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VOLUME 2-1

ALIGNMENT OF VERTICAL SHAFT HYDROUNITS

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UNITED STATES DEPARTMENT OF THE INTERIOR
BUREAU OF RECLAMATION
DENVER, COLORADO

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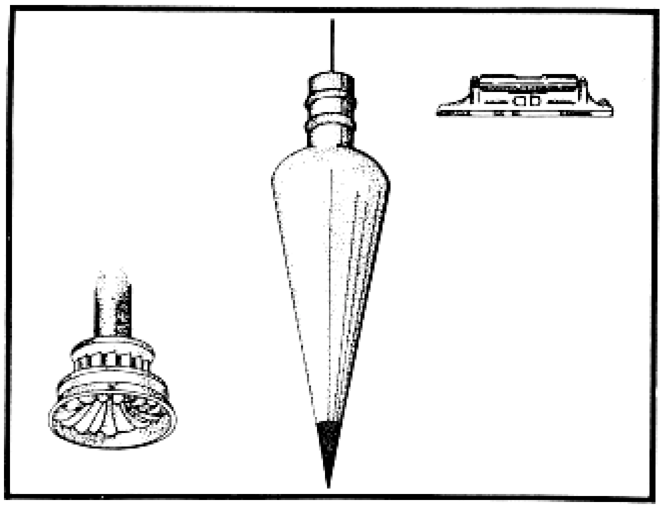

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VERTICAL SHAFT HYDROUNIT ALIGNMENT

1. INTRODUCTION

The proper alignment of a vertical shaft hydrounit is critical to trouble free operation. A misaligned unit cannot only cause the premature failure of bearings, but through excessive vibration, cause wear and stress on other machine components as well. Unscheduled outages caused by misalignment can, in most cases, be avoided if the machinery is aligned correctly initially. The purpose of this document is to provide the reader with enough information to align a vertical shaft hydrounit within acceptable limits.

2. VERTICAL SHAFT HYDROUNITS DESCRIPTION

To better understand the alignment process, it is important to understand the basic construction of vertical shaft hydrounits. Figure 1 shows a typical vertical shaft hydroelectric unit as found in Bureau of Reclamation powerplants. There is a thrust bearing located above the generator rotor, upper and lower generator guide bearings, and a turbine guide bearing. The rotating weight of the unit is transferred through the thrust bearing, through the upper bridge, and through the stator frame to the foundation. The lower bridge supports the lower generator guide bearing and must

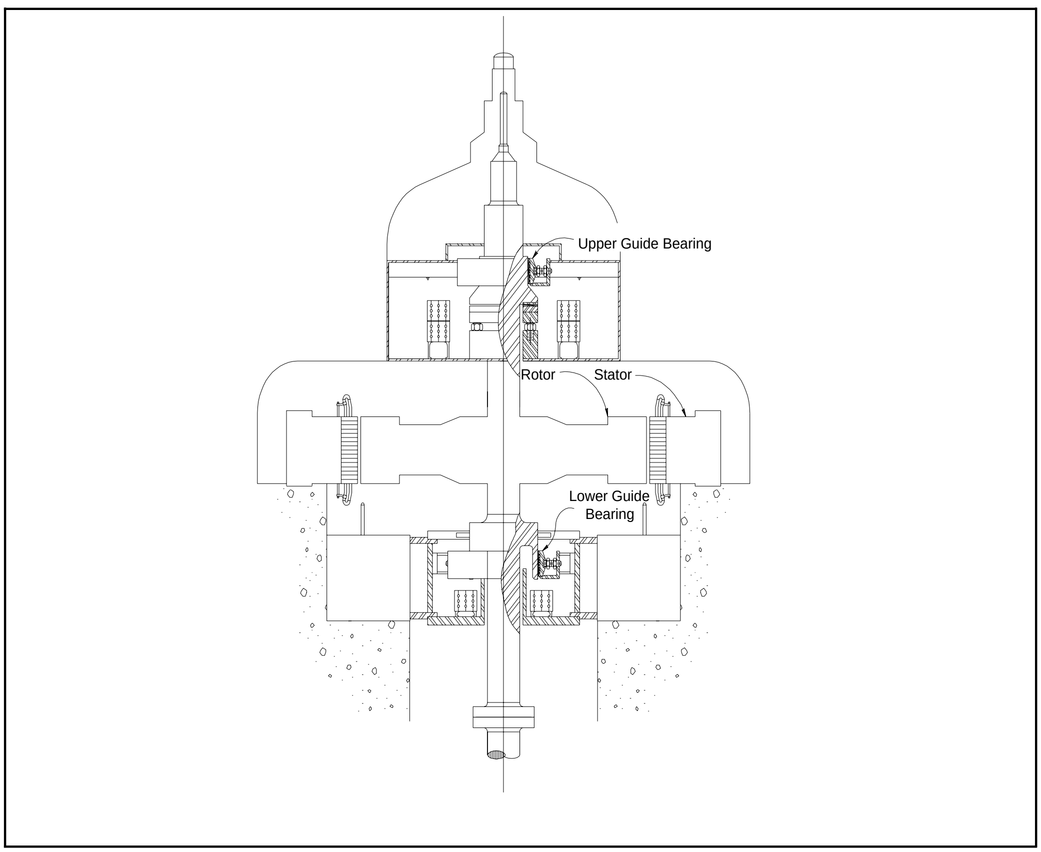


Figure 1.—Typical hydroelectric unit.

also be capable of supporting the weight of the unit when it is supported by the jacks. Figure 2 shows an umbrella unit, where the thrust bearing is located below the rotor. In the umbrella unit, the rotating weight is transferred to the foundation through the lower bridge. The jacks are also attached to the lower bridge. The upper bridge supports only the deck plates and the upper guide bearing, if there is one. Both figures 1 and 2 are very general sketches of hydrounits, and while most vertical units will resemble one of the figures, the specific construction and design details vary between manufacturers. Understanding these design details, particularly the bearing designs, is critical in developing a working alignment procedure. Listed below are descriptions of some of the components most closely associated with the unit alignment.

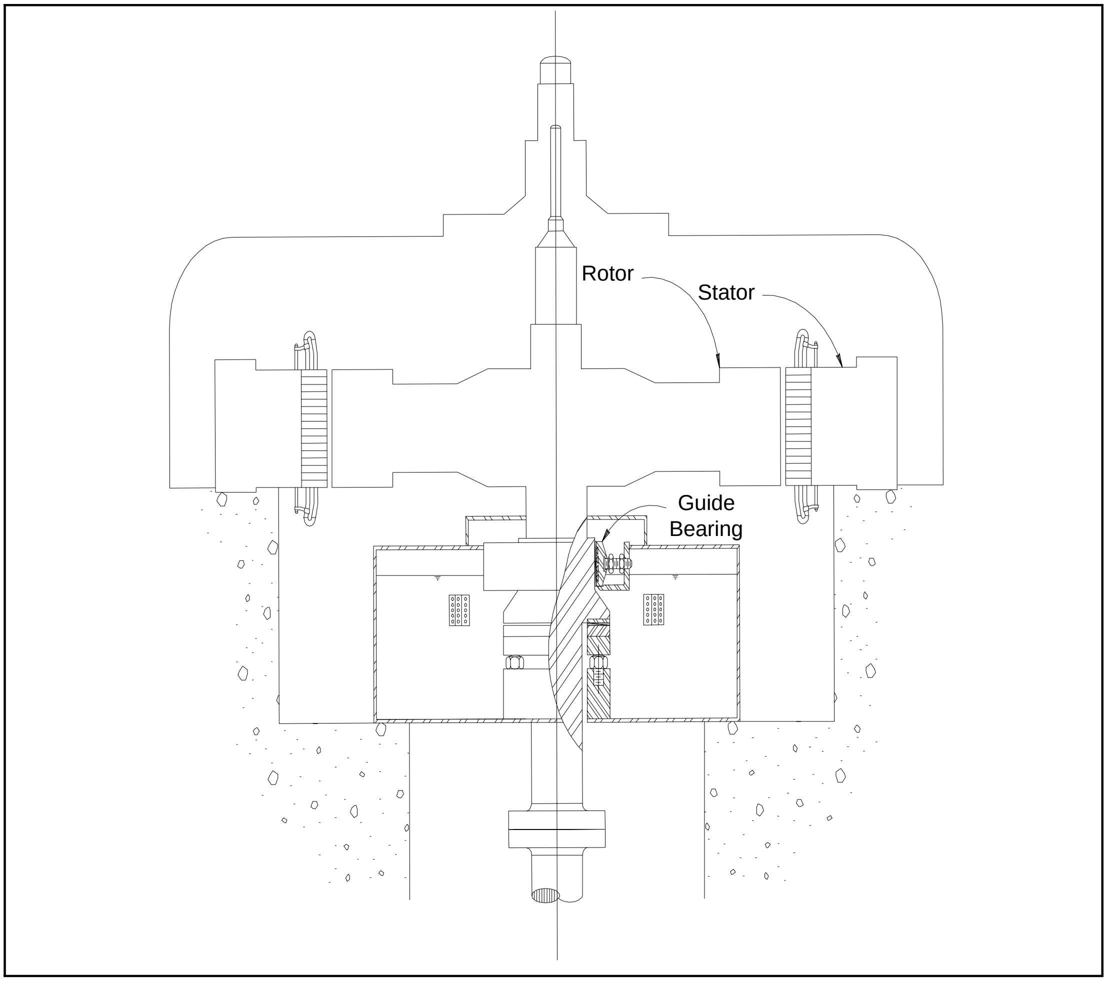


Figure 2.—Umbrella unit.

2.1 Thrust Bearings

Thrust bearings support the axial load on a rotating shaft. On a vertical shaft hydrounit, the thrust bearing supports the entire rotating weight of the unit, as well as any hydraulic down thrust from the turbine. There are typically three types of thrust bearings used in hydroelectric units: the adjustable shoe, the spring loaded bearing, and the self equalizing. To the casual observer, all three bearing types would look very similar. All three use babbitt lined, pie shaped bearing shoes that are tiltable to allow a wedge of oil to form automatically between the shoes and the thrust runner. The differences lie in the supporting structure for the bearing shoes.

The adjustable shoe thrust bearing uses a jack screw under each of the shoes for adjusting the height and loading of the shoes. Figure 3 illustrates the basic components. A pivot point on top of each of the jack screws allows the shoe to pivot freely and form the required oil wedge.

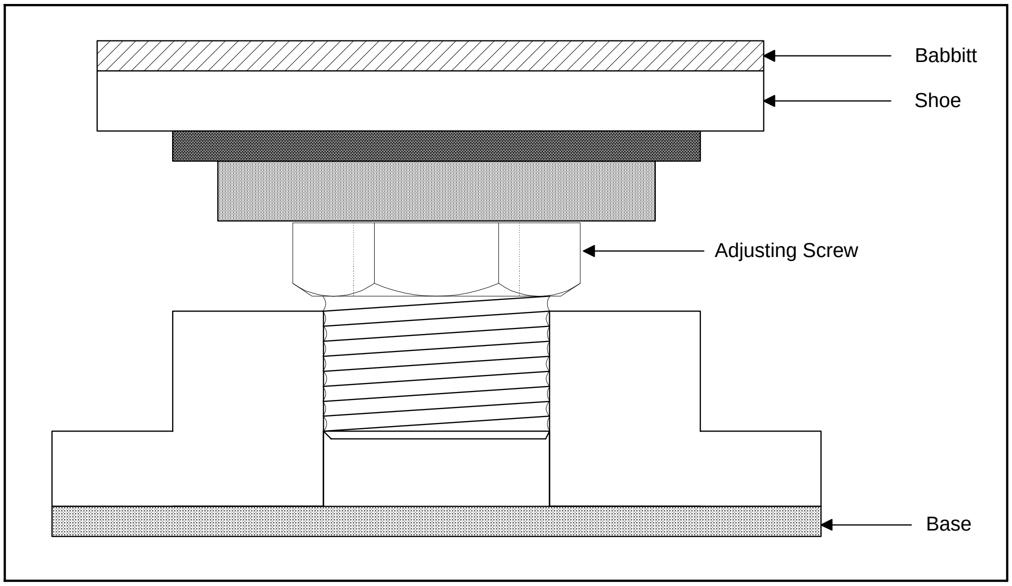


Figure 3.—Adjustable shoe thrust bearing.

The spring loaded thrust bearing consists of the bearing shoes supported by a number of coil springs on the baseplate, as shown in figure 4. The springs are usually preloaded to a point that there is very little deflection with the static weight of the rotating parts that they support. With the addition of the hydraulic down thrust of the turbine, the springs will deflect to equalize the load between shoes. A variation of this design uses a single Belleville washer or conical spring under each shoe, rather than multiple coil springs.

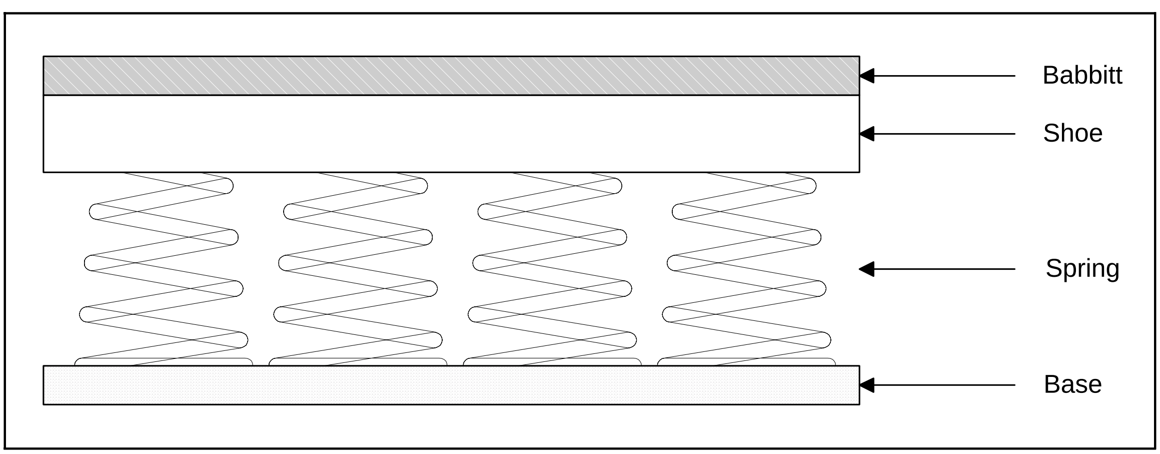


Figure 4.—Spring loaded thrust bearing.

The self equalizing bearing, as the name implies, is designed to automatically equalize the load between bearing shoes. Figure 5 is a simplified sketch of a self equalizing bearing. The bearings consist of the bearing shoes, upper leveling plates, and lower leveling plates. The lower leveling plates rest on the baseplate on blunt pivot points that allow them to rock slightly. The upper leveling plates are each supported by two of the lower leveling plates. The bearing shoes are mounted on top of the upper leveling plates and are free to pivot as necessary to form the oil wedge. As can be seen in the figure, if one shoe is forced down due to higher loading, the lower leveling plates on each side of the depressed shoe will tilt slightly, lifting the shoes on either side of the depressed shoe. This action allows the self equalizing bearing to maintain equal loading on all shoes even with slight inaccuracies in shoe thickness or alignment.

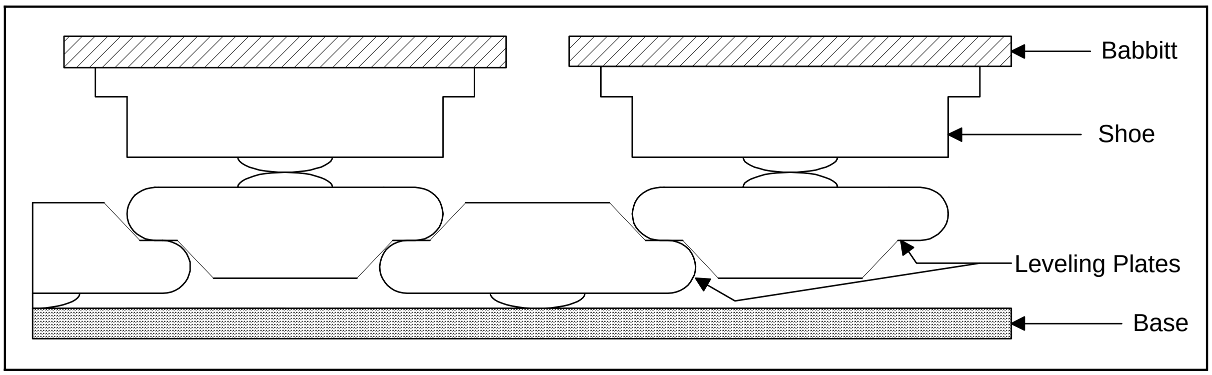


Figure 5.—Self equalizing thrust bearings.

There are other less common type thrust bearing designs in use. The shoes of the semi-rigid thrust bearing (figure 6) are designed with a pivot and rest on a layer of insulation. The insulation is slightly compressible to provide some load equalization between shoes, similar to the spring loaded bearing.

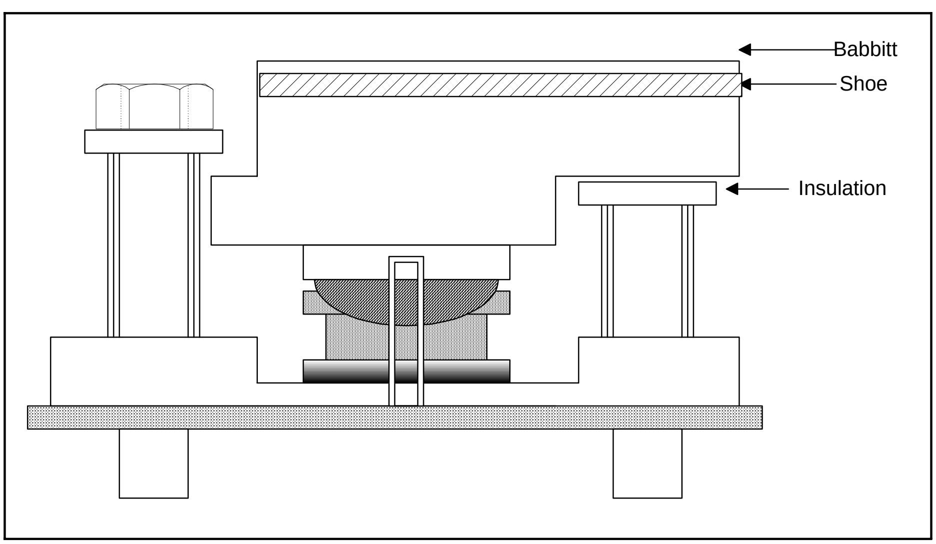


Figure 6.—Semi-rigid thrust bearing.

Another type of thrust bearing occasionally found in older units uses a plate rather than separate bearing shoes. The plate is usually babbitt lined and has radial oil grooves machined in the plate to give an appearance similar to segmented shoes. The plate may be attached directly to the baseplate with bevels machined into the plate to help form the oil wedge. The plate also may be made fairly flexible and set on a bed of springs. In this case, the plate flexes slightly to help create the oil wedge.

2.2 Thrust Block

The rotating components of a thrust bearing are the thrust block and runner. In most cases the thrust block and thrust runner are separate parts. The thrust block is usually a shrink fit onto the shaft and the runner is bolted or doweled to the block. On umbrella units, the thrust block is usually an integral part of the shaft, while the thrust runner is split into two pieces. The bottom surface of the runner is highly polished to provide a mating surface for the bearing shoes. In some instances, the outer diameter of the thrust runner is also polished to provide a bearing surface for a guide bearing. The purpose of the separate runner is to provide a replaceable component in the event it is damaged when a bearing fails.

There are a number of thrust block designs, but the most common is shown in figure 7. The block is keyed to the shaft with an axial key and held onto the shaft with a split radial key. A solid keeper is usually placed over the radial keys to hold them in place. When removing this type of thrust block, the unit jacks are used to raise the generator rotor high enough to remove the weight from the thrust block. Then, depending on the design of the jacks, the jacks are locked in position, or blocks are installed to prevent the rotor from drifting down. The thrust block is then heated quickly using large propane torches or large "rosebud" type oxyacetylene torches. When the block is expanded sufficiently for removal, it will drop slightly, allowing the radial keys to be removed. The block can then be lifted off of the shaft. To install the thrust block, it is heated to a predetermined temperature and lowered over the shaft, again with the unit on the jacks. The block is set on the thrust shoes, the rigging removed, and the radial keys and keeper installed. With the block still hot, the jacks are released to allow the full weight of the unit to set the block in place against the keys.

Another type of thrust block found on Reclamation units is shown in figure 8. Like the previously described thrust block, an axial key is used between the block and the shaft, but with this type, the block is held to the shaft using a series of radial clamping keys. The keys clamp the block to a shoulder on the shaft. To remove this type of block, the unit is lifted and blocked on the jacks, the clamping keys unbolted, and rigging to lift the block is attached. Before heating, a slight amount of tension is placed on the rigging so that the block will pop up slightly when it is loose. A crane scale should be used to prevent overloading the rigging. To install the block, it is heated to a predetermined temperature and lowered onto the shaft until it sets on the ledge on the shaft. The unit must be on jacks and high enough to allow the thrust block to reach the ledge. The keys are then installed and the bolts torqued according to the manufacturers instructions.

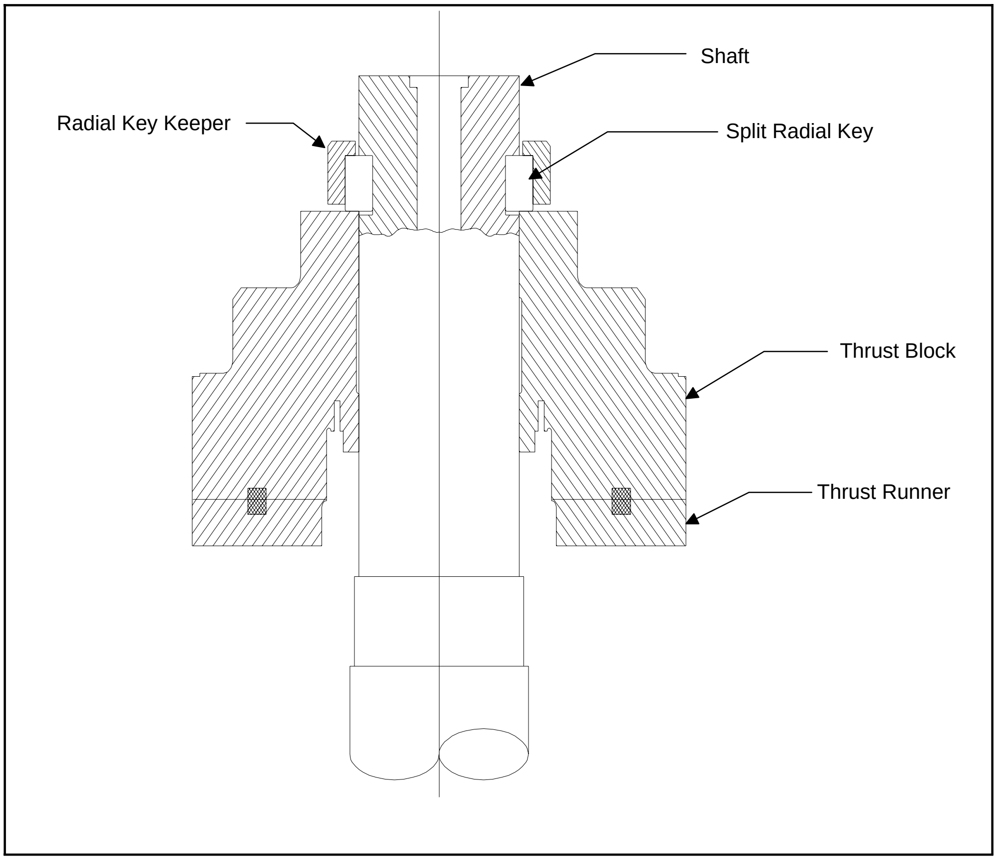


Figure 7.—Thrust block.

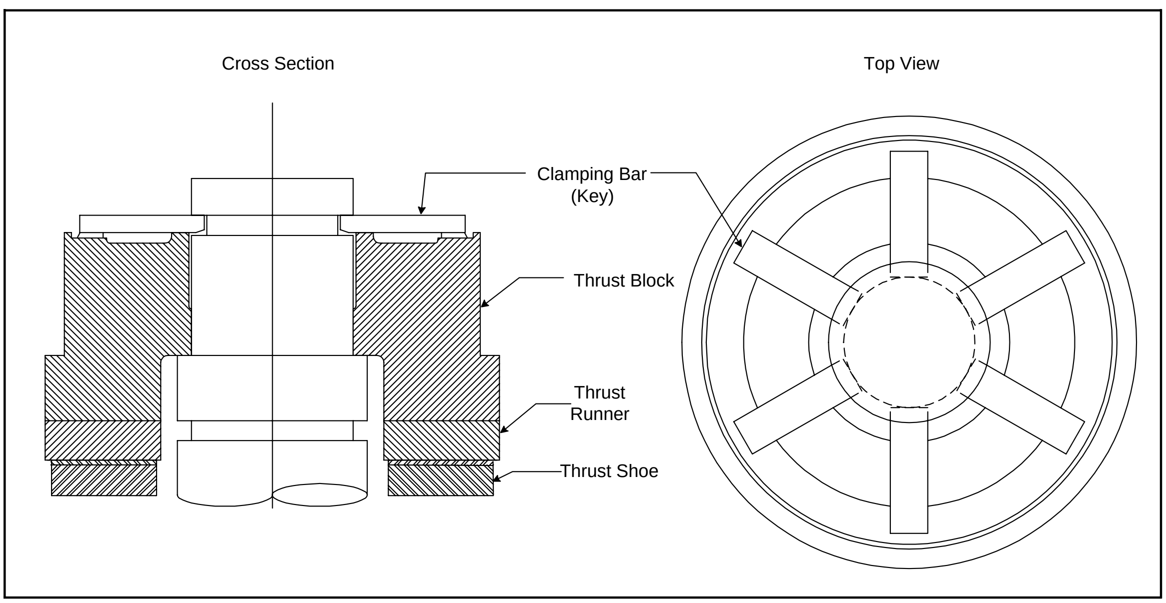


Figure 8.—Thrust block with clamping bars.

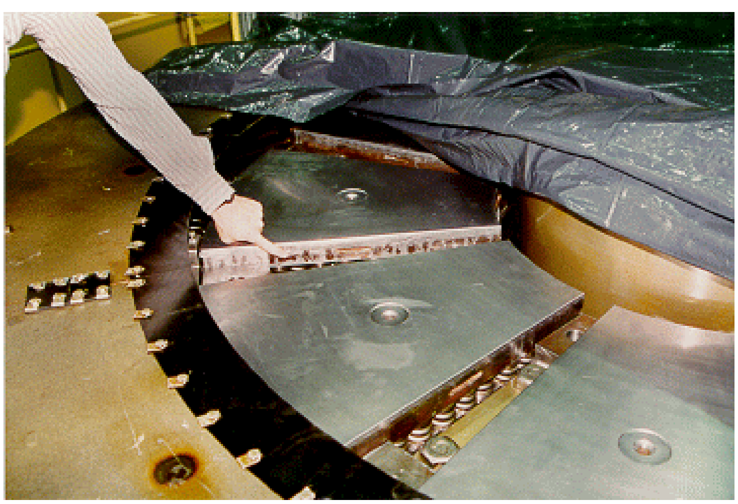
2.3 Thrust Bearing High Pressure Lubrication System

The thrust bearing high pressure lubrication system provides high pressure oil between the thrust shoes and the runner to provide lubrication on start-up and shut-down of a unit. The oil is pumped from the bearing oil pot by a high pressure pump, through a manifold to a port machined in each of the shoes. Photograph 1 shows a typical oil ring on a thrust shoe for a high pressure lubrication system. The primary use for the high pressure lubrication system is to reduce friction during start-up and shut down, but it is also a very useful system during alignment. With the system on, it is possible for a couple of people to rotate a unit by hand or move the rotating components laterally on the thrust bearing. Both rotation and lateral movement are required during the alignment process, which will be discussed later in this document.

2.4 Guide Bearings

Guide bearings support the shaft radially and help hold the shaft in alignment. Ideally, the guide bearings in a vertical shaft unit should be very lightly loaded. In reality, due to imperfect alignment, unbalance, hydraulic forces from the turbine, and other factors, the guide bearings can see significant loads. The designs of guide bearings vary a great deal. The bearing surface is usually babbitt, but there are older units that use water lubricated lignum vitae, a hardwood, or high density polyethylene bearings. The bearing may be a sleeve type journal bearing or a segmented shoe design. The turbine bearing is nearly always a sleeve type journal bearing with a cast steel shell (figure 9). The axial length of a turbine bearing is usually greater than its diameter. Turbine bearings are typically lubricated by an auxiliary pump that pumps oil to the top of the bearing and the oil flows by gravity through the bearing. The turbine bearing may be held in place in the turbine bearing housing by dowels or with a tapered fit allowing very little or no adjustment.

The generator guide bearings may be a sleeve type journal bearing or may be made up of segmented shoes (figure 10). The axial length of the bearing is usually less than the diameter.



Photograph 1.—Thrust bearing high pressure lubrication port.

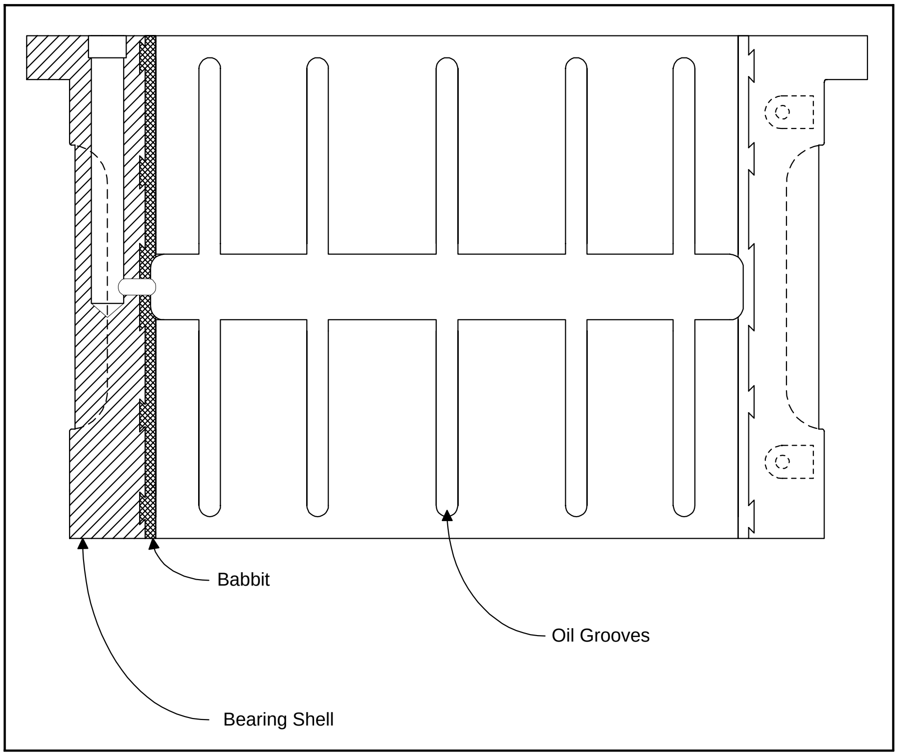


Figure 9.—Typical turbine guide bearing.

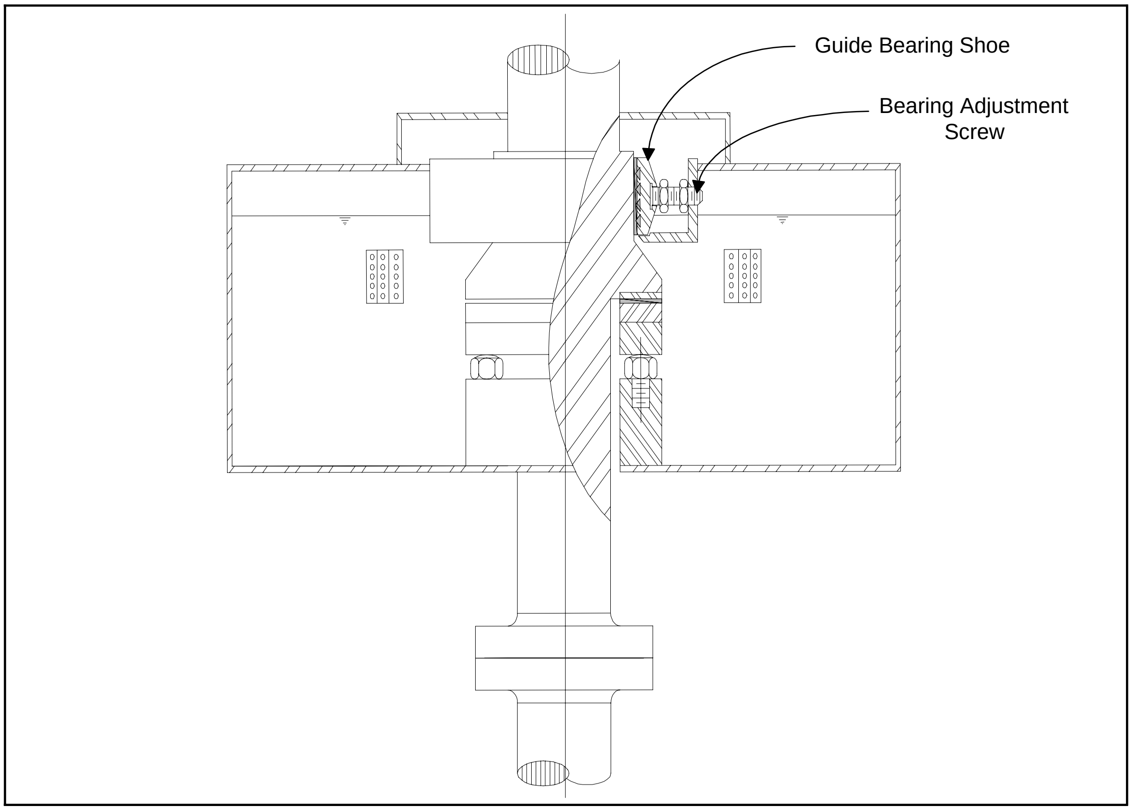


Figure 10.—Typical segmented shoe guide bearing.

The segmented shoe type bearings are adjustable to allow adjusting the bearing clearance and the position of the center of the bearing. The sleeve type journal hearing may be doweled in place, or the bearing shell may be a tight fit in the upper or lower bridge. Both the sleeve type and the segmented shoe bearings used on generators are partially submerged in an oil bath and lubricate through the rotation of the shaft.

3. OBJECTIVES OF VERTICAL SHAFT ALIGNMENT

In a perfectly aligned vertical shaft hydrounit, all the rotating components would be perfectly plumb and perfectly centered in the stationary components at any rotational position. The thrust bearing shoes would be level, with each shoe equally loaded and the thrust runner would be perfectly perpendicular to the shaft. As the shaft turns, perfectly centered in the guide bearings, the only loading on the guide bearings would be from mechanical and electrical imbalance. As alignment deviates, loading on the guide bearings will increase and so will vibration levels. Any increase in vibration from misalignment will decrease the factor of safety for operation in severe circumstances, such as rough zone operation. If a unit has a moderate vibration problem caused by misalignment, the driving forces that occur with draft tube surging or mechanical imbalance may be enough to cause damage to the unit.

Since a perfect alignment isn't possible, we need guidelines or tolerances to let us know when we are "close enough." Table 1 lists tolerances for use in aligning a vertical shaft hydrounit. These are general tolerances, and some judgement must be used in specific cases. In most cases, a unit can easily be aligned within these tolerances, but in some special circumstances, it may not be possible without major modifications. When a major modification is required, such as moving the generator stator, the possible consequences of not doing it should be compared to the benefits before making a decision.

To meet the tolerances of table 1, concentricity, circularity, straightness, perpendicularity, and plumb must be addressed. The following are definitions of these characteristics as they apply to vertical shaft alignment.

3.1 Concentricity

By definition, concentric refers to anything sharing a common center. In the alignment of a vertical shaft unit, the stationary components are considered concentric when a single straight line can be drawn connecting the centers of all of the components. This straight line will be plumb or within the allowable tolerances for plumb.

The concentricity of the stationary components can be checked by measuring clearances, or if the unit is completely disassembled, such as during an overhaul, a single tight wire can be used as a plumb reference. Clearance measurements, i.e., bearing, turbine seal ring, and generator air gap, can be used to locate their centerlines with reference to the shaft. If the unit is disassembled, the upper and lower bridges and the head cover can be installed temporarily and a single tight wire hung through the unit. The concentricity is determined by measuring from the stationary

Table 1.—Tolerances for vertical hydrounit assembly [1]

Measurement	Tolerance
Stator air gap	± 5% of nominal design air gap
Stator concentricity (Relative to turbine guide bearing)	5% of nominal design air gap
Upper generator guide bearing concentricity (Relative to turbine and lower generator guide bearing)	20% diametrical bearing clearance
Lower generator guide bearing concentricity (Relative to turbine and upper generator guide bearing)	20% diametrical bearing clearance
Seal ring concentricity (Relative to turbine guide bearing and each other)	10% diametrical seal ring clearance
Circularity of stator	± 5% of nominal design air gap
Circularity of rotor	± 5% of nominal design air gap
Stator verticality (Relative to plumb)	± 5% of nominal design air gap
Rotor verticality (Relative to generator shaft)	± 5% of nominal design air gap
Shaft Straightness	No reading point deviates more than 0.003 inch from a straight line connecting the top and bottom reading point.
Static shaft runout (Orbit diameter)	0.002 inch multiplied by the length of the shaft from the thrust bearing to the point of runout measurement divided by the diameter of the thrust runner. All measurements in inches.
Plumb of center of shaft runout	0.000025 multiplied by the length of the shaft from the highest plumb reading to the lowest plumb reading.
Distance from wicket gate to unit center (® - figure C1)	± 0.0002 X R
Distance between wicket gates (D - figure C1)	± 0.0001 X D
Plumb of wicket gates	20% of minimum diametrical wicket gate bushing clearance
Parallelism of facing plates	20% of total (top + bottom) wicket gate clearance
Levelness of facing plates[2]	20% of total (top + bottom) wicket gate clearance

[1] These tolerances are intended to be used when manufacturer's tolerances are not available. Always consult the equipment manufacturer first, if possible. This table is based on the table "Bureau of Reclamation Plumb and Alignment Standards for Vertical Shaft Hydrounits," by Bill Duncan, May 24, 1991.

[2] Plumb of wicket gate and levelness of facing plates can be outside these tolerances as long as the facing plates meet the criteria for parallelism and the gates are within 20 percent of the minimum diametrical wicket gate bushing clearance of being perpendicular to the facing plates.

components to the wire. If the centers are not within tolerance for concentricity, the moveable components, such as the bearing brackets or, in some cases, the generator stator, are moved into concentricity with the non-movable components, such as the turbine seal rings, and redowelled.

3.2 Circularity

Circularity refers to the deviation from a perfect circle of any circular part. On the generator rotor or stator, the circularity is measured as a percent deviation of the diameter at any point from the nominal or average. This is referred to as roundness and the deviation as out-of-roundness.

On bearings, seal rings, and similar components, circularity is usually referenced as the out-of-roundness and is measured as the difference between the maximum and minimum diameter.

3.3 Perpendicularity

Perpendicularity in the alignment of a vertical unit refers to the relation of the thrust runner to the shaft or guide bearing journals (figure 11). If the bearing surface of the thrust runner is not perpendicular to the shaft, the shaft will scribe a cone shape as it rotates. Figure 12 illustrates this. The diameter of this cone measured at any elevation is referred to as the static runout at that point. The perpendicularity of the thrust runner to the guide bearing journals is measured indirectly by measuring the diameter of the static runout at the turbine guide bearing journal.

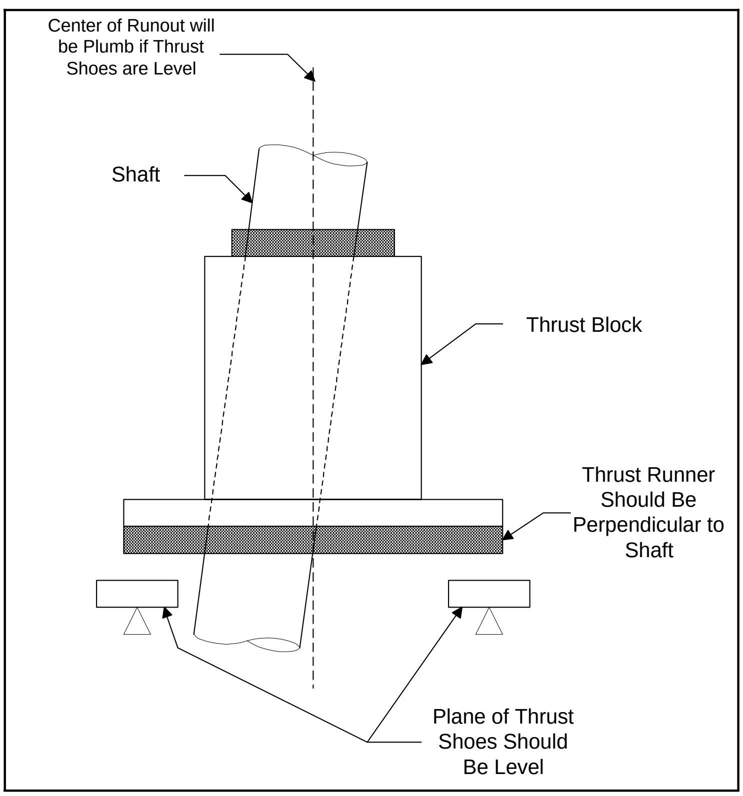


Figure 11.—Thrust bearing perpendicularity and level.

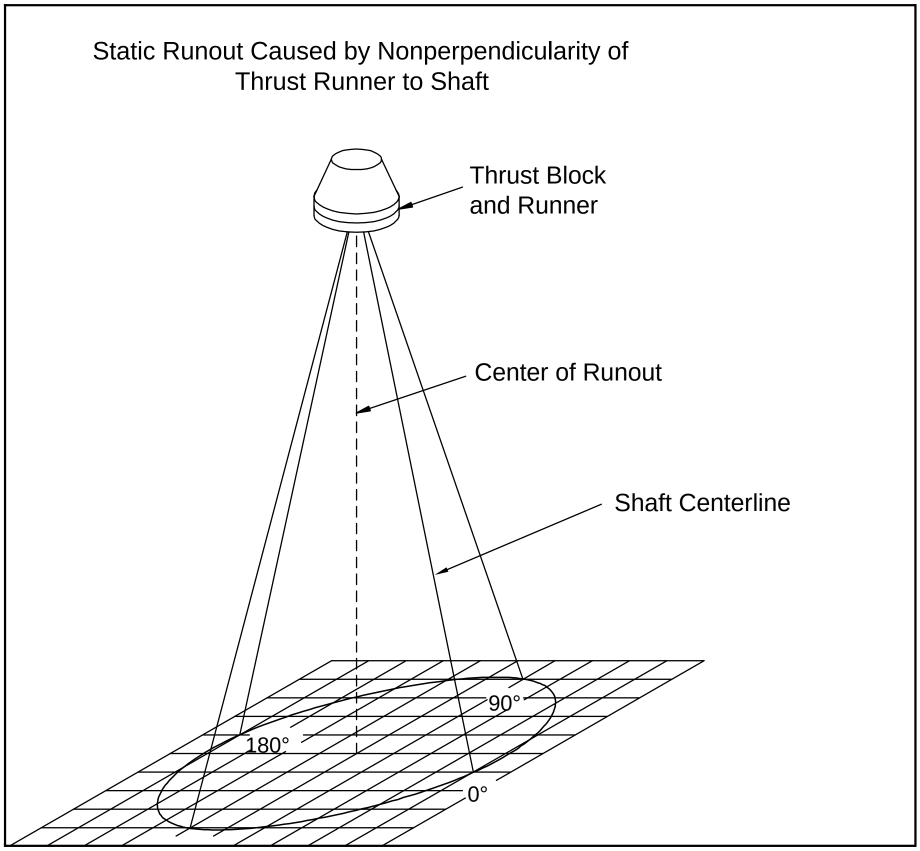


Figure 12.—Static runout.

3.4 Plumb

A line or plane is considered plumb when it is exactly vertical. In the alignment of vertical shaft units, plumb is essentially the reference for all measurements. A common misconception in unit alignment is that the primary goal is to make the shaft itself plumb. The actual goal is to make the thrust bearing surface level. The levelness of the shoes is checked indirectly by plumb and runout readings. If the thrust runner was perfectly perpendicular to the shaft when the shaft was plumb, the thrust shoes would be level. Due to non-perpendicularity of the thrust runner to the shaft we instead must make the center of runout plumb. Referring again to figure 12, we can see that if the shaft is plumb in the 0-degree position, it will be out of plumb by the runout diameter once the shaft is rotated 180 degrees. If the center of runout is plumb, the shaft will be out of plumb by half the runout diameter in any rotational position. As long as the runout diameter is within tolerance, this will be acceptable. By making the center of runout plumb, the thrust shoes are made level (figure 11).

3.5 Straightness

Straightness refers to absence of bends or offset in the shaft. Offset is the parallel misalignment between two shafts and occurs at the coupling between the generator and turbine shafts. Angular misalignment at the coupling is referred to as dogleg (figure 13). Usually, the individual

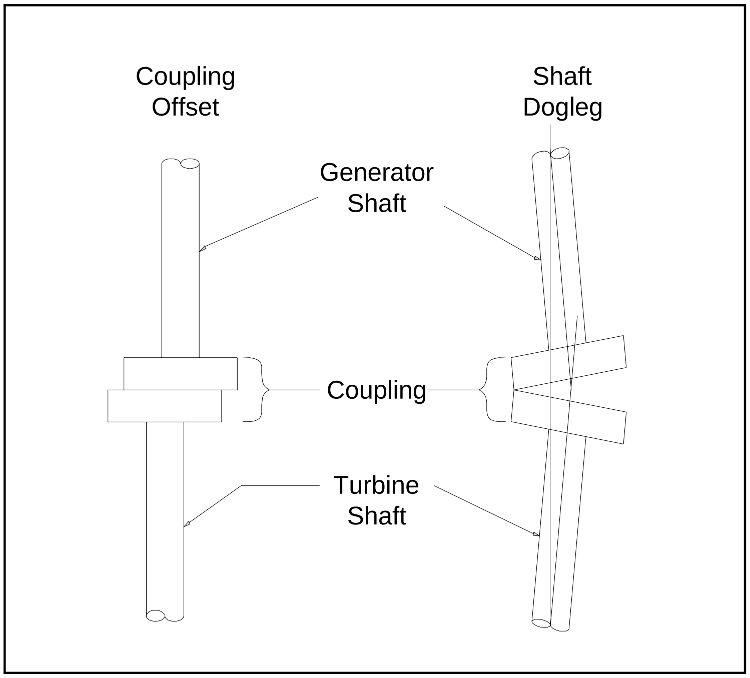


Figure 13.—Dogleg and offset.

generator or turbine shafts are assumed to be straight and any angular misalignment is assumed to be in the coupling. In most cases this is true, but in some cases, the generator or turbine shaft is not straight. The shaft is considered straight when no point varies more than 0.003 inch from a straight line joining the top and bottom reading points. Nothing is normally done to correct dogleg or offset unless it is large enough to significantly affect the static runout. If necessary, dogleg can be corrected by shimming the coupling. Offset is rarely large enough to cause a problem and usually can be corrected only by remachining the coupling flanges and reboring the coupling bolt holes.

4. EQUIPMENT

The basic equipment required for vertical shaft alignment consists of:

- At least four dial indicators with bases.
- Feeler gauges for measuring bearing, seal ring, and other clearances.
- A taper gauge or other means of measuring the generator air gap.
- Inside micrometers for measuring the distance between the shaft and bearing brackets.
- Some means of measuring plumb.

Plumb readings can be taken using the traditional plumb wire system or a laser-based system.

4.1 Plumb Wires

The most common method of obtaining plumb readings is with stainless steel, nonmagnetic piano wires and an electric micrometer. Four wires are hung 90-degrees apart with a finned plumb bob (photo 2) attached to each wire and suspended in buckets filled with oil to dampen movement. The electric micrometer (photo 3) is used to measure the distance from the wires to the shaft. There are variations in design, but the basic concept is the same. The electric micrometer is made up of an inside micrometer head, head phones, battery, shaft, and "Y-shaped" end. A simple circuit is completed when the micrometer head touches the plumb wire, which causes static in the headphones. Banding material is installed on the shaft to provide a place to rest the "Y" end of the micrometer and to ensure repeatability in the readings.

Photograph 2.—Plumb wire setup.

The readings taken with the electric micrometer are not calibrated as would be done with a normal inside micrometer. Since the wire is perfectly plumb, the plumb of the shaft is determined by comparing the difference in readings at different elevations. If the turbine and generator shafts were exactly the same diameter and neither shaft had any taper, only two wires, 90 degrees apart would be required to obtain plumb data. Since the turbine and generator shaft are rarely exactly the same diameter and slight tapers in the shaft are common, four plumb wires are normally used, 90 degrees apart. The difference in the north-south and the east-west readings are used in determining the shaft plumb. The four wires

Photograph 3.—Electric micrometer.

also provide the added benefit of a check for accuracy of readings. Figure 14 is an example of the form used to record the readings.

Where plumb wires are being used, care should be taken to ensure there are no kinks in the wires. With the weights installed, the entire length of each wire should be checked by feel for any bend or kinks. If any kink can be felt, the wire should be replaced. While the wires don't have to be an equal distance from the shaft, they should be within ½ inch so that they are within the range of the micrometer head. The brackets for the oil buckets should be sturdy and secure to prevent spilling oil while taking readings. The weights should be heavy enough to keep the wires very taut but not so heavy as to consistently break the plumb wires. The weights, when suspended in the oil, should be completely submerged, but they should not touch the bottom or the sides of the bucket. The steel banding material placed around the shaft at the reading elevations should be level, and the distance from the coupling should be rechecked occasionally during the alignment process to make sure it corresponds with the dimensions used for plotting.

4.2 Hamar Laser System

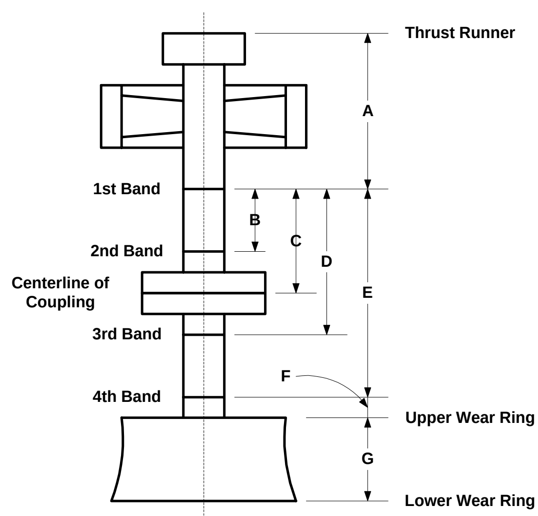
The Hamar laser system uses a laser beam to replace the wire and a micrometer adjustable target attached directly to the shaft with a magnetic base to measure the distance from the shaft to the laser (photo 4). There are two photoelectric cells mounted next to each other in the target with opposite polarity. When the laser beam is perfectly centered between the two cells, the voltage output of the target is zero. Four rigid steel bases are installed 90 degrees apart around the shaft in the turbine pit corresponding to north, south, east and west. Magnetic bases on the laser attach it to the steel bases and precision levels in the base of the laser act as the reference for plumb. The laser must be moved and releveled for each set of readings (north, south, etc.). The readings are recorded and the shaft centerline plotted in the same manner as with the wires.

The foremost problem encountered with the Hamar laser system is vibration from the mounting baseplate. Any vibration of the baseplate will be transferred to the laser and be magnified as the laser beam projects upward, making the top reading very unstable. Very solid base plates, rigidly attached to the head cover or the turbine bearing bracket, limit the vibration transferred to the laser. To prevent errors from the laser not being perfectly verical, the same end of the laser should always be pointed toward the shaft. In this way, any error in verticality will be subtracted out in the worksheet the same way as a taper in the shaft is corrected.

Another critical item to observe is the level. The laser must be leveled precisely initially and rechecked frequently to obtain accurate measurements.

Unit Alignment Worksheet

Elevation	Direction	Column 1 Actual Reading	Column 2 Mathematical amount to be added to Column 1 to theoretically move all wires an equi-distance from center of shaft	Column 3 Total Column 1 plus Column 2	Column 4 Difference N&S E&W	Column 5 ½ Column 4 (Out of Plumb between top and bottom reading)	Column 6 Direction bottom of shaft is out of plumb. (Direction of smaller number in Column 3)	Column 7 Total N+S and E+W from Column 3	Column 8 Out of Roundness or inaccuracy of readings (N+S)-(E+W) Should be less than 0.002
First Reading Elevation	North	0.3445	0.0000	0.3445	0.0000				
	South	0.1505	0.1940	0.3445					
	East	0.1710	0.1735	0.3445	0.0000				
	West	0.2985	0.0460	0.3445					
Second Reading Elevation	North	0.3425	0.0000	0.3425	0.0035	0.00175	N	0.6885	0.0000
	South	0.1520	0.1940	0.3460					
	East	0.1710	0.1735	0.3445	0.0005	0.00025	W	0.6885	
	West	0.2980	0.0460	0.3440					
Third Reading Elevation	North	0.3495	0.0000	0.3495	0.0080	0.0040	N	0.7070	0.0010
	South	0.1635	0.1940	0.3575					
	East	0.1800	0.1735	0.3535	0.0010	0.0005	W	0.7060	
	West	0.3065	0.0460	0.3525					
Fourth Reading Elevation	North	0.347	0.0000	0.3470	0.0120	0.0060	N	0.706	0.0005
	South	0.1650	0.1940	0.3590					
	East	0.1805	0.1735	0.3540	0.0015	0.00075	W	0.7065	
	West	0.3065	0.0460	0.3525					



A = 170

B = 25

C = 40

D = 55

E = 80

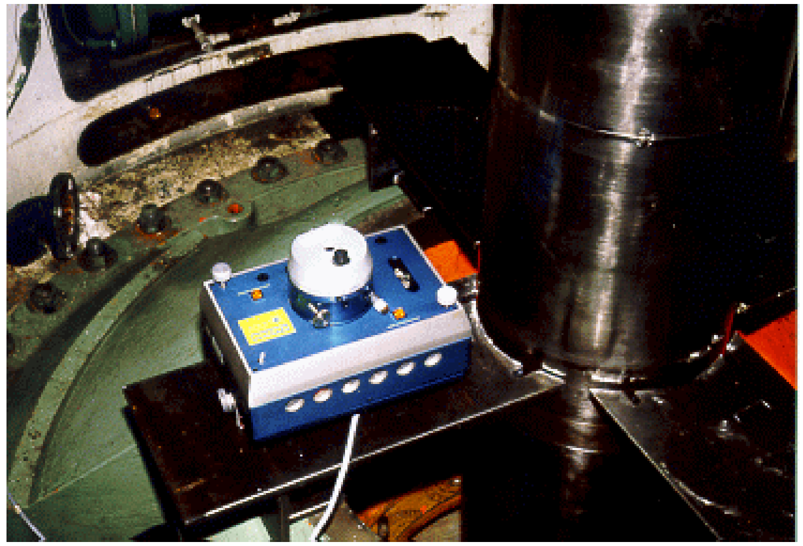
F = 85

G = 25

Figure 14.—Unit alignment worksheet.

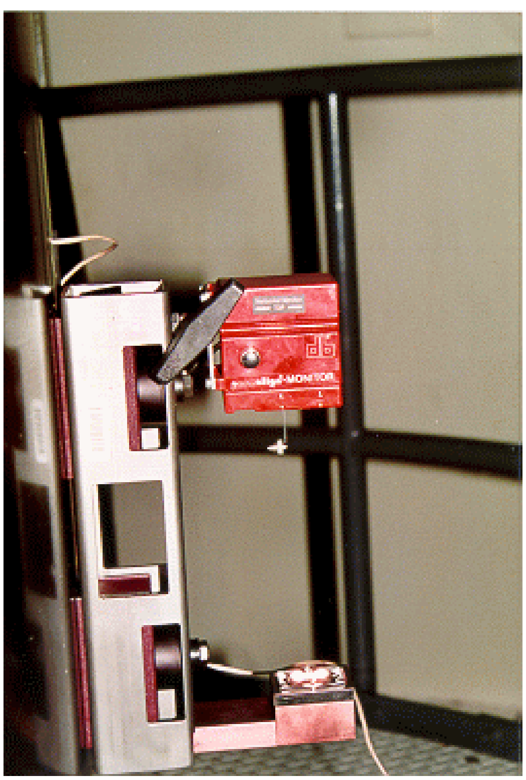
4.3 Permaplumb Laser Alignment System

The Permaplumb system uses a semiconductor laser, a photoelectric semiconductor position detector, and a mirror to measure shaft plumb. The laser and the position detector are enclosed in a single monitor. The mirror is calibrated and balanced so that it is always horizontal. The monitor and mirror are mounted on the shaft with a single mounting bracket with two magnetic bases (photo 5).



Photograph 4.—Hamar laser system.

When the bracket is mounted to the shaft, the laser beam is directed down to the mirror and reflected back to the position detector. The detector determines the relative position of the reflected beam. The system takes samples of the X and Y coordinates of the beam position, averages these samples, and transmits the average to a laptop computer. The computer has a buffer that stores the last 120 readings. A smoothing function in the software of the computer is applied to these readings to compensate for vibration. Once the averaged or smoothed reading has stabilized, it can be stored.



Photograph 5.—Ludeca permaplumb system.

The mirror's surface is always level and acts as the reference for plumb for the system. If the laser beam was perfectly parallel to the shaft center line, shaft plumb could be determined from the averaged X and Y coordinates on the computer screen. Since it would be very time consuming, if not impossible, to make the beam perfectly parallel to the shaft, the shaft must be rotated and readings 180 degrees apart averaged. This average provides the out of plumb of the center of runout and not the actual position of the shaft. As mentioned earlier, the goal of the alignment procedure is to plumb the center of runout to make the thrust bearing shoes level, so in most cases this is not a problem. To determine the static runout diameter, dial indicators can be set up at the thrust bearing and turbine bearing elevations. From this information, the shaft position and plumb can be determined.

The results portion of the computer program provides the total out of plumb data for the center of runout in mils per inch. There is also an automatic out-of-roundness check to check for accuracy of the readings.

Units with self equalizing bearings cannot use the Permaplumb system because it is not possible to obtain a static runout check. With the Permaplumb system, it is difficult to accurately determine dogleg in the shaft, and there is no way at all to check for offset at the coupling. Limited wire or Hamar laser readings may be used to check for shaft straightness, but if the static runout diameter is acceptable at all of the guide bearing journals, the straightness of the shaft should not be critical.

5. BASIC MEASUREMENTS

The position of the generator and turbine shafts relative to plumb and the stationary components need to be determined. Also, the straightness of the shafts and the perpendicularity of the thrust runner to the shaft has to be addressed.

5.1 Preliminary Checks for All Units

a. Use a precision machinist level to level the upper bridge (the lower bridge on umbrella units.) Check for any "soft feet" condition on any of the bridge legs. A "soft foot" condition is similar to short leg on a four legged table and if left uncorrected, can cause distortion of the bridge. Check for a "soft foot" by first checking that all bridge leg bolts are securely tightened. With a dial indicator, check the rise of each leg as its mounting bolts are loosened. Retighten the mounting bolts after the rise is recorded, so that only one leg is loose at a time. If one leg rises more than the other legs, it is a "soft foot" and shims should be placed under that leg to correct the condition. For example, if one leg of a six leg bridge rises 0.025 inch while the other five only rise 0.015 inch, a 0.010 inch shim should be added to the "soft foot." There may be more than one “soft foot.” Shims should be added accordingly so that the rise of each leg is nearly the same.

b. Allow the thrust block to cool over night after installation before any readings are taken.

c. Establish direction convention for readings so that all readings agree. Directions don't have to match actual compass directions as long as all readings are consistent and everyone involved with the alignment understands the convention used. For example, many plants use upstream and downstream for directions.

d. Remove packing and guide bearings. Install four jacking bolts with bronze heads at the upper guide bearing elevation or, if the guide bearing is a segmented shoe type, install four guide bearing shoes. Four jacking bolts installed at the turbine guide bearing may also be useful.

e. Install dial indicators at upper guide and turbine guide bearing elevations. Two indicators, 90 degrees apart, should be installed at each elevation. To prevent errors in readings, ensure that the dial indicators are in good condition and do not stick prior to installation.

f. Install plumb reading equipment. If plumb wires are used, install wires, plumb bobs, bases for oil buckets, and banding on the shaft. If the Hamar system is used, install banding on the shaft and sturdy steel bases for the laser in the turbine pit at north, south, east, and west directions. The Permaplumb system should be mounted directly to the shaft, and the data for the particular unit entered into the computer according to the manufacturer's directions.

g. Ensure that the thrust bearing high pressure lubrication system is operational. This may require installing a temporary oil source for the pump.

h. One of the most important things to be checked before any readings are taken is whether the shaft is free. A "free shaft" is essential for the readings to have any value whatsoever. The shaft is free when the thrust runner is sitting on the thrust bearing and the rotating components are not in contact with any stationary component. This means that all guide bearings must be removed or backed off, packing or mechanical seals must be removed, and the turbine runner should be somewhat centered in the seal rings. The shaft of a vertical shaft hydrounit, when it is free, should be able to swing like a pendulum. A "free shaft" will move easily a minimum of 0.005 inch in any direction with very light hand pressure, and, in many cases, one finger is all that is required to start the shaft swinging. If a lever is required between the shaft and the bearing housing to move the shaft, it is not free. A "free shaft" is critical for several reasons. First of all, plumb readings are taken to determine the natural position of the shaft and thrust shoes. If the shaft is touching anything that will prevent the shaft from moving to its neutral position, no readings will be indicative of the true plumb of the unit. The apparent straightness of the shaft can also be affected by the shaft contacting a stationary component. Since we are working with thousands of an inch, if the shaft is put in a bind, it can actually bend the shaft to the point that a plot of plumb data will show a dogleg that may not exist. It is important to check for a free shaft before each reading because a slight shift on the thrust block can cause contact somewhere on the shaft.

5.2 Plumb Readings

Plumb is the reference for all readings on vertical shaft alignments. While some measurements are relative to the position of unit components, eventually all measurements are tied back to a plumb reference. For example, bearing centers, seal ring clearances, and generator air gap measurements are taken relative to shaft, turbine runner, and rotor, respectively, but they are all tied together with the shaft plumb readings.

To determine the straightness of the shaft, two reading elevations are required on all shafts. Most units have only a generator and a turbine shaft and, therefore, require only four reading elevations, but on units that have an intermediate shaft, six reading elevations are required. The bands on each shaft for the readings should be located as far apart as possible to improve the accuracy of the plot. The top reading band for the generator shaft should be as high as possible, and the lower one just above the coupling flange. On the turbine shaft, the lower band should be as low as possible, with the top band just below the coupling flange. Ladders or scaffolding may be required to provide access to the upper band. If a ladder is used, it must not rest against the shaft.

Taking two readings per shaft makes the assumption that the individual shafts are straight and any bends will be at the coupling. If there is any reason to believe that a bend exists in a shaft, more reading elevations should be used. If there is only a short section of the generator shaft accessible below the rotor, readings above the rotor may be required.

Shaft plumb readings allow a plot of shaft centerline to be drawn as in figure 15. This plot uses the data from figure 14. The plot of the shaft will provide information on straightness of the shaft. Once the shaft is plotted, the relative position of other components can be plotted as well. From the plot, plumb and concentricity of the stationary components can be determined.

5.3 Static Runout

Due to non-perpendicularity between the thrust runner and the shaft, as the shaft rotates, the shaft centerline will scribe a cone shape, as shown in figure 12, when the guide bearings are removed. This is referred to as static runout. A bent shaft or dogleg and offset at the coupling can also contribute to excessive static runout. The larger the static runout, the higher the loading on the guide bearings and, in most cases, the higher the vibration levels.

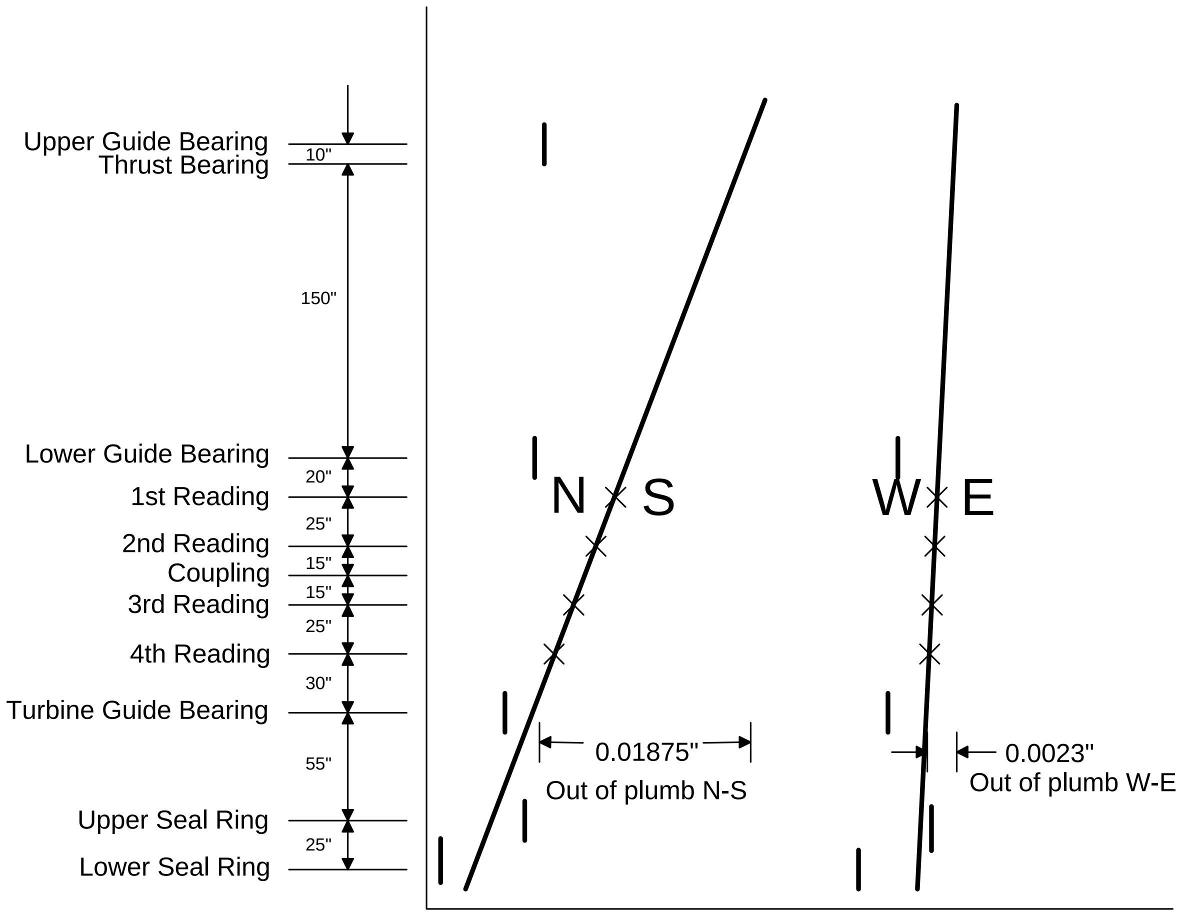
Static runout cannot be measured on units with self equalizing thrust bearings. The self equalizing bearings correct for non-perpendicularity of the thrust runner, making static runout data impossible to obtain, as well as unnecessary.

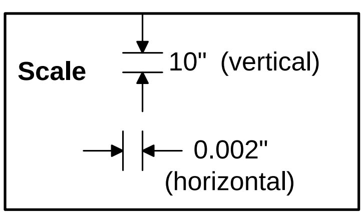
Static runout is measured in either of two ways, both requiring rotating the shaft. To rotate the shaft, the high pressure lubrication system must be operational. This may require providing a temporary source of oil because, in some cases, it is necessary to remove the oil tub during the alignment. If this is the case, some temporary method of routing the oil from the bearings to the drain is required as well. If a high pressure lubrication system is not installed, it will be necessary to jack the unit to get oil under the shoes prior to each rotation. In this case, the rotor is jacked, and then, immediately after the jacks are released, the rotor is rotated.

The first method of taking static runout readings requires taking plumb readings with the shaft rotated to the 0, 90, 180, and 270 degree positions. Readings are usually taken only at two elevations to speed up the process because the straightness of the shaft should already be verified. From the plumb readings, it is possible to determine the diameter of runout at the turbine bearing and the location of the center of runout with respect to plumb. Figure 16 is an example of the form used to record the data and perform the calculations.

Shaft Plumb Plot

Showing Bearing and Seal Ring Centerlines





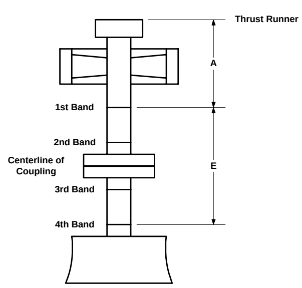
Bearing and Seal Ring Clearance Readings
(Bearing Clearance Readings Taken To Bearing Housing with Bearings Removed)

Upper Guide Bearing	Lower Guide Bearing	Turbine Guide Bearing	Upper Seal Ring	Lower Seal Ring
N - 0.080	N - 0.062	N - 0.050	N - 0.040	N - 0.041
S - 0.040	S - 0.040	S - 0.044	S - 0.046	S - 0.039
E - 0.056	E - 0.047	E - 0.043	E - 0.044	E - 0.034
W - 0.064	W - 0.055	W - 0.051	W - 0.042	W - 0.046

Figure 15.—Plot of shaft centerline.

Unit Runout Worksheet

Position	Elevation		Column 1 Actual Reading	Column 2 Mathematical amount to be added to Col. 1 to theoretically move all wires an equi-distance from center of shaft	Column 3 Total Column 1 plus Column 2	Column 4 Difference N&S E&W	Column 5 ½ Column 4 (Out of Plumb between top and bottom reading)	Column 6 Direction bottom of shaft is out of plumb. (Direction of smaller number in Column 3)	Column 7 Total N+S and E+W from Column 3	Column 8 Out of Roundness or inaccuracy of readings (N+S)-(E+W) Should be less than 0.002
0° Position	First Reading Elevation	N	0.3445	0.0000	0.3445					
		S	0.1505	0.1940	0.3445	0.0000				
		E	0.1710	0.1735	0.3445					
		W	0.2985	0.0460	0.3445	0.0000				
	Fourth Reading Elevation	N	0.3470	0.0000	0.3470					
		S	0.1650	0.1940	0.3590	0.0120	0.0060	N	0.7060	0.0005
		E	0.1805	0.1735	0.3540					
		W	0.3065	0.0460	0.3525	0.0015	0.00075	W	0.7065	
90° Position	First Reading Elevation	N	0.3000	0.0000	0.3000					
		S	0.1800	0.1200	0.3000	0.0000				
		E	0.1420	0.1580	0.3000					
		W	0.2370	0.0630	0.3000	0.0000				
	Fourth Reading Elevation	N	0.3460	0.0000	0.3460					
		S	0.2405	0.1200	0.3605	0.0145	0.00725	N	0.7065	0.0000
		E	0.191	0.1580	0.3490					
		W	0.2945	0.0630	0.3575	0.0085	0.00425	E	0.7065	
180° Position	First Reading Elevation	N	0.3315	0.0000	0.3315					
		S	0.1485	0.1830	0.3315	0.0000				
		E	0.1620	0.1695	0.3515					
		W	0.2175	0.1140	0.3515	0.0000				
	Fourth Reading Elevation	N	0.3510	0.0000	0.3510					
		S	0.1720	0.1830	0.3550	0.0040	0.0020	N	0.7060	0.0005
		E	0.1785	0.1695	0.3480					
		W	0.2445	0.1140	0.3585	0.0105	0.00525	E	0.7065	
270° Position	First Reading Elevation	N	0.3650	0.0000	0.3650					
		S	0.1120	0.2530	0.3650	0.0000				
		E	0.0955	0.2695	0.3650					
		W	0.2845	0.0805	0.3650	0.0000				
	Fourth Reading Elevation	N	0.3520	0.0000	0.3520					
		S	0.1010	0.2530	0.3540	0.0020	0.001	N	0.7060	0.0005
		E	0.0835	0.2965	0.3530					
		W	0.2730	0.0805	0.3535	0.0005	0.00025	E	0.7065	



A = 170

E = 80

Figure 16.—Runout worksheet.

The other method for measuring static runout requires installing dial indicators at the turbine bearing and at thrust bearing elevations. Two indicators are located at each elevation to indicate movement in the north-south and east-west axes. The indicators are zeroed with the shaft in the 0 degree position, and plumb readings taken. These plumb readings will serve as a reference for the other readings. The shaft is then rotated 90 degrees. If the shaft is not totally free after rotating, it must be moved laterally at the thrust bearing until it is free. The indicators are read once the shaft is free. This is repeated for 180, 270, and 360 degree positions. The corrected data for the 360 degree data should be zero. An example of a form for recording the data using this method is shown in Figure 18. It is important that the dial indicators are not moved or adjusted after they are zeroed at the 0-degree position. The top reading is subtracted from the bottom reading to correct for any lateral movement at the thrust bearing and to provide the actual runout at the turbine bearing. The plumb reading in the 0-degree position is used to determine the position of the center of runout with respect to plumb. The dial indicator method of measuring static runout is faster than the wire method and, if done correctly, will provide accurate results.

5.4 Clearance and Concentricity Readings

If the unit is completely disassembled, the concentricity of the stationary components can be checked by temporarily installing the upper and lower bridges and the head cover and hanging a single plumb wire through the unit. An electric micrometer is used to measure from the wire to the stationary components. This procedure is particularly useful during major overhauls. If new stationary seal rings are being installed, this procedure provides a reference to allow the seal rings to be bored concentric to the stator. It also allows a more accurate profile of the stator to be determined. With the rotor installed, only the top and bottom of the stator can be measured. With the rotor removed and the single wire installed, readings can be taken at several elevations to get a true profile of the stator bore. The turbine bearing housing can also be centered to the seal rings at this time. Once the wicket gate linkage is installed, moving the turbine bearing is difficult or impossible.

The single wire can also be used to center and redowel the upper and lower bridges. This is especially important on units that have sleeve type generator guide bearings. If the unit has sleeve type generator guide bearings, the bridges should be temporarily installed with the bearings in place and the bridges centered using the center of the bearing bores as the reference point. This ensures that the bearings will be centered even if they are not concentric to their fit in the bridges.

When the unit is assembled, the concentricity of the stationary components can be determined by taking clearance readings, (i.e., bearing clearance, seal ring clearance, generator air gap, etc.), and plotting the centers against the plot of the shaft centerline. The concentricity should be verified using this method regardless of whether the concentricity was checked with a single wire. Don't assume that everything is still concentric. Even doweled components can shift slightly.

The internal diameter of a sleeve type guide bearing should be concentric with the outside fit of the bearing shell. Therefore, when the bearing is not installed, the bearing center can be determined by measuring with an inside micrometer from the fit on the bearing bracket or bridge to the journal. On turbine bearings that use a tapered fit, a jig or some other means must be used to insure that the readings are taken at the same point of the taper at all four measurement points. When measurements are taken from the shaft to the bearing housing with an inside micrometer, it is not necessary to calibrate the micrometer because only the differences between readings and not absolute dimensions are of interest. The bearing clearances should always be verified after installation in case the bearing surface is not concentric to its fit.

6. PLOTTING THE DATA

6.1 Plumb Data

Plumb readings from either plumb wires or the Hamar laser system are used with the worksheet in figure 14. The actual readings are entered in column 1. As mentioned above, the electric micrometer readings are not calibrated, so these readings mean nothing by themselves. The difference between readings is what is used to determine the plumb of the unit. Since the wires will not be the same distance from the shaft, an amount is added to each reading in column 2 to mathematically make all four wires the same distance from the shaft at the first reading elevation. This will simplify subsequent calculations. The first elevation is considered the origin for the plot of the shaft. The values in column 2 are calculated by taking the largest value of column 1 in the first reading elevation and subtracting each of the other three measurements. As three wires have been mathematically moved these distances at the first elevation, these values must be carried through the rest of the reading elevations. Column 3 is the sum of columns 1 and 2. If the values in column 3 at the first elevation are all equal to the largest value in column 1, the values in column 2 are correct. Column 4 is the difference between north and south and east and west. Column 5 is one half of column 4, which is the amount the shaft is out of plumb from the first elevation, the origin of the plot. Column 6 indicates the direction the shaft is out of plumb from the first reading. Columns 7 and 8 are used to calculate the accuracy of the readings. Column 7 is the sum of the north and south and east and west readings. As most shafts are machined to a high degree of accuracy regarding roundness, any value in column 8 of more than 0.002 inches is considered excessive and is probably due to an error in a measurement or in reading the micrometer.

To plot the plumb of the shaft centerline, the values in column 5 and the directions in column 6 are used. Two separate plots will be required, one for the north-south profile and one for the east-west profile. Usually, both plots are drawn on a single sheet of graph paper. To determine the vertical scale for the plot, the vertical distances shown on the sketch on the bottom of figure 14 are used. The distances between the thrust bearing and coupling and the distances from the coupling to the seal rings are obtained from the manufacturer’s drawings. After choosing a suitable scale on graph paper, mark on the vertical scale the elevation marks for the thrust bearing, the reading elevations, and the shaft coupling. To plot the centerline of the guide bearings, seal rings, and generator stator, their elevations will have to be added to the graph as well. Figure 15 is an example of a shaft plumb plot.

The horizontal axis will be the plumb of the shaft. The horizontal scale should be chosen based on the total out-of-plumb of the shaft. Usually, a scale of 0.001 inch per division will work, but if the shaft is considerably out-of-plumb, as is the case many times on the first reading after reassembly, a scale of 0.002 inch or more per division may be required.

Once an acceptable scale is laid out, draw two vertical lines on the graph. These lines represent zero, or perfect plumb, for the north-south and the east-west plots. Label north, south, east, and west on their respective sides of the lines. The point for the first reading elevation will be directly on the vertical line for both the north-south and east-west plots. The second, third, and fourth reading elevation points are all plotted the amount indicated in column 5 away from the vertical line in the direction indicated in column 6.

With all the points plotted, draw a line from the first elevation point to the second elevation point and extend the line to the shaft coupling elevation on both the north-south and the east-west plots. This line represents the generator shaft. Draw a line from the fourth to the third elevation points and extend it up to the coupling elevation. This line represents the turbine shaft. The horizontal distance between the lines at the coupling is the amount of offset. Any angle between the two lines indicates dogleg.

To determine the total effect of the dogleg and offset on the static runout, extend the generator shaft line down to the fourth elevation. The horizontal distance at the fourth reading elevation from the extended generator shaft line to the turbine shaft line, multiplied by two, is the total effect of dogleg and offset on the static runout at the fourth elevation. If this value is near or exceeds the maximum allowable runout as calculated in the next section, some correction will probably be required. If the dogleg and offset are acceptable, only the first and fourth elevation readings are required for subsequent readings.

If the generator and turbine shaft are straight, the total out-of-plumb can be determined by drawing a line from the first to the fourth elevation points and extending it upward to the thrust bearing elevation. From the point where this line intersects the thrust bearing elevation, draw a vertical line downward to the fourth reading elevation. The horizontal distance from where the projected line crosses the fourth reading elevation is the total out-of-plumb at that elevation.

If the dogleg is significant enough to require readings at all four elevations, the total out of plumb is determined by extending the generator shaft line upward to the thrust bearing elevation. Again a vertical line is drawn downward from the point where this line crosses the thrust bearing elevation down to the fourth reading elevation. The horizontal distance from where the projected line crosses the fourth reading elevation is the total out-of-plumb at that elevation.

Bearing and seal ring centerlines can be plotted by taking half of the difference between the north-south and east-west clearances and plotting that value against their respective shaft centerline plot. The bearing centerline will lie on the side of the shaft centerline in the direction of largest clearance reading. In the example in figure 15, the difference between the north-south readings is 0.040 inch. The centerline is half of that value, 0.020 inch to the north of the shaft centerline. In the east-west direction, the difference is 0.008 inch, so the bearing centerline is 0.004 inch to the west of the shaft centerline.

6.2 Correcting Excessive Dogleg and Offset

Correcting a dogleg between the generator and turbine shafts requires installing a shim pack between the coupling faces. If readings indicate that a dogleg exists, the first step in correcting it is to verify that it really exists. A dogleg may show up when a shaft is in a bind or is not totally free. Check for a free shaft. If the shaft is free, rotate the shaft 90 degrees and take another set of plumb readings. If the dogleg is real, the second set of readings should verify this. The dogleg should simply move from the north-south plot to the east-west plot or vice versa. If the dogleg is still in the same plane, the shaft is not free.

When calculating the amount of shims to install in the coupling, several consistent readings are important. Installing shims in the coupling is a very time consuming process and, preferably, should be done only once. The amount of shims required should be calculated for several sets of readings, and, if there are any major differences between calculations, more readings should be taken until an acceptable level of consistency is achieved. It should be remembered that the shims should be installed so that the shim pack creates a wedge to prevent distortion of the coupling.

Excessive offset occurs when the generator and turbine shafts are coupled together and are not concentric. This can occur if the coupling bolts are a loose fit in the coupling. If excessive offset is present, it usually requires realigning the shafts and reboring the coupling for oversized bolt holes. On most couplings, there is also a register fit between the two shafts. If this is the case, the register fit will have to be machined as well.

6.3 Static Runout Data

Static runout can be measured either of two ways. Both methods require rotating the shaft 90 degrees, four times. With Method I, described below, plumb readings are taken at each position. Method II uses dial indicator readings. With either method, the shaft should be centered at the upper guide bearing or, with an umbrella unit, at the guide bearing closest to the thrust bearing. Before any readings are taken, it should be verified that the shaft is free. It may be necessary to move the shaft off center to obtain a free shaft, especially if clearances are tight or the unit is severely out of plumb. On spring loaded bearings where the springs are relatively soft (i.e., the springs deflect significantly under just the weight of the unit), the shaft plumb may change if the thrust runner is moved off the center of the thrust bearing. In these cases, it may be necessary to shim the bridge to make it possible to obtain a full rotation with the shaft free and the thrust block centered on the thrust bearing. It may take several shim moves before a full free rotation is possible. Prior to each rotation, the shaft should be oiled and the shaft held in place snugly with jacking bolts with bronze heads or, if the guide bearing is a segmented shoe type, four guide bearings. This prevents excessive lateral movement, or "skating," of the thrust runner during the rotation.

To start, the maximum allowable runout diameter should be calculated by the formula:

$$\textbf{\textit{Allowable Static Runout}} \leq \frac{\textbf{0.002 \textit{X Length of Shaft}}}{\textbf{\textit{Diameter of Thrust Runner}}}$$

All dimensions are in inches. In Method I, the runout is going to be calculated at the fourth reading elevation, the "Length of Shaft" would be, based on the dimension labels on figure 14, equal to A+E, or the distance from the thrust runner to the first elevation plus the distance from the first to the fourth elevation.   In Method II, the "Length of Shaft" is simply the distance between the dial indicators.

The static runout is not a measure of the dynamic runout that will occur when the unit is operating because the guide bearings will hold the shaft in place to some extent. Most of the movement caused by the nonperpendicularity will be seen at the thrust bearing. The formula above limits the up and down movement of the thrust bearings to 0.001 inch, assuming that the shaft is held in position with the guide bearings.

6.4 Static Runout Method I

For this method, the form in figure 16 should be used. The form is like the one discussed above for four reading elevations, except readings are taken only at the first and fourth elevations. After all the readings have been taken and the plumb calculations made, the runout calculations can be made.

Once the allowable runout is calculated, the points for the runout plot are determined. The values in column 5 are the values the shaft is out of plumb from the first to the fourth readings and will be transcribed to Column B of figure 17. To correct these values to reflect the out of plumb from the thrust bearing to the fourth elevation, a multiplication factor must be calculated. This factor, based on similar triangles, is (A+E)/E. Each of the values in Column 5 are multiplied by this factor and entered into the appropriate spot on the table. These values can then be plotted to show the runout diameter and its relative location to the thrust bearing.

An example of this plot is shown in figure 17. This plot is a top view. The origin of the plot (point 0,0) is the shaft centerline at the thrust runner elevation, or the center of the thrust runner. The points at the 0, 90, 180, and 270 degrees are the positions of the shaft at the fourth reading elevation as the shaft is rotated. The intersection of the lines drawn from 0 to 180 and from 90 to 270 is considered the center of runout. A line drawn from the origin to the center or runout would be the axis of rotation for that unit. As mentioned before, the primary objective is to make the center of runout or axis of rotation, plumb. In this plot, the center of runout will be plumb when it is located directly under the center of the thrust runner (point 0,0). How this is done will depend on the design of the thrust bearing. These specific procedures will be discussed in the next section. The runout diameter, the distance from 0 to 180 and from 90 to 270, should be checked at this point. The diameter can be checked graphically by simply measuring the distance on the plot.

Unit Runout Data and Runout Plot

		Column A Multiplier to Determine Total Out-of-Plumb (A+E)/E	**Column B** Values in Column 5 of Runout Worksheet	**Column C** Total Out-of-Plumb (Column A*Column B)	**Column D** Direction Shaft is Out-of-Plumb (Column 6)
0° Position	North-South	3.125	0.0060	0.0187	N
	East West	3.125	0.00075	0.0023	W
90° Position	North-South	3.125	0.00725	0.0227	N
	East West	3.125	0.00425	0.0133	E
180° Position	North-South	3.125	0.0020	0.0063	N
	East West	3.125	0.00525	0.0164	E
270° Position	North-South	3.125	0.0010	0.0031	N
	East West	3.125	0.00025	0.0008	E

A = Distance from First Elevation to Thrust Bearing = 170

E = Distance from First Elevation to Fourth Elevation = 80

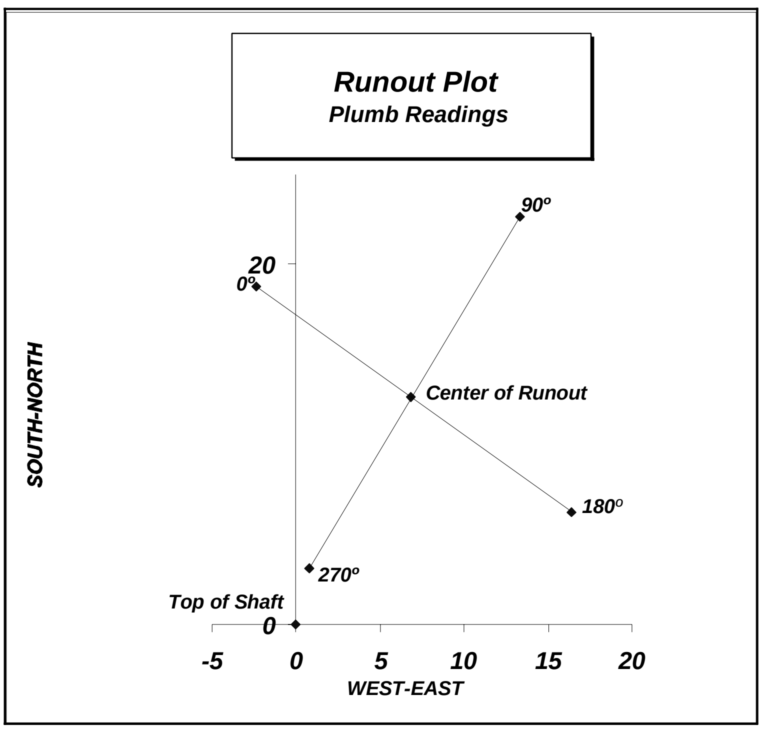


Figure 17.—Runout data and plot.

6.5 Static Runout Procedure II

When dial indicators are used, the form in figure 18 should be used. The plot of this data will be only the plot of the runout at the location of the lower dial indicators. The origin is the position of the shaft at 0 degrees. The center of runout is again the intersection of the lines from 0 to 180 and 90 to 270 degrees. This plot is also shown in figure 18. To correlate the runout plot to the plumb of the center of runout, one set of plumb readings is required at 0 degrees. In this example, the plumb data from figures 14 and 15 are used. The position of the thrust runner with reference to the runout plot can be determined by measuring the out of plumb from the thrust bearing to the elevation where the lower dial indicators are located on the plumb plot. For this example, we will assume that the dial indicators are located at the thrust bearing elevation and at the same elevation as the fourth plumb reading elevation. These values can then be used to plot the center of the thrust runner with respect to the 0-degree point. As with the other method of measuring static runout, the plot is a top view of the unit. To make the center of runout plumb, it must be moved under the center of the thrust runner. This is accomplished by plumbing the unit as described in the next section.

If plumb readings were obtained with the Permaplumb system, the runout diameter will be determined with dial indicators as discussed above. The plumb data from the Permaplumb system provides the out of plumb of the center of runout. To correlate the plumb data to the runout data, the total out of plumb from the thrust bearing to the location of the lower dial indicator must be calculated. This distance should have been input as part of the setup data in the computer. If this is done, the total out of plumb for that distance will automatically be calculated. The thrust bearing center can then be plotted on the runout plot from the out of plumb data. Once again, the unit will be plumb once the center of runout is directly below the center of the thrust bearing.

6.6 Correcting Excessive Static Runout

In the event the measured static runout is greater than the recommended maximum allowable value, some correction will be required. Before any corrective action can be taken, the source of the excessive runout needs to be determined. The most likely cause is non-perpendicularity between the thrust runner and the shaft, but a dogleg or a bend in the shaft can also cause excessive runout. If the plumb readings and plots indicate that the shaft is straight, the problem lies in the thrust runner not being perpendicular to the shaft. This may be due to inaccuracies in machining or to an improper installation procedure. The thrust block is usually a shrink fit onto the generator shaft. Normal procedures call for the weight of the unit to be put on the thrust block while it is still warm. If the block was allowed to cool before any weight was applied, it may cock slightly when weight is applied, causing the runner not to be perpendicular to the shaft. To minimize machining inaccuracies, the thrust block and keys should be match marked to the shaft so that they can be installed in the same orientation as they were in before they were removed. If the thrust block was installed properly and there is still a problem, shimming may be required to reduce the runout magnitude. Depending of the thrust block design, shimming the thrust

Runout Worksheet Using Dial Indicators

	0°		90°		180°		270°		360°	
	N	E	N	E	N	E	N	E	N	E
Bottom	0	0	4	16.5	-11.5	17.5	-14.5	2.5	1	0
Top	0	0	0	1	1	-1	1	0	1	0
Corrected (Bottom - Top)	0	0	4	15.5	-12.5	18.5	-15.5	25	0	0

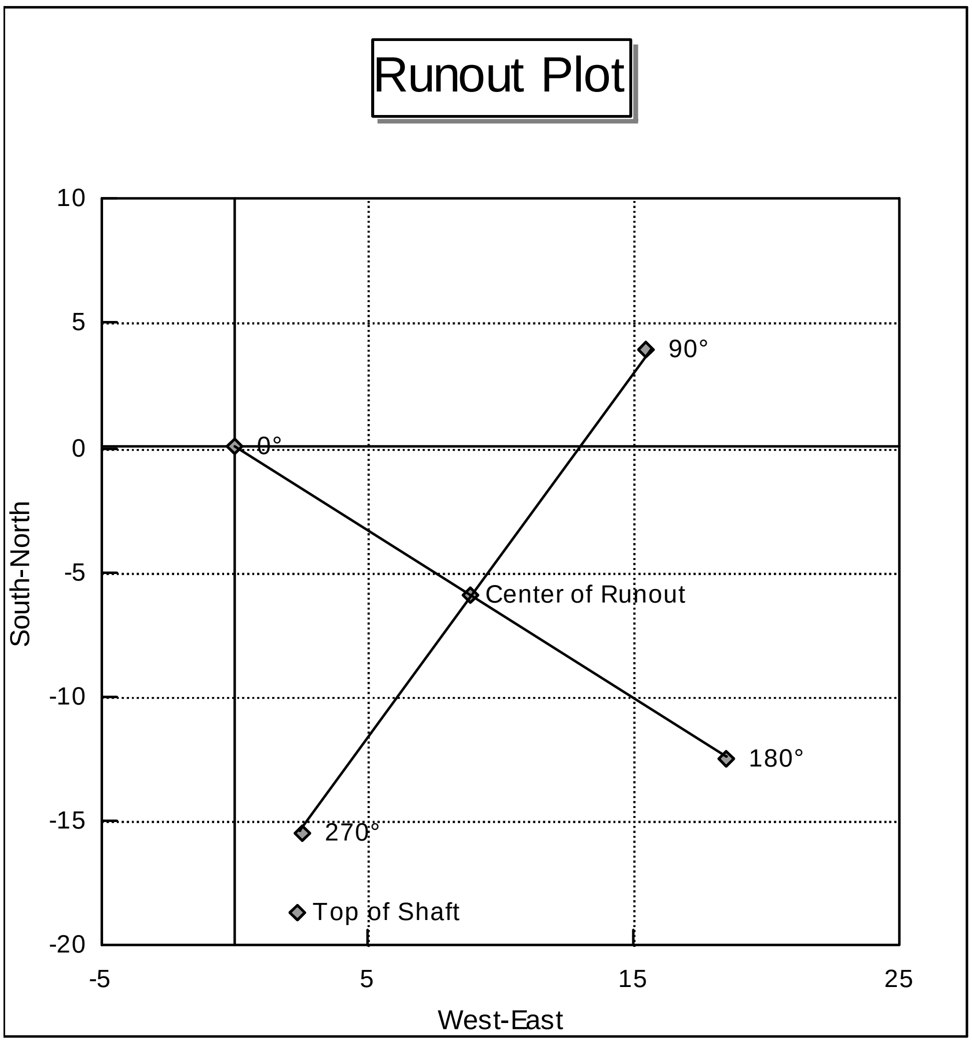


Figure 18.—Runout worksheet using dial indicators.

block can be a very time consuming process. Anytime the thrust block is removed, it should be allowed to cool overnight before any readings are taken. As several shim changes may be required, it may take several days to achieve the desired results.

The easiest place to shim is between the thrust runner and the thrust block. Many times, the shims may be installed by jacking the unit and unbolting the thrust runner, letting it down on the thrust shoes. Some problems have been noted with shims installed between the runner and the block, such as fretting corrosion and the shims coming loose. If the runner is not bolted to the thrust block, all options should be evaluated before installing the shims between the thrust block and runner. The placement and thickness of the shims should be calculated to form a wedge to prevent distortion of the thrust runner.

Installing the shims between the shaft and the thrust block is another consideration. This requires removing the thrust block for every attempt at changing the shim. As the fit is already a shrink fit, the addition of a shim can be very difficult. Also, the effect of a given shim is not always predicable. It will likely take several attempts to make the runout acceptable.

If the thrust block is of the type shown in figure 8, the shim can be placed on the shoulder on the shaft. This still requires removing the thrust block every time, but it is more predictable than installing the shim between the shaft and the block.

On units with shims installed in the thrust blocks, attention should be paid to vibration levels measured at the guide bearings. An increase in vibration may mean that the shims have shifted or been damaged.

7. ALIGNMENT PROCEDURES

7.1 Procedure for Spring Loaded, Semi-Rigid, and Solid Plate Thrust Bearings

a. Take plumb readings with the shaft in the zero degree position and plot the shaft profile. If dogleg or offset is excessive, make corrections as discussed in section 6.2. Take clearance readings of the turbine seal rings, turbine bearing housing, generator stator, and generator guide bearing housings, if not adjustable. Plot the centerlines of the static components on the shaft plumb plots to determine concentricity. The concentricity should be checked even if the stationary components were centered with a single plumb wire with the rotating components removed.

b. Take static runout readings using either Method I or II. If the magnitude of static runout exceeds the tolerance in table 1, make necessary corrections as discussed in section 6.6. Plot the runout readings and, using the plumb plot, determine the position of the center of runout relative to the shaft at the thrust bearing elevation.

c. If the plumb of the center of runout is out of tolerance, calculate the thickness of shims for bridge legs to plumb center of runout using either graphical or analytical methods below. To prevent distortion, shims must be added to all except one leg of the bridge so that a wedge shape of shims is maintained.

Graphical Procedure for Shim Calculation (Figure 19)

(i) Draw two circles and plot bridge legs. One circle will be used for the North-South orientation and one for East-West.

(ii) Plot pivot axis on each circle. The pivot axis will line up with the plumb wire locations.

(iii) Plot change in bridge elevation point from appropriate end of pivot axis and connect by line to opposite end of pivot axis.

(iv) Project a line from the end of each leg perpendicular to the pivot line. Count and tabulate the number of divisions from the shim line to the pivot line along the projected line.

(v) Total divisions of both circles for each bridge leg and subtract the smallest total value from all the total values to determine amount of shim to add to the legs.

Analytical Procedure for Shim Calculation (Figure 20)

(i) Draw two circles and plot bridge legs. One circle will be used for the North-South orientation and one the East-West.

(ii) Plot the pivot axis on each circle. The pivot axis will line up with the plumb wire locations.

(iii) Project a line from the end of each leg perpendicular to the pivot line. Calculate the distance along the pivot line from the pivot point to the projected lines.

(iv) Calculate and tabulate the shims required for each bridge leg. Change in elevation= (Distance from Pivot Point)*(Out of Plumb)/Length of Shaft.

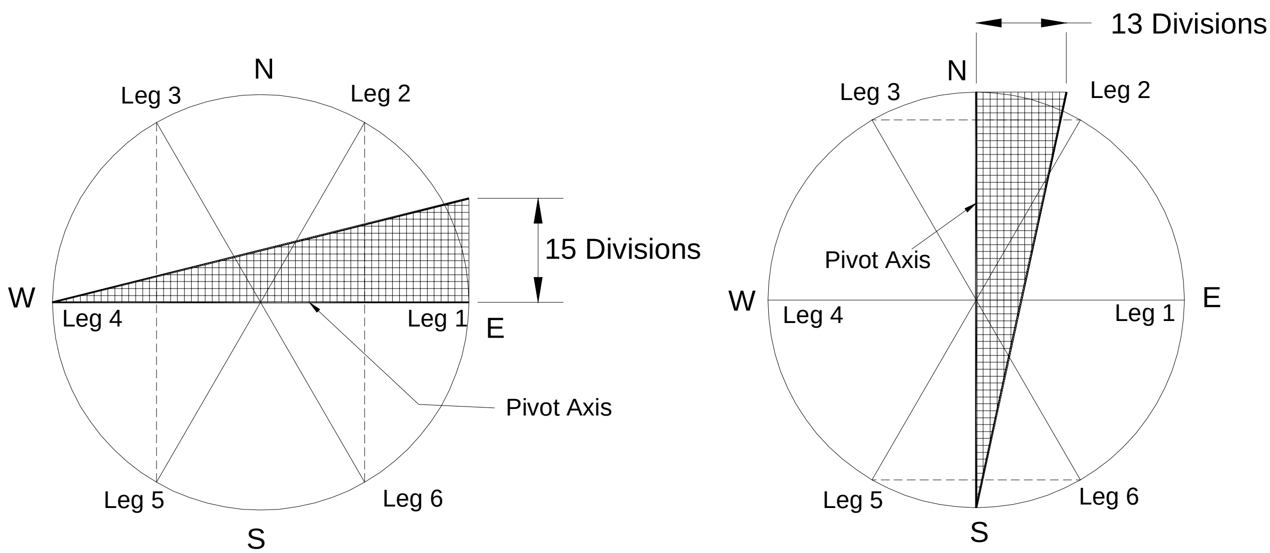
(v) Total shims north-south and east-west for each bridge leg, subtract the smallest total value from all the total values to determine the thickness of shims to add to legs.

d. After shims are installed, repeat steps a and b. If the plumb of the center of runout is still out of tolerance, repeat step c.

Graphic Shim Calculation - 6 Legged Bridge

Given Data
Shaft Length =434.5"
Bridge Diameter = 180"
Out of Plumb of Center of Runout = 0.037 West, 0.032 South

$$Required\ Bridge\ Elevation\ Change = \frac{(Bridge\ Dia.)(Out\ of\ Plumb)}{Shaft\ Length}$$



$$EAST-WEST = \frac{(180)(37)}{434.5} \approx 15 mils \qquad NORTH-SOUTH = \frac{(180)(32)}{434.5} \approx 13 mils$$

Bridge Shim Calculation(Thousands of an inch or mils)				
Bridge Leg No.	EAST-WEST	NORTH-SOUTH	TOTAL	SHIM ADDITIONS
1	15	6.5	21.5	16.75
2	11.25	12	23.25	19
3	3.75	12	15.75	11
4	0	6.5	6.5	1.75
5	3.75	1	4.75	0
6	11.25	1	12.25	7.5

Figure 19.—Graphic bridge shim calculation

Analytical Shim Calculation - 6 Legged Bridge

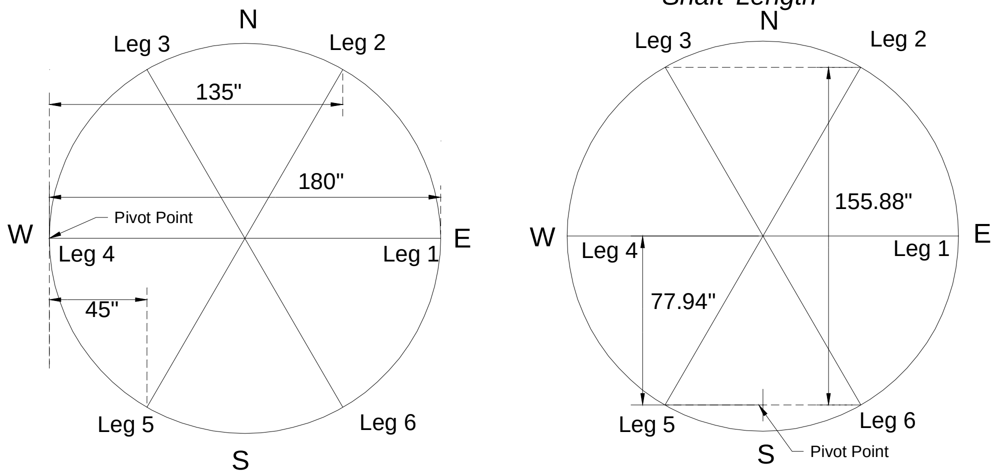
Given Data

Shaft Length =434.5"

Bridge Diameter = 180"

Out of Plumb of Center of Runout = 0.037 West, 0.032 South

$$\textit{Required Bridge Leg Elevation Change} = \frac{(\textit{Pivot Point Distance})(\textit{Out of Plumb})}{\textit{Shaft Length}}$$



East-West

$$\textit{Leg } 1 = \frac{(180)(37)}{434.5} = 15.3 \textit{ mils}$$

$$\textit{Legs } 2+6 = \frac{(135)(37)}{434.5} = 11.5 \textit{ mils}$$

$$\textit{Legs } 3+5 = \frac{(45)(37)}{434.5} = 3.8 \textit{ mils}$$

$$\textit{Leg } 4 \textit{ is the Pivot Point} = 0 \textit{ mils}$$

North-South

$$\textit{Legs } 1+4 = \frac{(77.94)(32)}{434.5} = 5.74 \textit{ mils}$$

$$\textit{Legs } 2+3 = \frac{(155.88)(32)}{434.5} = 11.48 \textit{ mils}$$

$$\textit{Legs } 5+6 = 0 \textit{ mils}$$

Bridge Shim Calculation (Thousands of an inch or mils)				
Bridge Leg No.	EAST-WEST	NORTH-SOUTH	TOTAL	SHIM ADDITIONS
1	15.3	5.75	21.04	17.24
2	11.5	11.48	22.98	19.18
3	3.8	11.48	15.28	11.48
4	0	5.74	5.74	1.94
5	3.8	0	3.8	0
6	11.5	0	11.5	7.7

Figure 20.—Analytical bridge shim calculation

e. Move the shaft so that the centerline of the thrust runner is directly over the center of the turbine bearing housing. Since the center of runout is plumb, this will also make the center of runout concentric with the turbine bearing housing. Lock the thrust runner in place with jacking bolts or bearing segments in preparation for guide bearing installation. See section 8 for guide bearing installation procedures.

7.2 Procedures for Adjustable Shoe Thrust Bearing

There are two basic procedures listed below for aligning units with adjustable shoe thrust bearings. The first method requires making all shaft plumb and bearing loading adjustments by adjusting the thrust bearings. The bearings are loaded and made level by adjusting bearing height. The second method uses the adjustable feature of the shoes only to achieve equal loading. The bearings are leveled, and therefore the center of runout made plumb, by shimming the bridge similar to the procedure for spring loaded bearings.

Some adjustable shoe thrust bearings are equipped with strain gages to measure the loading on the individual shoes. Before using the strain gages, they should be thoroughly checked to make sure they are properly bonded and functioning properly. After 20 or more years submersed in oil, there are usually one or more gages that are not working properly. In most cases, if strain gage measurement is desired, it is a good idea to install all new gages.

Adjustable Shoe Thrust Bearing - General

a. Take plumb readings with the shaft in the zero degree position and plot the shaft profile. If the dogleg is excessive, make corrections as discussed in section 6.2. Take clearance readings of the turbine seal rings, turbine bearing housing, generator stator, and generator guide bearing housings if the guide bearing housings are not adjustable. Plot the centerlines of the static components on the shaft plumb plots to determine concentricity. The concentricity should be checked even if the stationary components were centered with a single plumb wire with the rotating components removed.

b. Take static runout readings using either Method I or II. If the magnitude of static runout exceeds the tolerance in table 1, make necessary corrections as discussed in section 6.6. Plot the runout readings and, using the plot of the plumb readings, determine the position of the center of runout relative to the shaft at the thrust bearing elevation.

Adjustable Shoe Thrust Bearing - Method I

(i) If the plumb of the center of runout is out of tolerance, corrections will be made by adjusting the thrust shoes. Check location of adjustment screw and that there is clearance for the slugging wrench and hammer at all bearings. If the center of runout is significantly out of plumb, it may be desirable to shim the bridge to try to bring the center of runout closer to plumb. This will limit the amount of movement required of the thrust shoes. Follow the shimming procedure under section 7.1.

(ii) Use the data is step (b) to make a new plot with points for the relative position of the center of the shaft at the thrust bearing elevation and the center of runout at the turbine bearing elevation. Verify, from drawings, the direction of rotation (clockwise or counter-clockwise) of the thrust bearing jack screw to raise the shoe.

(iii) Check for free shaft and zero the dial indicators at the turbine guide bearing elevation and at the thrust bearing elevation.

(iv) Start loading with the high shoe, hitting the slugging wrench just hard enough to get 0.0005 to 0.001 inch of movement of the shaft at the turbine bearing. Check for a free shaft. If the shaft is not free, turn on the high pressure lubrication system and move the shaft at the thrust bearing until the shaft is free. Subtract the dial indicator readings at the thrust bearing from the readings at the turbine bearing and record the corrected value, plot the point, and label it with the number of the shoe. Figure 21 is an example of a table for recording the dial indicator readings and a plot of the data.

(v) Moving to the next shoe, hit the slugging wrench to achieve more movement than the first shoe. Again, check for a free shaft, make it free if it is not, record the readings, and plot the point. Continue loading each successive shoe, increasing the amount of movement for each shoe until the low shoe is loaded. After loading the low shoe, the movement should be decreased until the starting shoe is reached. When adjusting the shoes, never unload a shoe and never skip shoes.

(vi) The plot of the points will create a spiraling pattern as the shoes are loaded (figure 21). It will likely take several rounds to move the center of runout to the desired position. Keeping track of the plot during the loading will help determine how hard or how many times to hit the slugging wrench. Once the center of runout is at the desired position, all of the shoes should be loaded one more time, striking each shoe just hard enough to get approximately 0.0005 inch movement. The purpose of the final round is to ensure that each shoe is equally loaded.

(vii) Take plumb and runout readings again to verify the position of runout. Take hard micrometer readings at the turbine bearing housing to determine relative position of turbine bearing center.

(viii) Move shaft so that the centerline of the thrust runner (point 0,0) is directly over the center of the turbine bearing housing. Because the center of runout is plumb, the center of runout will be concentric with the turbine bearing housing. Lock the thrust runner in place with jacking bolts or bearing segments in preparation of guide bearing installation. See section 8 for guide bearing installation procedures.

Adjustable Shoe Thrust Bearing - Method II

(i) If the plumb of the center of runout is out of tolerance, shim the bridge according to the procedure in section 7.1.

(ii) When the center of runout is plumb, set up dial indicators at the turbine bearing at positions corresponding to the thrust shoe positions. One indicator will be required for each thrust shoe.

(iii) Start at any shoe and strike the slugging wrench. It is important that the same person do all the loading on the shoes so that they can get a “feel” for the loading.

Adjustable Shoe Thrust Bearing Loading

Thrust Shoe Number	Starting Point		5		6		7		8		1		2		3	
Direction	N	E	N	E	N	E	N	E	N	E	N	E	N	E	N	E
Bottom	0	0	-1	-2	-3	-3	-5	-2	-8	9	-2	27	2	32	22	27
Top	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	1
Corrected	0	0	-1	-2	-3	-3	-5	-2	-8	9	-2	26	2	31	22	26

Thrust Shoe Number	4		5		6		7		8		1		2		3	
Direction	N	E	N	E	N	E	N	E	N	E	N	E	N	E	N	E
Bottom	24	22	24	20	22	19	19	20	18	29	26	41	32	43	36	42
Top	1	1	1	1	1	1	1	2	1	2	1	2	1	2	1	2
Corrected	23	21	24	19	21	18	18	18	17	27	25	39	31	41	35	40

Thrust Shoe Number	4		5		6		7 Final									
Direction	N	E	N	E	N	E	N	E	N	E	N	E	N	E	N	E
Bottom	37	40	36	38	34	37	33	39								
Top	1	2	1	2	1	2	1	2								
Corrected	36	38	35	36	33	35	32	37								

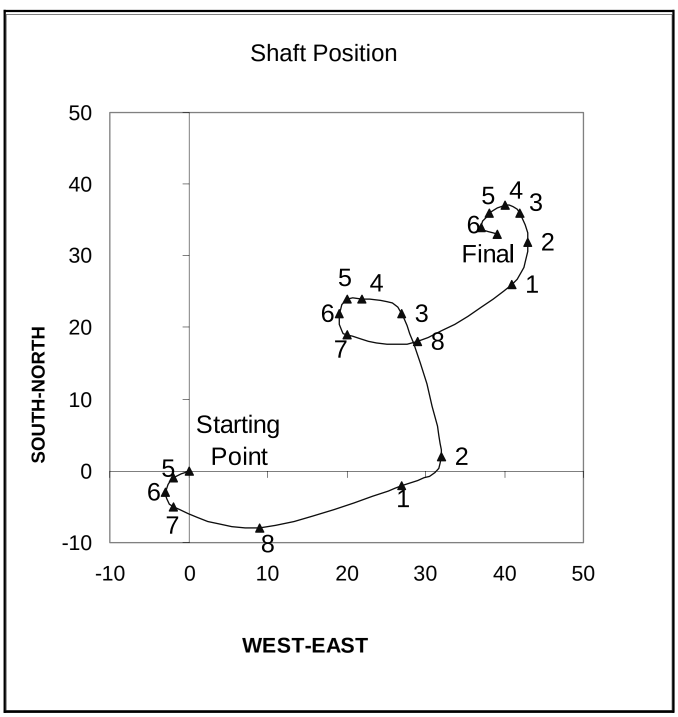


Figure 21.—Adjustable shoe thrust bearing loading readings and plot.

(iv) Continue loading each shoe until a "hit" on a shoe provides the same movement on the corresponding dial indicator for each shoe. The shoes should be equally loaded at this point.

(v) Unless the shoes were very close to being equally loaded initially, the center of runout will have moved significantly. Shim the bridge according to the procedure in section 7.1 to again plumb the center of runout.

(vi) Load all the shoes one more time, hitting each shoe equally while watching the dial indicators. As the final shoe is hit, the center of runout should be back at its original position.

(vii) Move the shaft so that the centerline of the thrust runner is directly over the center of the turbine bearing housing. Because the center of runout is plumb, the center of runout will be concentric with the turbine bearing housing. Lock the thrust runner in place with jacking bolts or bearing segments in preparation for guide bearing installation. See section 8 for guide bearing installation procedures.

7.3 Procedure for Self Equalizing Thrust Bearing

a. Use a precision machinist level to level the upper bridge (lower bridge on an umbrella unit). Level must be measured on a machined surface parallel to the surface of the bearing support.

b. Take plumb readings with the shaft in the zero degree position and plot the shaft profile. If the dogleg is excessive, make corrections as discussed in section 6.2. Take clearance readings of the turbine seal rings, turbine bearing housing, generator stator, and generator guide bearing housings, if not adjustable. Plot the centerlines of the static components on the shaft plumb plots to determine concentricity. The concentricity should be checked even if the stationary components were centered with a single plumb wire with the rotating components removed.

c. Move shaft to center in turbine bearing housing and move the top of the shaft to make it plumb.

d. Hold shaft in place at upper guide and turbine guide bearings using jack bolts or bearing segments in preparation for guide bearing installation. See section 8 for guide bearing installation procedures.

8. GUIDE BEARING INSTALLATION AND ADJUSTMENT

The final step in the alignment process is the installation and adjustment of the guide bearings. Once the guide bearings are installed correctly, the alignment is finished and the reassembly of the unit can be completed. At this point in the alignment process, the magnitude of static runout is acceptable and the center of runout, or, in the case of the self-equalizing type thrust bearing, the shaft, should be plumb and centered in the turbine bearing housing. The concentricity between the seal rings and the turbine bearing should have been confirmed earlier. To complete the alignment, the generator guide bearings must be installed concentric to the turbine guide bearing.

To make the generator guide bearings concentric to the turbine guide bearing, the shaft is used as a reference. While not absolutely necessary, centering the shaft in the turbine bearing and making the shaft plumb greatly simplifies installing the generator guide bearings if they are the adjustable shoe type. If the shaft is plumb and centered in the turbine bearing, the shoes can all be set at their nominal radial clearance. If the shaft isn't plumb and centered, the clearances can be calculated based on a final plot of the shaft and turbine bearing centerline, similar to the plot in figure 15, after the center of runout is plumb. Sleeve type journal bearings usually are a tight fit in the upper and lower bridges so that the position of the shaft is not critical.

While the turbine bearing bore should be concentric with its shell, there can be some deviation. If there is any doubt as to whether the bearing bore is concentric to its shell or if the housing is not concentric to the bearing bore, as may be the case with a doweled bearing, the turbine guide bearing should be installed at this point. With the turbine guide bearing in place, a free shaft will no longer be possible; but for installing the bearings, the shaft will simply be used as a reference and a free shaft is no longer important.

The most common methods of securing the turbine bearing in its housing are employing a tight fit between the bearing and housing, employing a tapered fit between the bearing and housing, or using dowels. A bearing with a tight fit is lowered into place and the flange is bolted tight to the bearing housing. The tight fit between the bearing shell and housing prevents any lateral movement. There may also be dowels in the flange to prevent angular movement.

The bearing with the tapered fit is somewhat self centering. As the bearing shell is lowered into the housing, the taper centers the bearing and holds it in place. Bolts in the bearing flange are used to hold the bearing in place but there is always a gap between the flange and the housing. When installing a bearing with a tapered fit, it is important to keep the bearing level. There is usually a machined surface on top of the bearing that is suitable for a precision level. The flange bolts should be tightened so that the bearing shell is tight in the housing but not so tight that the clearances are reduced. When tightening the flange bolts, it is important to frequently check the clearances on the bearing. This will provide an indication of the level of bearing and whether it is being driven too far into the fit.

The bearings that use dowels normally have some clearance between the bearing shell and the housing. Several dowels are used to prevent lateral movement of the bearing. To install, the bearing is lowered into place, the dowels are installed, and then the flange bolts are tightened.

Once the turbine bearing is in place, the shaft should be centered in the bore, either with jacking bolts or with shims.   A set of plumb readings are then taken to verify the position of shaft and to determine how far to move the top of the shaft to make it plumb. With the shaft plumb, the generator guide bearings can be installed. The design of adjustable shoe guide bearings varies, but most use jack bolts or adjustment screws that also act as pivot points for the shoes. The adjustment screw is used to set the bearing clearance. Because the bearing segments are free to pivot in any direction, setting the clearances accurately can be very challenging. Feeler gauges should extend all the way through the bearing when taking readings to prevent a false high reading at the top of the bearing when the bottom is tight against the shaft. To provide proper lubrication, the radius of tilting pad bearings may be machined to a larger value than the shaft radius plus the design clearance. Because of this, clearances measured at the edges of the bearing will be larger than the clearance at the center. The design clearance or the specified clearance on the drawings refers to the clearance in the center of the bearing, so feeler gauge readings should be taken directly in front of the pivot point.

The installation of sleeve type journal bearings is usually straightforward. The sleeve type bearings are usually a tight fit in the bridge, or they are doweled in place. Installation consists of bolting the bearings in place and checking the centers with feeler gauges. Checking the centers is critical. In some instances, what was thought to be a tight fit actually has considerable clearance, allowing the bearing to be installed off center from the bearing housing. In these cases, the bearing should be made concentric to the turbine bearing and secured with dowels to prevent lateral movement. If the bearing is a tight fit and the bearing concentricity with the turbine bearing is out of tolerance, the bridge will have to be moved. Moving the bridge without the thrust bearing can be difficult, but, if it must be moved, moving it should not affect the rest of the alignment. If the bridge with the thrust bearing must be moved, the plumb of the unit can be changed, depending on the amount of movement required. If the thrust bearing bridge is moved, the bearings should be removed and the plumb rechecked.

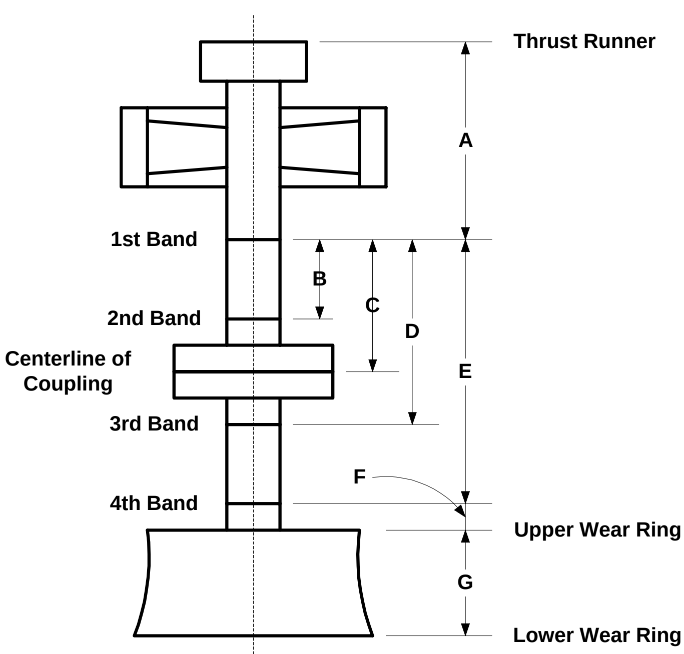
APPENDIX

Blank Forms

Unit Alignment Worksheet

Powerplant:	Unit Number:	Date:
Note:		

		Column 1 Actual Reading	Column 2 Mathematical amount to be added to Col. 1 to theoretically move all wires an equi-distance from center of shaft	Column 3 Total Column 1 plus Column 2	Column 4 Differenc e N&S E&W	Column 5 ½ Column 4 (Out of Plumb between top and bottom reading)	Column 6 Direction bottom of shaft is out of plumb. (Direction of smaller number in Column 3)	Column 7 Total N+S and E+W from Column 3	Column 8 Out of Roundnes s or inaccuracy of readings (N+S)-(E+W) Should be less than 0.002
First Reading Elevation	North								
	Sout								
	East								
	West								
Second Reading Elevation	North								
	Sout								
	East								
	West								
Third Reading Elevation	North								
	Sout								
	East								
	West								
Fourth Reading Elevation	North								
	Sout								
	East								
	West								



A = __________

B = __________

C = __________

D = __________

E = __________

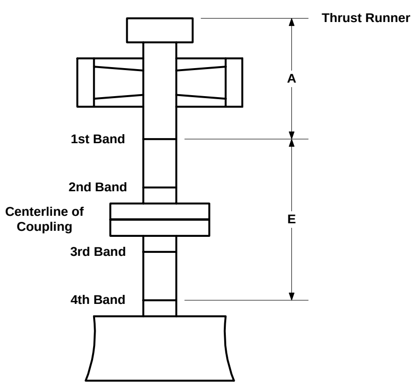
F = __________

G = __________

Unit Runout Worksheet

Powerplant:	Unit Number:	Date:
Note:		

Position	Elevation		Column 1 Actual Reading	Column 2 Mathematical amount to be added to Col. 1 to theoretically move all wires an equi-distance from	Column 3 Total Column 1 plus Column 2	Column 4 Difference N&S E&W	Column 5 ½ Column 4 (Out of Plumb between top and bottom	Column 6 Direction bottom of shaft is out of plumb. (Direction of smaller	Column 7 Total N+S and E+W from Column 3	Column 8 Out of Roundness or inaccuracy of readings (N+S)-(E+W)
0° Position	First Reading Elevation	N								
		S								
		E								
		W								
	Fourth Reading Elevation	N								
		S								
		E								
		W								
90° Position	First Reading Elevation	N								
		S								
		E								
		W								
	Fourth Reading Elevation	N								
		S								
		E								
		W								
180° Position	First Reading Elevation	N								
		S								
		E								
		W								
	Fourth Reading Elevation	N								
		S								
		E								
		W								
270° Position	First Reading Elevation	N								
		S								
		E								
		W								
	Fourth Reading Elevation	N								
		S								
		E								
		W								



A = __________

E = __________

Unit Runout Data and Runout Plot

Powerplant:		Unit Number:		Date:	
Note:					
		Column A Multiplier to Determine Total Out-of-Plumb (A+E)/E	**Column B** Values in Column 5 of Runout Worksheet	**Column C** Total Out-of-Plumb (Column A*Column B)	**Column D** Direction Shaft is Out-of-Plumb (Column 6)
0° Position	North-South				
	East West				
90° Position	North-South				
	East West				
180° Position	North-South				
	East West				
270° Position	North-South				
	East West				

A = Distance from First Elevation to Thrust Bearing = _______

E = Distance from First Elevation to Fourth Elevation = _______

Runout Worksheet Using Dial Indicators

<table>
<tr><td colspan="4">Powerplant:</td><td colspan="4">Unit Number:</td><td colspan="3">Date:</td></tr>
<tr><td colspan="11">Note:</td></tr>
<tr><td rowspan="2"></td><td colspan="2">0°</td><td colspan="2">90°</td><td colspan="2">180°</td><td colspan="2">270°</td><td colspan="2">360°</td></tr>
<tr><td>N</td><td>E</td><td>N</td><td>E</td><td>N</td><td>E</td><td>N</td><td>E</td><td>N</td><td>E</td></tr>
<tr><td>Bottom</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Top</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Corrected</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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MISSION STATEMENTS

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to tribes.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.