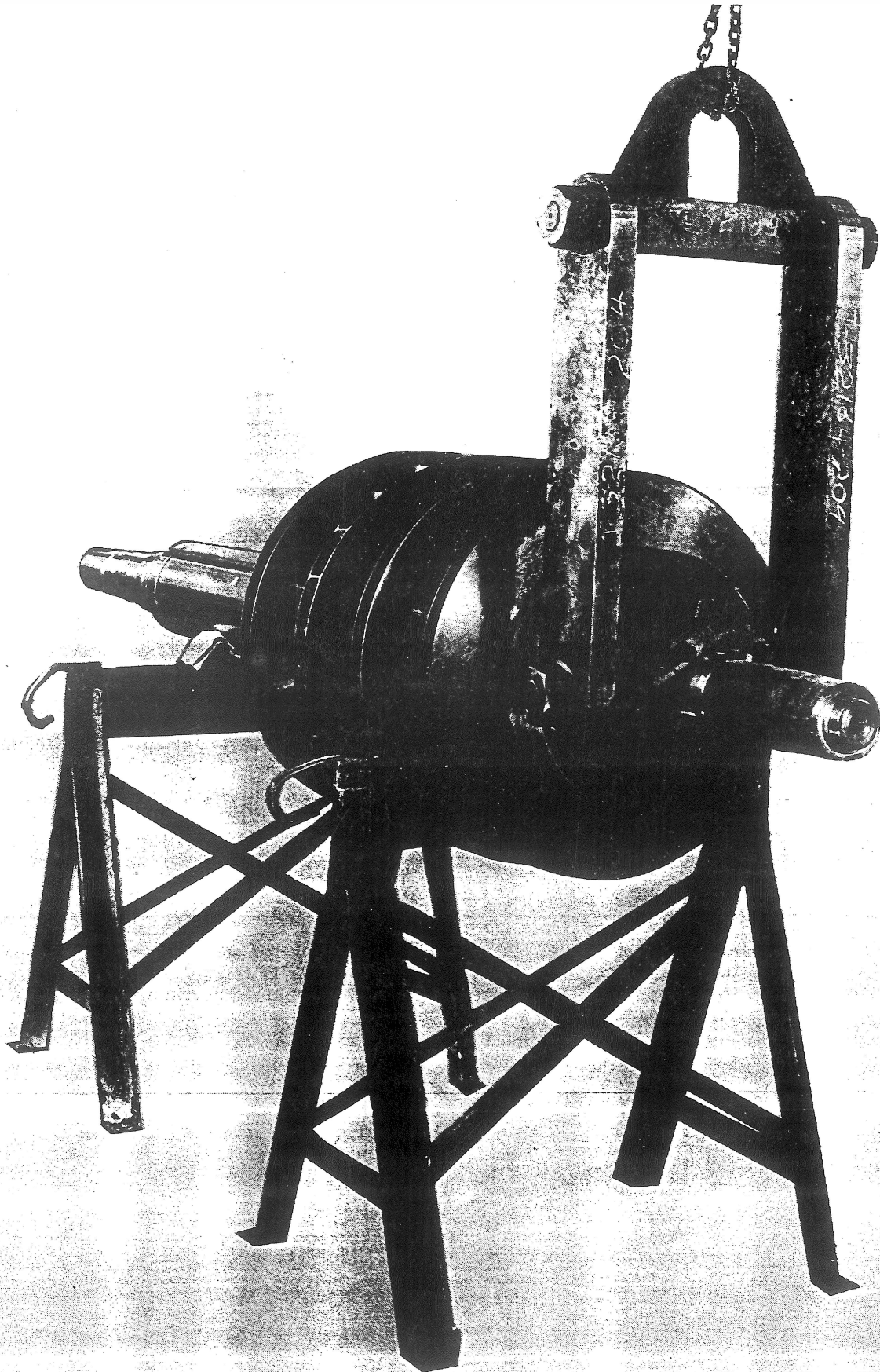


Figure 4. Stands for Holding Rotor in Horizontal Position.

the wheels should be supported horizontally at three equalized points with hydraulic-jack-supported, uniform springs. The equalizing springs used should be the weakest possible but should be checked with the wheel on them before shrinkage is attempted. The spring compression with the wheel alone should be no more than 30% of the total free compression. This will permit upward forces on the wheel of $2 \times g$ without the springs becoming coil bound. Obviously the tops of the springs should be level with one another.

9. The hydraulic jack support should be placed with the jacks in approximately mid position and locked.

10. The heated wheel should be bore checked at about the center of the bore and as soon as the pin gauge can be inserted freely into the wheel bore, the wheel should be quickly moved to the support structure and the shaft with keys in place should be quickly dropped into the wheel bore. The jack pressure should be noted: and when the shaft is approximately fully into position to the wheel fit, the hydraulic jacks should be raised until the jack pressure registers two times the pressure required to support the wheel alone. This pressure should be maintained on the wheel until it has fully grabbed the shaft, but frequent jack adjustments must be made to keep the jack pressure uniform. Actually, the rotor should be fully cooled in this position, using normal air circulation.

11. Artificial cooling of the wheel during assembly must be resorted to if the geometry of the wheel on both sides of the vertical centerline is different and/or if it is necessary to accurately locate the turbine wheel in a given fixed axial position. This latter requirement is generally the case. This requirement necessitates that artificial air cooling, using air under pressure, must be immediately applied after the wheel is in place. The side of the wheel where air cooling is applied is nearest to the fixed locating and/or support point.

For centrifugal compressor wheels where the geometry on both sides of the vertical centerline is widely different and where the usual assembly is to insert the shaft into the hot wheel with inlet down, then the inlet side of the wheel must be heated after the wheel is in place with water cooling applied to the disc side of the wheel. The purpose of this is to have the heavy section of the hub grab first and pull the light section toward it as the wheel is shrinking onto the shaft. Unless this artificial heating and cooling is applied, the light section will seat first and will walk the heavy section away from the axial fit as much as .040"-.050" for large wheels.

12. To disassemble rotors, naturally the parts do not have to be checked for uniformity but should be carefully marked as taken apart so that identical parts can be replaced in the proper position.

To heat the wheel, provide a gas ring made as described above. The rotor should be suspended vertically from a quick-acting hoist with the gas ring lightly supported just below the wheel so that the wheel when loose from the shaft can drop a short distance to a wheel support. Just as soon as this happens, the quick-acting hoist must be activated until the wheel becomes free of the shaft fit.

13. As an addition to this for ease in disassembly, a pit with a vertical cylindrical tank with circulating

water connections deep enough to accommodate the maximum free length of the shaft should be provided. This additionally has the advantage that the free end of the shaft can be kept cool while the wheel is being heated. The important thing to be remembered when removing wheels is that the heat must be applied quickly to the rim section first and after that has been heated—then to the hub section starting at the outside. NEVER APPLY HEAT TOWARD THE BORE WITH THE REMAINDER OF THE WHEEL COOL.

14. If the first trial is successful, thoroughly cool the entire wheel and shaft BEFORE starting the second attempt.

Although the above may appear to be complex, if the method of application of heat is thoroughly understood and if all preparations have been completed before starting, wheel assembly and removal is fairly simple. Also, if the method of application of heat is understood, heating torches can often be used to advantage during disassembly to supplement the heat from the gas ring to attain rapid heating of the wheel. When this is done, use several torches and slowly and uniformly rotate the vertical assembly to ensure uniform heating of the wheel.

15. Assembly and disassembly of turbomachinery rotors can be performed in the field if equipment and facilities are available. However, the equipment needed and facilities required in the usual case can only be found in manufacturing or service shops.

As a matter of interest, the writer used the above data in a plant in England where, after we had trained the personnel and provided the equipment, they were able on their own to completely assemble new units and to disassemble, inspect, clean, and reassemble and balance rotors for a wide range of sizes.

Successful straightening of bent rotor shafts which are permanently warped has been practiced for the past forty or more years, the success generally depending on the character of the stresses which caused the shaft to bend.

In general, if the stresses causing the bend are inherent in character, resulting from improper forging, rolling, heat treating, thermal stress relieving, and/or machining operations, then the straightening will generally be only temporary in character and will generally be unsuccessful.

If, however, the forging, rolling, heat treating, stress relieving, and/or machining operations have been properly carried out and no inherent stresses remain and a bent shaft results from stresses set up by a heavy rub in operation—by unequal surface stresses set up by heavy shrink fits on the shaft,—by stresses set up by misalignment,—or by stresses set up by improper handling, then the straightening will generally be permanent in character and may be attempted with good chances of success.

Before attempting to straighten a shaft, first determine, if possible, how the bend was produced. If the bend was produced by an inherent stress, relieved during the machining operation; during heat proofing or on the first application of heat during the initial startup; or by vibration during shipment—then straightening should only be attempted as an emergency measure, with the chances of success open to serious question.

The first thing to do, therefore, is to carefully indicate the shaft and "map" the bend or bends to determine exactly where they occur and their magnitude. In transmitting this information, care should be taken to identify the readings as "actual" or "indicator" values. With this information, a knowledge of the shaft available, the method used for straightening can be selected.

For medium carbon steel shafts (carbon .30 to .50) three general methods of straightening the shaft are available. Shafts made of high alloy or stainless steel should not be straightened except on special instructions which can only be given for individual cases.

The PEENING METHOD used for straightening carbon steel shafts consists of peening the concave side of the bend at the bend. This method is generally the most satisfactory where shafts of small diameters are concerned—say shaft diameters of 4" or less. It is also the preferred—in many cases, the only—method of straightening shafts which are bent at the point where the shaft section is abruptly changed such as at fillets, ends of keyways, etc. By using a round end tool ground to about the same radius as the fillet and a 2½ lb. machinist's hammer, shafts which are bent in fillets can be straightened with hardly any marking on the shaft. Peening results in cold working of the metal, elongating the fibres surrounding the spot peened and setting up compression stresses which balance stresses in the opposite side of the shaft thereby straightening the shaft. The peening method is the preferred method of straightening shafts bent by heavy shrink stresses such as sometimes occur when shrinking turbine wheels on the shaft. Peening the shaft with a light (½ lb.) peening hammer near the wheel will often stress-relieve the shrink stresses causing the bend without setting up balancing stresses.

The HEATING METHOD used for straightening carbon steel shafts consists of applying heat to the convex side of the bend. This method is generally the most satisfactory where shafts of large diameters are concerned—say shaft diameters of 4½" or more. It is also the preferred method of straightening shafts of very large diameters or of straightening shafts where the bend occurs in a constant diameter portion of the shaft (say between wheels); but is generally not applicable for shafts of small diameter or if the bend occurs at a region of rapidly changing shaft section. Because this method partially utilizes the compressive stresses set up by the weight of the rotor, its application is limited and care must be taken to properly support the shaft.

The shaft bend should be mapped and the shaft placed horizontally with the convex side of the bend placed on top. The shaft should be supported so that the convex side of the bend will have the maximum possible compression stress available from the weight of the rotor. For this reason, shafts having bends beyond the journals should be supported in lathe centers. Shafts with bends between the journals can usually be supported in the journals; however, if the bend is close to the journal, it is preferable to support the shaft in centers so as to get the maximum possible compression stress at the convex side of the bend. *In no event should the shaft be supported horizontally with the high spot on top and the support directly under the bend as this will put tension stresses at the point to be heated and heating will generally permanently increase the bend.* Shafts can be

straightened by not utilizing the compressive stress due to the weight of the rotor but this method will be described later.

To straighten carbon steel shafts using the heating method, the shaft should be placed as outlined above and indicators placed on each side of the point to be heated. Heat should be quickly applied to a spot about two to three inches in diameter using a welding tip of an oxy-acetylene torch. Heat should be applied evenly and steadily carefully watching the indicators until the bend in the shaft has about tripled its previous value. This may only require perhaps 3 to 30 seconds, so that care must be taken to closely observe the indicators. The shaft should then be evenly cooled and indicated. If the bend has been reduced, repeat the procedure until the shaft has been straightened. If, however, no progress has been made, increase the heat bend as determined by the indicators in steps of about .010" to .020" or until the shaft spot heated approaches a cherry red. If results are not obtained on the third or fourth try, using heat, a different method must be substituted.

The action of heat applied to straighten shafts as described above is that the fibres surrounding the heated spot are placed in compression by the weight of the rotor; the compression due to the expansion; and the resistance of the other fibres in the shaft. As the metal is heated, its compressive strength decreases so that ultimately the metal in the heated spot is given a permanent compression set. This makes the fibres on this side shorter and by tension they counterbalance tension stresses on the opposite side of the shaft thereby straightening it.

The HEATING AND COOLING method of straightening shafts is especially applicable to large shafts, which cannot be supported so as to get appreciable compression stresses at the point of the bend. This method consists of applying extreme cold (say, using dry ice) on the convex side of a bend and then quickly heating the concave side of the bend. This method is especially applicable to straightening shaft ends beyond the journals or of large vertical shafts which are bent anywhere.

The action is that the shaft side having the long fibres is artificially contracted by the application of cold. Then this sets up a tension stress in the fibres on the opposite side which, when heated, lose their strength and are elongated at the point heated. This sets up compression stresses in the concave side which balance the compression stresses in the opposite side. Indicators should also be used for this method of shaft straightening,—first bending the shaft in the opposite direction from the initial bend, about twice the amount of the initial bend,—by using dry ice on the convex side,—and then quickly applying heat with an oxy-acetylene torch to a small spot on the concave side.

Various shafts of turbines and turbine-generator units have been successfully straightened using one method or another of straightening. These include several 5000 KW turbine-generator units, one 6000 KW unit, and many smaller units. Other manufacturers of turbines and other equipment have long used these straightening procedures. The same procedures have also been used by the U.S. Navy and other users to straighten shafts. With sufficient care, a shaft may be straightened to .0005" or less, (.001" indicator reading). This is generally satisfactory.

RESTORING WORN, ERODED AND/OR CORRODED SHAFTS ON TURBOMACHINERY

Wear in machine parts is reduced by proper design, proper operating procedures, and proper preventative maintenance. In spite of this, certain parts on turbines and associated high speed rotating machinery shafts such as journal surfaces, packing ring surfaces, etc., may become worn, scored, eroded, and/or corroded to such a degree that refinishing of the surfaces is the only alternative to renewal of the shaft in order to restore the unit to a normal serviceable condition.

Within limits, these journal or packing ring surfaces of shafts can be refinished to a good surface by turning down and grinding to a good finish; but this immediately introduces the requirement of special odd-size bearings and/or shaft sealing rings, not generally carried in the machine builder's stock. Such special odd-size renewal parts are more costly than standard size parts—and in general cannot be furnished by the machine builder except on a long term shipping basis. For these reasons the turning down of shaft journals or packing ring surfaces is not recommended except in an extreme emergency.

Fusion or braze welding cannot safely be resorted to to restore these worn or scored shaft surfaces to their original dimensions because of the possibility of shaft warpage. New shafts, even if separate from the other parts of the rotor, present problems in field disassembly and assembly, requiring specially skilled personnel and equipment. In addition, in many of these units the shaft is integral with the rotor, hence obtaining a replacement shaft is extremely costly and may be prohibitive from an outage time standpoint.

The progress in the art of metal spraying within the past forty years has made it possible to safely and quickly restore these worn or scored shaft surfaces to their original dimensions, and this alone is perhaps the greatest single factor in reducing maintenance and repair costs of this class of equipment. Moreover, since most of these shafts are of ordinary carbon or alloy steel and are subject to corrosion and/or abrasion at the journal and packing ring surfaces, metal spraying of these surfaces with an abrasion- and corrosion-resisting metal may result in a restored shaft which is superior to the original shaft. In fact, many rotors are now built with the packing surfaces metal-sprayed with a hard stainless steel to eliminate corrosion and reduce abrasion at these surfaces.

To better understand the useful applications and limitations of sprayed metal, it is necessary to briefly examine its structure. Sprayed metal consists of tiny laminar particles joined together and to the parent metal by interlocking and oxide cementation. The surface of the parent metal must, therefore, be prepared in such a way that it is covered with tiny anchorages into which the laminar particles can interlock themselves. The surface must also be free of rust, dirt, oil, grease, etc.

Sprayed metal is inherently more porous than the usual forms of the same metal and, therefore, minimum thickness coatings are required to make them impervious to moisture and corrosive agents which might attack the parent metal. The minimum thickness for packing surfaces on rotor shafts is approximately .030".

The porosity of sprayed metal reduces its resistance to indentation but its abrasion-resistance is generally

greater than the same metal in the usual forms. This makes it particularly applicable for packing and journal surfaces. Similarly, it is not suitable for applications under concentrated or very high compressive stress intensity as would occur on cams or cam rollers or on turbine shafts under the turbine wheels. Also, in general, metalizing is not recommended for applications under more moderate compressive stress—but which are required to transmit torque. Therefore, it is not to be used to build up shafts or couplings to restore coupling fits or under gears or pinions to restore those fits.

Under special circumstances, metalizing may be used to restore shafts under light anti-friction bearing fits; but it is usually simpler and generally more satisfactory to use chrome plating for this purpose as the amount to be built up is usually only of the order of a few thousandths on the radius. Chrome plating is, therefore, the recommended method to be used for building up shafts, couplings, turbine wheels, or blower impellers to restore fits; PROVIDED that the plated surfaces are accurately ground to size; and FURTHER PROVIDED that the final ground size radial thickness of the chrome plating does not exceed .007" to .010". Chrome plating for radial thickness in excess of these may require multiple chrome plating operations at, say, .015" steps with intermediate grinding operations. This extends the time of chrome plating and should be investigated before any chrome plating is attempted.

Chrome plating may also be used to restore journal or packing surfaces to original size provided that the wear or abrasion or erosion is limited so that the chrome plate does not exceed the limit of .007" to .010" radial depth.

The reason for limiting the radial thickness of chrome plating is because if heavy plating is attempted the end junction of the plating will usually result in a "V" notch. Although this is of no serious engineering consequence, many customers and insurance inspectors will raise objections based on the appearance of this "V" notch.

A way of minimizing this "V" notch effect is to join the bottom of the underground surface to the shaft surface with a double fillet. This, however, extends the length of the chrome plated area; and this must be checked if there are any vibration pickups in the area of chrome plate. We recently had a case where the shaft was chrome plated under the pickup which was unknown at the time and showed runouts of .0025" at 12 rpm, .0025" at 1200 rpm, and .0025" at 12,000 rpm. We were unable to explain this until the chrome plate was discovered.

Therefore, the principal application of metalizing on turbines and associated rotating machinery is for building up and restoring to original size, packing and journal surfaces which have been worn or abraded beyond the limits for successful application of chrome plate. This can be done but the rotor must be moved to a shop equipped with metal spraying, turning, and grinding equipment. Assuming that the shop has adequate equipment and a skilled spray gun operator, the TWO FACTORS MORE RESPONSIBLE FOR A SUCCESSFUL METALIZING JOB ARE PROPER PREPARATION OF THE SURFACE AND KEEPING THE SURFACE CLEAN AFTER IT IS PREPARED. In humid atmospheres, the metal spraying should be done immediately

after the surface is prepared. In certain instances metalizing troubles have developed by permitting the prepared surface to stand for a matter of several hours before metalizing. Even finger marks on a prepared surface have resulted in faulty jobs. Therefore, the requirement for cleanliness cannot be emphasized too strongly. Here again, be careful to investigate whether or not there are vibration pickups in the area of the metalizing. We have no direct experience on how much this would affect the readings, but, if possible, move the vibration pickups so that they are at least $\frac{1}{8}$ " axially from the metalized or chrome plated area.

To prepare the shaft, undercut the surface to be metalized to a minimum of .030" radial depth, extending the undercutting approximately $\frac{3}{8}$ " beyond both ends of the wearing surface. Be sure, however, the undercutting does not extend out to the end of a shaft shoulder as a free metalized end is to be avoided. Originally the ends of the undercutting were dovetailed, but recent experience has indicated that the undercutting may not be filled underneath with sprayed metal and as such any dovetailing should be at a very slight angle—not over 20° . The corner of the undercutting should not be sharp but should have a slight fillet.

A rough thread should then be chased in the undercut portion, being careful that the thread stops and starts at least $\frac{1}{32}$ " from the end of the undercutting. This is to avoid a thread in the corner of the undercutting which may be difficult to fill with metal spray. The cutting of the thread should be done in one traverse and should be just the opposite of good thread chasing practice so as to obtain a dragged and torn surface instead of a clean-cut surface. Thread size should be about 16 threads per inch and the tool should be round end instead of sharp end. No lubricant should be used for the threading and the knurling operations.

After the thread has been chased, a knurling tool should be very lightly run over the ends of the thread in the opposite traverse from the thread. This is to remove burrs extending above the top of the thread and thereby prevent lumps in the final metal spray. The knurling tool can very lightly turn over the tips of the thread to provide additional anchorages, but care must be exercised to keep this turned-over portion not over .015"; otherwise, voids may be formed under these overhanging edges.

The shaft is now ready to metalize, and the following materials are recommended for packing surfaces:

Metco No. 2 — Metalizing Engineering Company, Long Island City, New York

Stainless No. 2—Metalizing Company of America, Chicago, Illinois

For bearing journal surfaces, the following materials are recommended:

Spraysteel 10 or 25—Metalizing Engineering Company, Long Island City, New York

Mild carbon steel—About .10 or .25 carbon

The metalizing should be started at once to avoid any rusting starting on the surface of the prepared metal. First, spray the fillets at both ends of the undercut using a surface speed of about 35 feet per minute and with the

gun at about 5" from the work—angling the gun about 30° at each end to insure filling up the end with metal spray. When both ends are completed, the metal can be sprayed on the undercut portion using the tool post to hold the gun. The traverse should be arranged to deposit about .010" of metal for each pass and the traverse reversed each time. The metal should be built up approximately .020" over the desired radius and then finish-ground to size.

A recent development in preparing the surface for metalizing involves the use of a special metal spraying material having the trade name of "Spray Bond." We have no direct experience with "Spray Bond," but any shop specializing in metalizing can no doubt give complete information on this process.

The above general notes are intended to cover only the application where metalizing is recommended and to give a brief description of the technique. The work should be done only in shops which have considerable experience in metalizing. Both of the companies named above have offices in the principal cities and can no doubt give data on reliable shops nearby.

Complete handbooks on methods of preparing shafts, metalizing, and machining the metalized shafts, and characteristics of sprayed metal, can be purchased from both companies named earlier.

Where an insurance carrier is involved, it is advisable to consult the insurance carrier before any work of this nature is attempted. In general, insurance carriers will approve metalizing; but specific cases should always be brought to their attention before the work has been done.

OTHER ROTOR REPAIRS

Other rotor repairs such as cracks in welded centrifugal impellers, blade cracks in turbine or axial flow impellers, erosion and/or corrosion wear in general require new impellers, new blades, etc. Unless spare rotors or spare wheels are available, this generally requires repairs at the factory or at an authorized service shop in the local area.

In some cases, minor cracks in welded impellers can be repair welded with appropriate heat treatment subsequent to welding. Here again this requires special knowledge and facilities usually only available at the factory or at an authorized service shop.

If the "turnaround" sequence has been established by the results of previous inspections, it is usually possible to have the long-term items available usually at the local service shop so that rotor repairs can be completed without undue delay. In the event that spare rotors are provided, the rotor to be repaired can be done in normal sequence to be ready for the next scheduled turnaround in case it is needed.

STATOR REPAIRS

Stator repairs are usually associated with erosion and/or corrosion or from failures resulting from improper installation, operation and repair, or faulty handling.

For stator repairs, it is difficult to generalize as conditions vary over a wide range. We will, therefore,

only include what might be called emergency repairs to stator parts such as fractured diaphragms and/or casings. These have on occasions been repaired by Metalock, but this requires a Metalock expert. In some cases where steel parts are involved, welding to a degree might be employed. Actually for fractures, specific repair techniques can only be specified after a study of the actual failure.

CASE STUDIES

Erosion and/or Corrosion—a defense plant built during World War II had several extraction turbines. These units performed well during the war; but when the plant was shut down at the war's end, the Defense Plant required a complete inspection of the turbines before returning the plant to the government.

The complete inspection including internal inspection showed that the condition of the turbines was almost in an "as new" condition.

Some time later the plant was sold to another operator who ran the plant for about three months after which the units were opened up and inspected. In that three-months' period, excessive erosion and/or corrosion took place to the extent that about $\frac{1}{4}$ " diameter holes were across the internal horizontal split at the extraction diaphragm. Other similar severe erosion and/or corrosion occurred in the casing in the diaphragms. The casing was repaired using stainless steel strips fastened to the inside of the case to cover over the eroded and/or corroded areas—and to give backing to the diaphragm supports in the casing. The damaged diaphragms had to be replaced and, ironically as I recall, there was no serious damage to the blading although they did show some erosion and/or corrosion.

The final explanation was that the new owner when he took over the plant installed a completely different feedwater treatment from what had been previously applied.

The background in this case is very clear; but had the severe erosion and/or corrosion occurred in the initial operation of the plant, I am certain the case would not have been as clear even though the materials employed on these turbines were the standard materials used in practically all steam turbines of this class.

Improper Installation—this particular case involved the thrust bearing of a steam turbine which failed every Monday morning at about 8:00 A.M. What brought up the case was that in this particular sugar mill originally there had been two foreign turbines installed which had performed very well—with no thrust bearing or other problems. The third turbine, a domestic-made unit, was installed taking steam from the same header as the original two turbines; and almost immediately thrust failures on the new turbine were experienced. Also almost immediately, it was proclaimed that the thrust bearing design was inadequate.

A careful examination of the steam piping layout (Figure 5.) (after about the fourth failure) showed first how the thrust bearing on the domestic unit could be overloaded, and second why this occurred at about 8:00 A.M. every Monday morning.

As stated above, this installation was in a sugar mill which shut down over the week ends at which time sugar syrup leaked into the condensate system in evaporators, heaters, etc. The mill was started up each Monday morning, and it apparently took about an hour for the condensate containing sugar syrup to be pumped to the boiler. Severe foaming occurred and water was forced over into the steam lines.

A careful inspection of the piping shows that that portion of steam going to the domestic unit carried the water direct to the turbine; but that on the two foreign units, the steam carrying the water went straight to the mill without making the sharp turns to get to the foreign turbines.

The obvious correction was the insertion of the knockout drum directly in line with the downcomer from the boiler—and equipping this drum with two large traps. This customer has never suffered a thrust bearing failure from that date.

As a further comment to this, I could cite other cases where similar conditions existed—all of which led to trouble.

Improper Operation—this case involves an ethylene plant where the charge gas unit consisted of compressor bodies in cascade with an iso-cooled section in the last

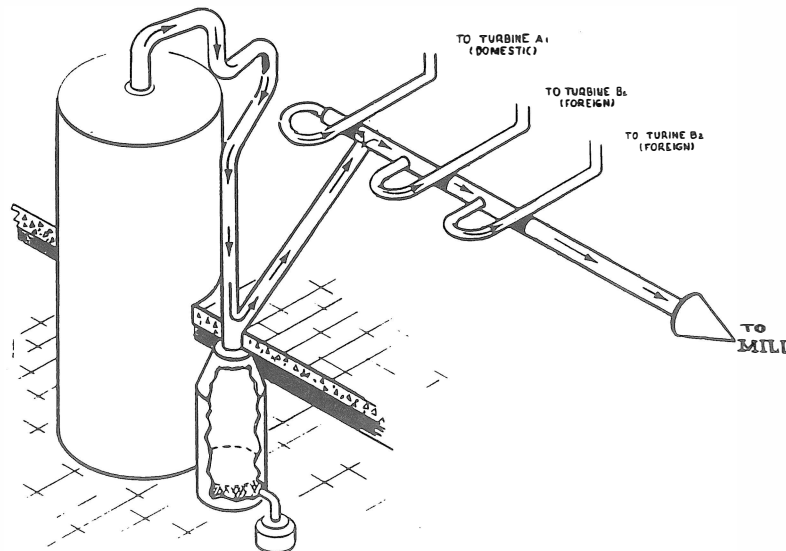


Figure 5. Steam Piping Layout.

body. A check valve was in the line from the last body iso-cooler discharge leading to the gas cooler, and on trip-out the check valve would close. If the unit was caught before the speed had decayed too much, it could be brought back on the line with little or no distress.

If, however, it was impossible to bring the unit back on the line, the speed would decay to 0 rpm. The pressure downstream of the check valve would be maintained at about full discharge pressure while the pressure upstream from the check valve would decay rapidly to about the suction pressure of the first body.

This resulted in two things. First, the differential pressure across the balance piston would increase materially, and the normal upstream thrust would approach bearing would far exceed its capabilities and would fail on the attempted startup. The reason for this failure was that the customer had insisted on a fixed taper land thrust for the inactive side. Many people are of the opinion that a fixed taper land bearing has about the same capacity as a tilting pad thrust bearing, and this is true—at design speed. However, a tilting pad can adjust for changes in speed whereas a fixed taper land bearing cannot. Resultingly a tilting pad bearing was installed, and this problem eliminated.

Another problem resulted on this same machine. The artificially high differential pressure across the iso-cooled diaphragm resulted in diaphragm failure. This was corrected by a steel diaphragm. This should not be construed as a design error as the maximum pressure differential for the diaphragm was known but no one considered the trip-out operation. I suggest that this case might also be labeled improper installation.

Improper or Faulty Maintenance or Repair — off hand, I can only refer to missing set screws or failure to tighten nuts in this category. Actually, the fact that no serious failures can be shown in this category points to the fact that most maintenance mechanics are careful workmen.

The above case studies, which could be practically duplicated many times, should clearly indicate why the variable factors between successful and unsuccessful installations should be carefully investigated before any "scheduled" repair work is attempted. Also we would like to point out that the deficiencies were in general quite simple—and the corrections in some of these cases were also quite simple.

BALANCING ROTORS

We will not go into the details of balancing rotors except to state that all elements of a rotor should first be balanced individually—and then fully assembled; and the assembled rotor balanced in three planes.

The residual dynamic imbalance should be corrected at the ends of the rotor, and the remaining residual static imbalance should be corrected at about the middle of the rotor.

Most manufacturers today give allowable limits for residual imbalance. Here is a simple expression developed from $CF = Mr\omega^2$ in case it is not specified.

Residual unbalance in inch ounces for 20% gravity is

$$\text{Inch Ounces} = \left(\frac{.1125}{\frac{N}{1000}} \right)^2 \times W$$

where N is Maximum Normal RPM of rotor and W is rotor weight in pounds.

Incremental balancing of a rotor after all the parts have been individual balanced is not recommended because of the well-known fact that the true center of the rotor moves about in a random fashion as heavy shrunk wheels are assembled on the shaft. If it were not for the random movement of the true center, an assembled rotor would not require any balance correction. Experience shows this is not so, so with incremental balancing of wheels as they are assembled—the first one may move toward, say, 12:00 so that metal must be taken off at 12:00. When the next wheel is shrunk on, the whole shaft may move toward 6:00; so now the balancing done on the preceding wheel must be counter-balanced on the second wheel, remembering that after a wheel is balanced no further balancing is permitted on it. This can only result in couples which certainly make this method open to question.

CONCLUSION

The basic repair techniques apply largely to disassembly and assembly of turbomachinery units and to disassembly and assembly of turbomachinery rotors. The assembly of seals, thrust bearings, etc., must follow the manufacturer's instructions. You will note that we have to a degree downgraded experience. This is because an experienced man is more likely TO NOT FOLLOW laid down techniques than a completely inexperienced man who has no way to go except to implicitly follow written techniques.

The best proof of this we have is that an inexperienced group recently assembled a rather complex compressor assembly and did a remarkable job. The instructions given to this group were substantially the data herein. We would have trouble in duplicating their workmanship.

It is not the purpose of these notes to train maintenance men to repair turbomachinery although these notes were originally made up for this purpose. Our purpose is to outline these repairs to acquaint operating people of what can be done if repairs become necessary for any reason and how these repairs can be properly handled. The most important point, in my judgment, is if excessive maintenance costs are encountered—don't start out by replacing these parts until the reasons for the failure of these parts has been determined.

The basic philosophy is "correct the cause if at all possible—do not attempt to minimize the effect."