Technical Reference: Flexible Couplings
First Presented at the 27th Turbomachinery Symposium

RETROFITTING LUBED COUPLINGS TO DRY

Steve D'Ercole is among the contributing authors of this Flexible Coupling Short Course first presented at the 27th Turbomachinery Symposium. D'Ercole is currently the President of TurboPower, based in Friendswood Texas. He has been working with rotating equipment and flexible couplings for the past 35 years and has three US patents. TurboPower specializes in fast turn-around repair and upgrades of turbomachinery components. Prior to joining TurboPower, D'Ercole served as the General Manager of Bearings Plus, Inc. Prior to that, he held the position of Manager of High Performance Product Engineering at Kop-Flex, Inc.

RETROFIT LUBE TO DRY

1. Introduction

Dry couplings have gained wide acceptance in the petrochemical and process industries. With most new Turbomachinery packages being supplied with dry (non-lubricated) couplings, there is an increasing interest in replacing many of the older gear couplings in existence with non-lubricated versions. Properly applied "dry" couplings have improved the performance of countless trains initially installed with gear couplings, while improperly applied "dry" couplings have created more problems than they have solved. This section provides some general guidelines that should be followed whenever a retrofit of "gear" to "dry" couplings is under consideration.

2. Why Change?

Most often the interest in retrofitting "gear" couplings to "dry" occurs when the life of the older gear coupling is reaching its end, or when a substantial system upgrade is planned. When coupling removal is planned in these situations, the opportunity presents itself to take advantage of the benefits associated with dry couplings.

The first question that arises is "should the coupling design be changed at all"? If the older gear coupling has provided satisfactory service over many years, it may be best to "*stick with what works.*" The cost of changing the design could exceed the price of the new dry coupling, especially if your maintenance mechanics are not experienced with the special considerations in handling and installing dry couplings.

If you've considered staying with the lubricated coupling but you've decided that you still want to make the leap anyway, dry couplings can provide several big advantages including: no lubrication, lower unbalance forces, lower and more predictable bearing loads (resulting from misalignments and axial movements of the equipment), and very long service life.

3. Proper Coupling Selection Responsibility

When the machinery was originally purchased, the OEM had the responsibility of reviewing the coupling design. The OEM provided the application information to the coupling manufacturer for proper selection and design. The coupling characteristics were then given back to the OEM, who determined if the affects on the train would be acceptable. Many systems require that the coupling design be refined during this process to "tune" the lateral and torsional responses. The coupling characteristics most frequently requiring modification during this tuning process are the coupling weight, center of gravity (CG), and torsional stiffness. Since the OEM is usually not involved with coupling retrofits years after the train has been operating, <u>the responsibility of ensuring that the new coupling design will not adversely affect the train shifts to the end user</u> wishing to change the coupling to dry.

When specifying the dry coupling, be certain to provide the coupling manufacturer with sufficient information to obtain the proper fit of the coupling to the equipment. It is critical to resolve any questions regarding hub to shaft fit before the coupling manufacture is started.

If the equipment interfaces are shaft ends, specify the coupling bore dimensions and tolerance exactly. Also specify the required hub fit length and tolerance. If you do not have the specifications of the old gear coupling hub, specify the shaft size and required interference rate - being certain to measure the shafts exactly with micrometers, and to check the slip torque at the hub/shaft interface. If the shafts are tapered, specify the amount of taper and supply the coupling manufacturer with plug gages from a matched ring and plug gage set - where you have verified that the ring gage provides proper contact to the shaft as well as the plug gage. If this is not possible, consider sending the coupling manufacturer the hub from a spare coupling.

If the equipment interfaces are integrally flanged, be certain to specify the flange thickness tolerance. Specify the rabbet size, tolerance, and length - along with bolt hole size and location tolerances - including countersinks to clear the bolt head radii, and any jacking holes. Be certain to specify who is to supply any new bolts and nuts at these connections.

Make certain that the coupling operating environment is adequately defined - including any unusual temperatures or corrosives. Make certain that all accessibility issues have been addressed.

4. Match the Coupling

Some users have in-house experts who perform the train analysis over again with the new couplings characteristics, or they turn to independent consultants for this work. Since the costs associated with having a new torsional and lateral analysis can be very expensive, the most widely accepted practice is to "match" the gear coupling characteristics with the new dry coupling. If the new dry coupling characteristics can not be matched to the old gear coupling, the resulting operation is effectively a "crap shoot", so a complete lateral and torsional analysis is unavoidable - where the resulting costs may outweigh the benefits of the coupling conversion.

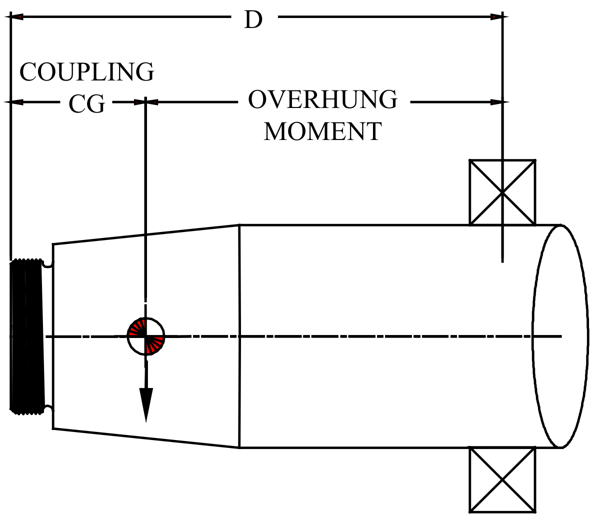
a. Most Significant Considerations

The most significant characteristics to consider when attempting to "match" the dry coupling to the gear coupling are: weight & CG locations, and torsional stiffness.

Other characteristics that must be at least comparable are: the balance classification, and the "coupling" first lateral mode of vibration. Additionally, there are a few "new" characteristics associated with dry couplings that must be considered. These include: space restrictions (dry couplings are often larger in OD), temperature rises due to windage, axial natural frequencies, axial & angular capacities, and handling/installation techniques.

1) Weight & Half Coupling Effective Center of Gravity (CG) Locations -This is one of the most critical characteristics to consider, especially for machines with a high sensitivity to unbalance e.g. where the operating speed is close to its critical speed - such as high speed compressors. The sensitivity of a rotor to unbalance is a function of the coupling's half weight (that portion of the coupling overall weight acting on the rotor of interest) and the distance of this half weight from the rotor's bearing centerline. Increasing the half weight or its distance to the bearing can adversely affect the rotor's sensitivity to unbalance and/or the rotor's lateral critical speed.

Figure 1 Coupling Influence on Equipment Laterals



The way in which the coupling's effective CG is calculated is to assume that negligible moment from the coupling weight can be transmitted across the flex point - thereby treating the coupling's flex point (disc pack, flexible diaphragm, or gear mesh) as a pin joint. The closer the flex point is to the equipment bearing, the less the resulting moment from coupling weight causing the shaft to deflect.

The rotor's lateral deflections are a function of this CG distance cubed, while the rotor's critical speed is a function of this distance squared. In analyzing different couplings' influence on a rotor's vibration response, good results have been found by considering the product of the coupling's half weight times this distance to the first power, and is referred to in this way by API 617. (See Figure 1). Hence this coupling characteristic is generally referred to as the coupling's "overhung moment".

When duplicating both the weight *and* the CG location is not possible, matching this overhung moment has been found to be a suitable criteria, for successful operation. Successful operation usually results when the retrofitted coupling is found to "match" the replaced coupling within the following guidelines:

Figure 2 Weight and Moment Criteria

(1) For operating speeds less than 3600 rpm- overhung moment matched within 20%.
(2) For operating speeds between 3600 and 6000 rpm - overhung moment matched within 15%.
(3) **For operating speeds greater than 6000 rpm - overhung moment matched within 10%.**

Note - When the coupling weight is a significant portion of the rotating weight, or if the equipment has been found to be sensitive to vibration, every effort should be made to match or reduce the dry coupling's overhung moment to that of the existing coupling.

2) Torsional Stiffness - Often couplings are used to "tune" the torsional resonant frequencies of multiple body trains. Since most applications can be effectively represented in lumped mass form with the couplings treated as torsional springs and the equipment rotors as lumped inertia's, close attention must be paid to the coupling's torsional stiffness, whenever retrofitting gear couplings to dry.

In general, the gear mesh flex point of the existing gear coupling will be torsionally stiffer than the flex point of the replacement dry coupling. Consequently, the coupling design of the dry coupling will usually have to be "*tailored*" for the application if it is to match the gear coupling.

The most common coupling design activity is to adjust the wall of the coupling's spacer (tubular piece usually found between the couplings flex points). Often, the activity of "stiffening" parts of the dry coupling to match the stiffness of the gear coupling leads to an increase in weight of the parts being "stiffened" - causing the coupling designer to look elsewhere in the dry coupling to reduce the weight of other parts which contribute less to the coupling torsional stiffness. In the case where the coupling length is relatively long in comparison to its diameter, a successful "match" can usually be obtained. However, for shorter couplings, alternate materials may have to be used and the end result may be a somewhat heavier coupling - where the overhung moment guidelines previously described are often employed.

Successful operation usually results when the retrofitted coupling is found to "match" the replaced coupling within the following guidelines:

Figure 3 Torsional Stiffness Criteria

(1) For two body trains with speeds to 3600 RPM - torsional stiffness matched within +/-25%.
(2) For three body trains without a gearbox and speeds less than 6000 RPM - torsional stiffness matched within +/-20%.
(3) For all other trains - torsional stiffness matched within +/-15%.

Note - When torsional pulsation's are known to exist in the train, every effort should be made to match the dry coupling's torsional stiffness to that of the existing coupling.

5. Other characteristics To Consider

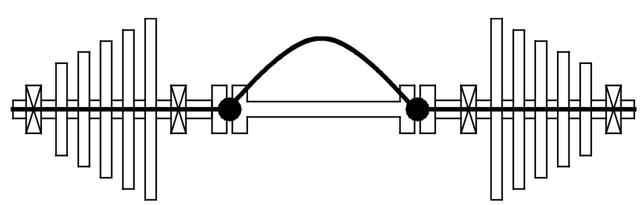
a. Balance Classification -

Dry couplings inherently exhibit better balance repeatability than gear couplings. Unlike gear couplings, which require a certain amount of clearance for the gear mesh to slip and tilt, dry coupling accommodate equipment movements through material flexure - and therefore do not require any clearances to operate successfully. Generally, it is recommended to specify that the dry coupling meet or exceed the AGMA Balance Class of the gear coupling being replaced.

b. Lateral Coupling Modes -

The first lateral mode of the coupling is generally calculated as a tube supported on each end at the flex points. This "*simply supported*" tube is able to bend and whirl in this deflected "*bowed*" shape (Figure 4). Consequently, most coupling arrangement drawings will define a "simply supported tube" lateral critical speed (LCS).

Figure 4 Coupling Mode "LCS" Typically Found on Coupling Drawings



It is important to note that this "coupling" LCS mode is for the center section of the coupling only. It is in no way an indication of the system lateral critical speed. The coupling's "simply supported tube" LCS also generally does not reflect any contributions or deflections of the equipment and associated mounting hubs. The coupling's effect on the equipment lateral critical speeds are more a function of the overhung moments, so the usefulness of the "coupling" LCS on simple supports is limited to ensuring that the coupling "whip" mode is sufficiently far enough away from the operating speed so as not influence the equipment LCS modes, or whirl around on its own (Figure 5A & B). Therefore, it is generally recommended that the coupling's first lateral mode be at least 50% above operating speed. In the case of very long equipment separations at high operating speeds this may not be possible, in which case a more in depth evaluation should be undertaken.

Figure 5A Typical System Lateral Modes

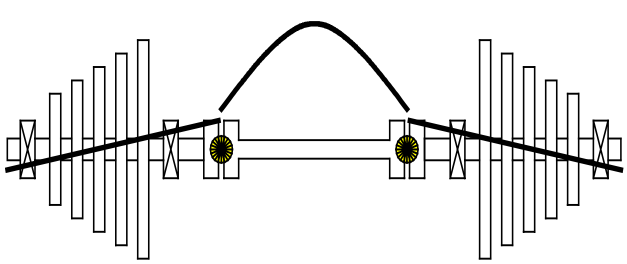
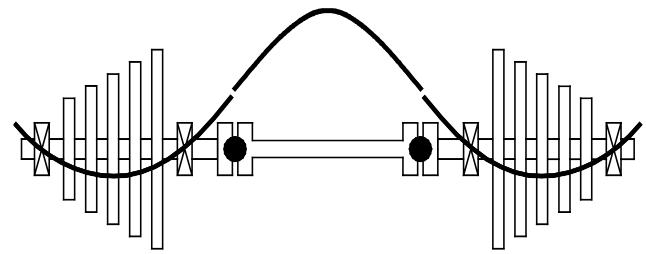


Figure 5B Typical System Lateral Modes



Space Restrictions -- For a given torque capacity, dry couplings are often somewhat larger in diameter than their gear coupling counterparts. Therefore, it is a good idea to provide the coupling manufacturer with a drawing of the existing coupling guard along with any other descriptive information regarding housing restrictions, piping, etc. to ensure that the coupling will physically fit in the application, and that if there are any modifications required to the equipment - they can be properly planned prior to the coupling installation.

c. Temperature Rises & Windage Effects -

When couplings operate at high speeds in oil-tight enclosures, - they shear the air; where the maximum air velocity is found at the coupling surface and the minimum air velocity is found at the enclosure surface. The friction between adjacent air layers generates heat. Since dry couplings are often larger in diameter than gear couplings, they often generate more heat due to these windage affects. The amount of heat that will be generated is a function of the coupling's operating speed and the geometry of the coupling and its surrounding enclosure.
The closer the rotating coupling is to the surrounding non-rotating parts (housing and

guard), the more heat that will be generated. As a general "*rule of thumb*", when the coupling surface (OD and faces) is less than 2" away from the non-rotating components (coupling guards and housings) calculations should be performed to ensure that the resulting temperatures will be within safe limits. The generation of turbulence can usually be minimized by incorporating shrouds in the coupling design in the areas of bolt heads and nuts. If the appropriate information of the surroundings is supplied, most coupling manufacturers can provide estimates for Horse Power losses and heat generation.
If this analysis indicates a problem, modifications to the housing, coupling, or coupling guard may be required. It is worth pointing out that if the dry coupling is being retrofitted for a continuously lubricated gear coupling, the guard temperature can be significantly cooled by continuing to use the oil spray system. Since the dry coupling will not be adversely effected by an oil spray, its usually a good idea to leave the oil system operational. Doing so may also serve to be valuable decision if the gear coupling is kept for an emergency spare.

Another potential problem that can be encountered when retrofitting dry couplings in oil-tight enclosures are related to pressure differentials. Although pressure problems are not usually related to heat generation, they can cause a different type of problem.

Negative pressures can be created in the area of the equipment seals where oil may be sucked from the machines into the coupling enclosure. This situation is usually found only when large disc shaped parts of the coupling are mounted on the equipment shafts near the seals (usually associated with the *"Reduced Moment"* variety coupling). The disc rotation creates an air flow from the slower moving ID to the faster moving OD, resulting in pressure differentials which can cause a loss of oil in the machine housings.

Typical solutions to these negative pressure problems often involve installing to the guard or housing a "baffle plate" (Figure 6) or in some cases an "air breather" tube (Figure 7) in front of the seal to increase the pressure at that location.

The topics of windage and the proper use of baffles, vents, and drains are covered in greater detail in the upcoming section regarding *Coupling Guards*.

Figure 6 Example of Baffle Plate

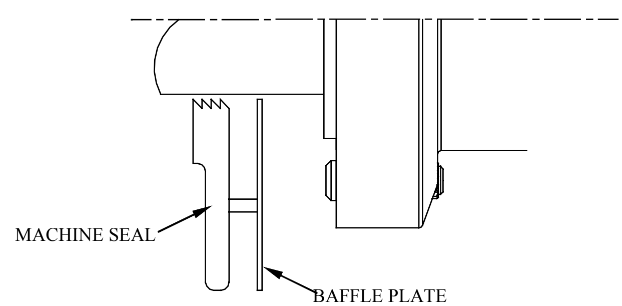
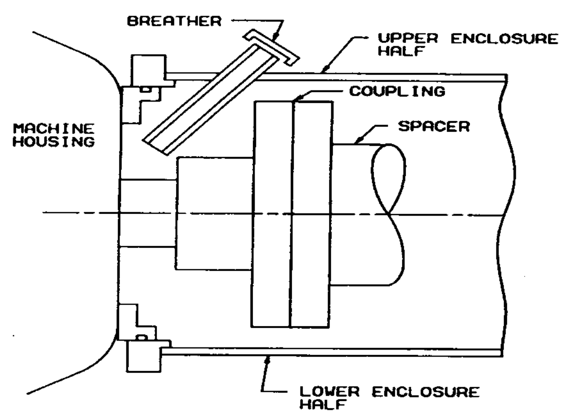


Figure 7 Example of Air Breather Tube

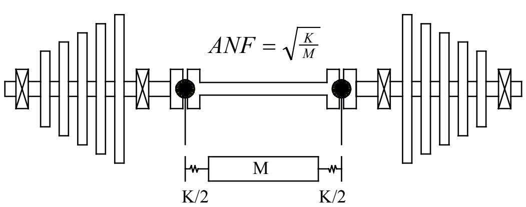


d. Axial Natural Frequencies -

Since the flex points in dry couplings are metallic springs, dry couplings exhibit a potential mode of vibration called the axial natural frequency (ANF) which is not found in gear couplings. This ANF results because the mass of the center member (between flex points) is supported between two axial springs (the two flexible elements typically found on each side of the coupling) (Figure 8).

In this way, dry couplings are unique from gear couplings in their potential to vibrate axially (along their longitudinal axis). However this mode is unlike lateral and torsional modes because it is difficult to excite and is isolated to the coupling itself. Potential excitation factors include out of square faces, and thrust bearing runout.

Figure 8 Coupling Axial Natural Frequency Model

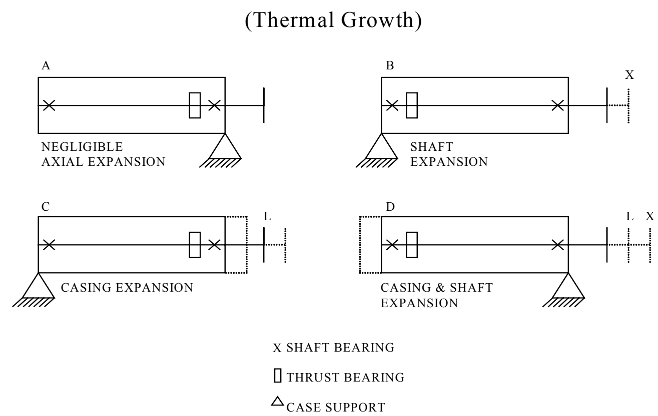


Because most dry couplings exhibit either nonlinear axial spring rates or are well damped, large axial deflections are not found at or near ANF's. In fact, there has never been a documented case of a coupling failure contributed to ANF. Therefore, the third edition of API 671 has virtually eliminated this previous requirement. Only undamped flex element couplings with linear spring rates are required to avoid having calculated ANF's within 10% of the operating speed range.

e. Axial and Angular Capacities -

Most machines require flexible couplings to accommodate movements of the machines during operation. Although the machines can be aligned very accurately, this alignment will not be maintained in operation. The most common cause of these machinery movements are differences in thermal growths of shafting, casings, and support structures (Figure 9)

Figure 9 Typical Equipment Movements



Other commonly encountered contributing factors include: piping forces; either temperature or pressure related (Figure 10), and changes in properties of fluids being handled (Figure 11).

Figure 10 Piping Forces

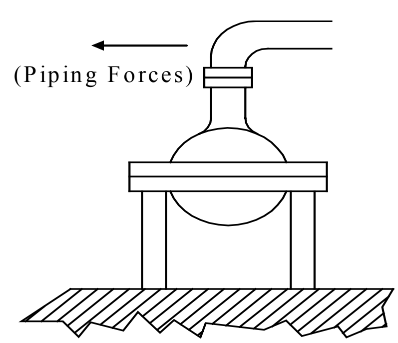
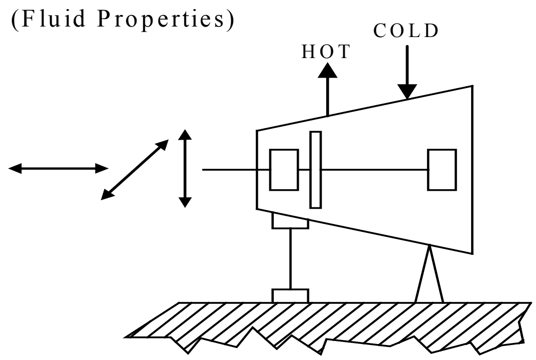


Figure 11 Fluid Pressures



Since ***the equipment will move***, it is the coupling's job to accommodate these movements with as little effect on the equipment as possible. The equipment will move in 3 basic directions: vertically (up and down), horizontally (sideways), and axially (along the shaft axis). Since these movements will not be the same on each side of the equipment, the machinery shaft centerlines will also become skewed from their original axis. In order to accommodate the "offset" that often results between the equipment centerlines, flexible couplings are provided which have a flex element on each end of the coupling.

To the flexible coupling, all of these combinations of equipment movements boil down to two basic parameters: axial movement, and angular misalignment. This is because all lateral machinery movements are resolved as angles at the coupling's flex elements. Hence the coupling's capability to handle these two parameters is usually called out by the coupling manufacturer on most coupling arrangement drawings as *Axial Displacement Capacity*, and *Angular Misalignment Capacity*. Since the operating angles seen at each end of the coupling are usually not equal, it is customary to give the angular capacity per *end* while the axial capacity is typically per *coupling.*

The way gear couplings are designed to handle these misalignments are very different from dry couplings. Gear couplings are effectively crowned splines, with a built in small amount of radial clearance and backlash between mating male and female teeth. These small clearances are necessary to allow the male teeth to slide and tilt along the mating female teeth. It is this sliding and tilting that requires the gear coupling to be lubricated. Most gear couplings are designed to operate continuously at ¼°, and are very generous in their ability to absorb axial movements of the equipment.

Dry flexible element couplings accommodate these misalignments in a very different way. The flex elements deflect by allowing the material to bend and stretch within specified limits. Because the material flex's instead of slides, there is no need for lubrication. These flexible elements must be strong enough to transmit the required power, but thin enough to deflect without failing or causing unacceptable loads on the equipment bearings. Like gear couplings most dry coupling are also designed for ¼°, but <u>the dry coupling's ability to absorb axial movements of the equipment is much less than gear couplings</u>. For this reason, *the axial movements of the machines must be known before the dry coupling can be selected*. (Be certain to specify whether or not you have accounted for the coupling's thermal growth whenever specifying the axial thermal growths of the machinery.)

If dry couplings are operated within their specified capacities, they will far outlast their gear coupling counterparts, and will impose more predictable and significantly lower loads on the machines. However, if exposed to conditions that exceed their stated capacities, the results can be extremely detrimental - including the possibility of catastrophic failure. For these reasons, it is important to <u>pay close attention to the axial and angular capacities</u> to make certain that the retrofitted dry coupling is operated within its intended useful range.

f. Handling and Installation Techniques

The most important activity of installing the dry coupling is to adequately review the installation procedure in advance, especially if the mechanics are used to installing only gear couplings. Unlike gear couplings, installations of dry couplings must involve the precise measurement of the distance between the equipment. Dry coupling manufacturers provide shims to adjust for slight differences in equipment spacing and coupling length from the nominal values, but this adjustment is usually not more than $^{1}/_{8}$" in either direction.

Most dry couplings are designed to be installed so that they run in a more *relaxed* state during steady state conditions. Since machine shafts typically grow toward each other, most dry couplings are intended to be "stretched" in the cold (installed) condition, so the coupling manufacturer intentionally designs the dry coupling to be "short" by a specific amount. Usually this amount is equal to or just less than the expected axial movements of the equipment during normal operation.

Another difference between dry couplings and gear couplings is the way in which rabbets (or spigots) are to be cleared when installing the center member. With gear couplings, you simply slide the sleeve (internal gear) over the hub (external gear) to clear the rabbets. With dry couplings, the restoring force tends to *"fight back*", so you have to mechanically collapse the flex element axially to hold it in place while the center section is brought in. Since these flex elements are sensitive to axial movement, you must be careful not to over collapse the flex element past its stated capacity (usually half of the coupling's capacity on the drawing). Many coupling manufacturers will provide separate hardware for the sole purpose of properly collapsing the flex elements. Since this activity is not found with gear coupling installations, it is critical to make certain that everyone involved knows that this collapsing hardware is not part of the coupling and must be removed (and double checked for removal) prior to start up.

The flexible elements of dry couplings are more sensitive to abusive handling, so the installers must take precautions not to scratch, dent, or ding these areas during installation.

It's important to have all coupling and equipment drawings, instruction sheets, tools, lifting devices, and parts on hand prior to scheduling the actual installation. The phone number of a contact at the coupling manufacturer is recommended to be available for any unforeseen circumstances.

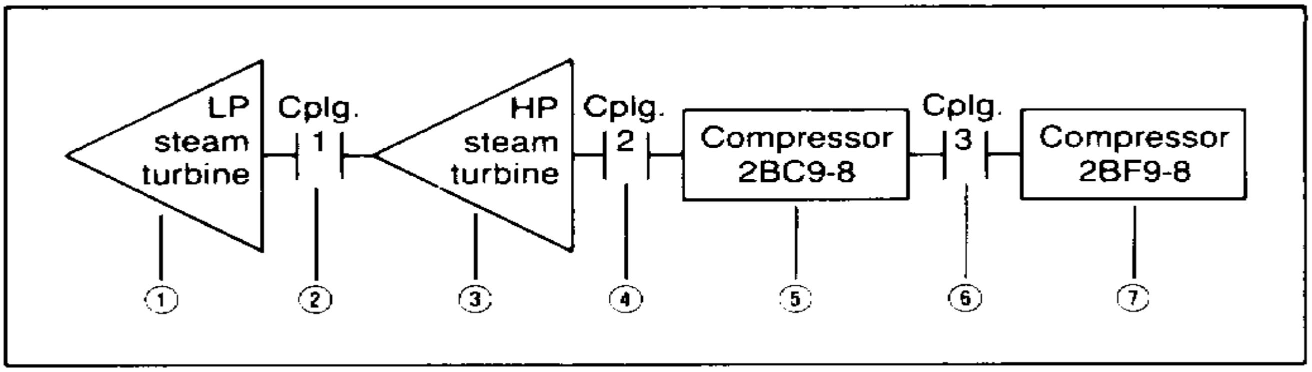
Since it's recommended to recheck the equipment alignment after the coupling is installed, it's important to know what surfaces of the dry coupling can be used for indication purposes.

Dry couplings sometimes have more fasteners than gear couplings. It's important to install the bolts in the direction shown on the coupling drawing and to use proper torque wrenches while tightening them to the prescribed value. The hardware will generally be supplied in weigh balanced sets and must not be mixed with other sets. Use only the coupling manufacturer's bolts and nuts. Pay attention to the matchmarks and serial numbers on the coupling to ensure each part is properly positioned in the assembly. If there are any questions that arise, you should not hesitate to call the coupling manufacturer for clarification.

Example of Retrofitting

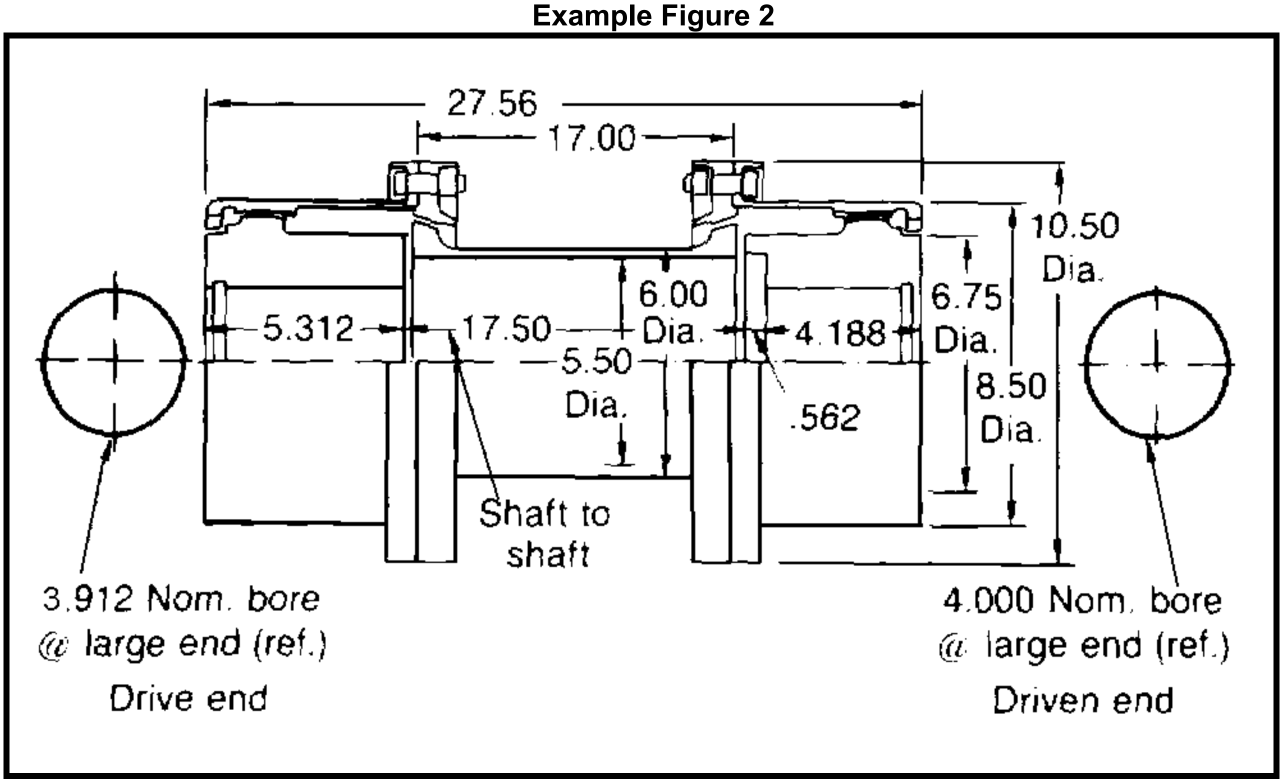
We will look at replacement of one coupling in a Syn-Gas train as shown below:

Example Figure 1



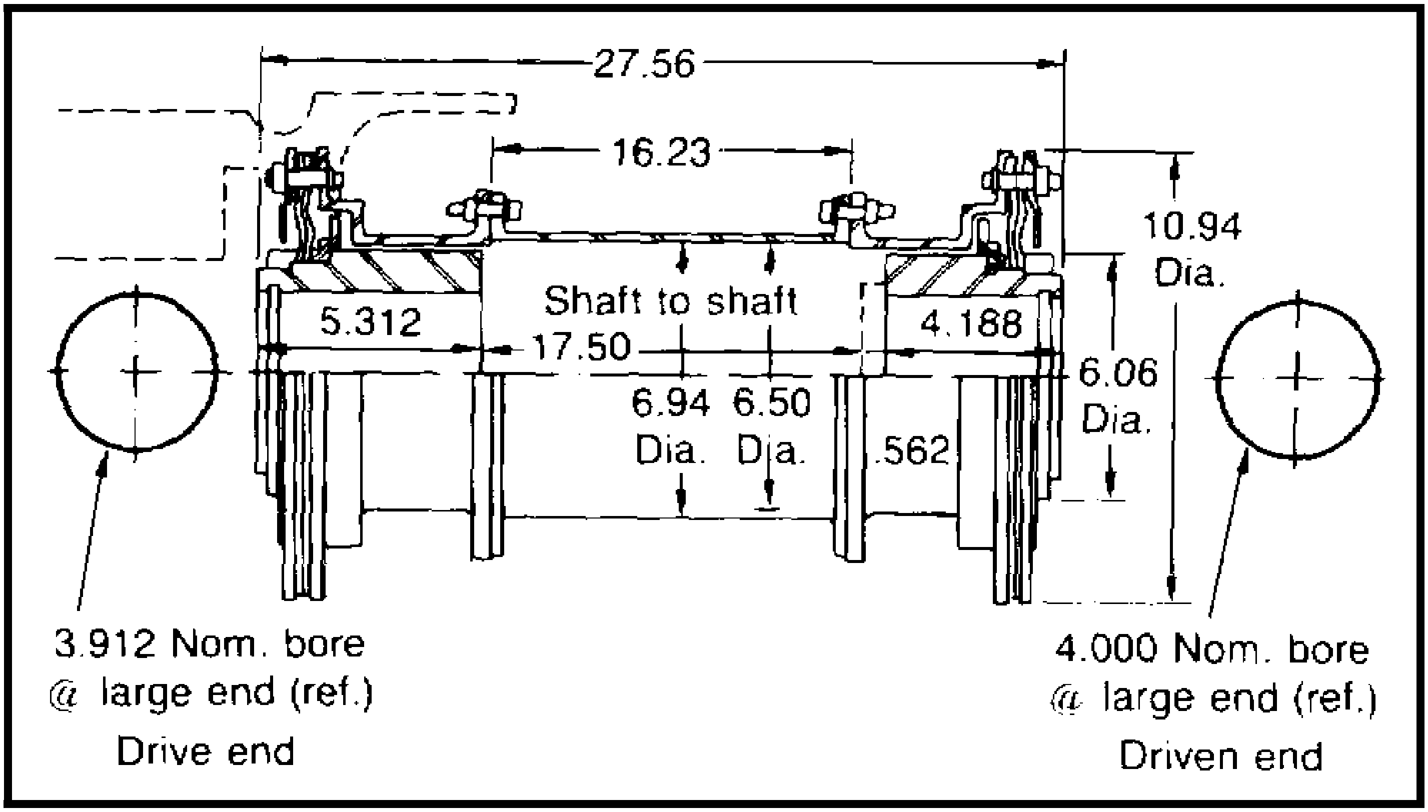
We will be looking at coupling #2 (position 4). The combined horsepower requirements for coupling #2 was 27,500 HP speed 10,300-11,000 RPM. The Figure 2 below shows the original gear coupling.

Example Figure 2



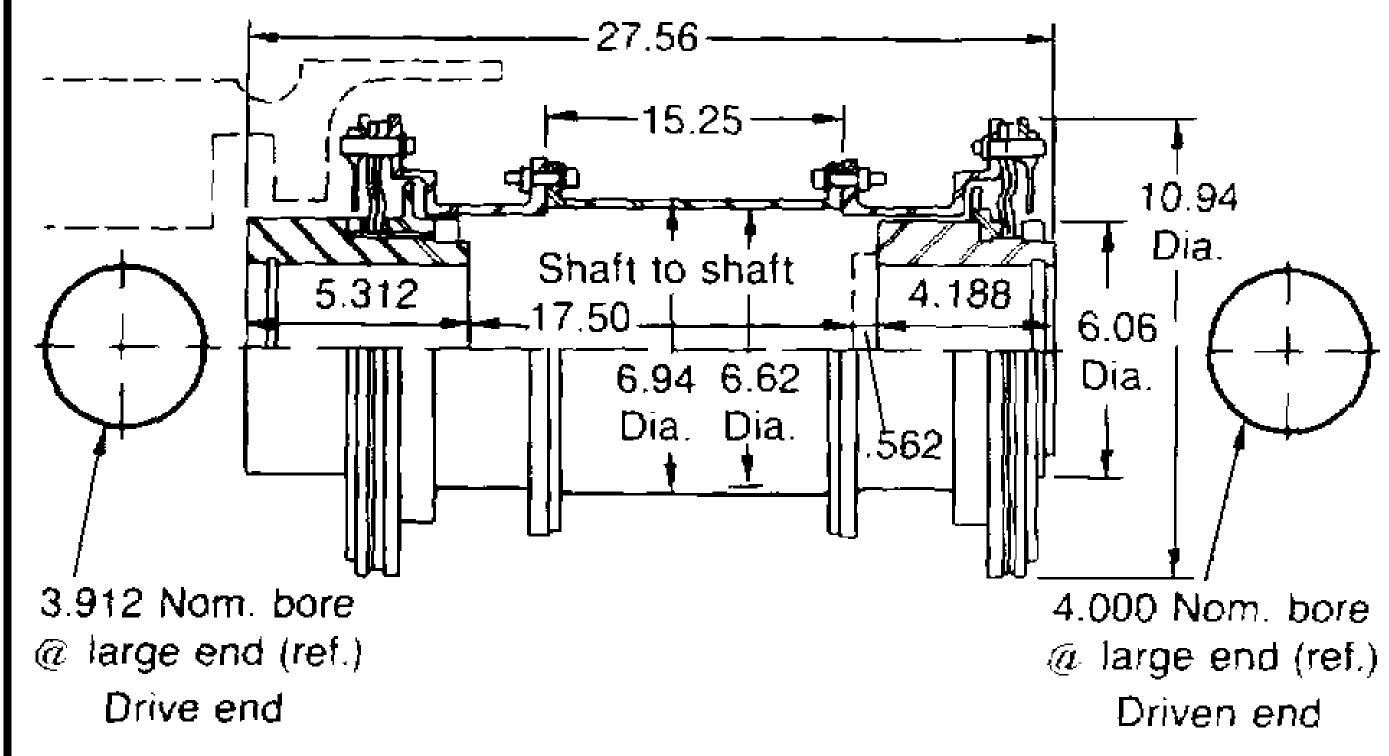
The proposed dry replacement coupling was initially selected and dimensional data was forwarded from the coupling manufacturer to the facility engineer. After a review of the equipment layout, it was found that the proposed diaphragm coupling (Example Figure 3) would interfere with the turbine housing as shown below:

Example Figure 3



After careful review of the housing layouts it was decided that the diaphragm pack had to be moved forward on the turbine shaft. However, if it moved too far, it could have upset the system lateral critical. It was moved forward only enough to provide clearance so that under operation the coupling bolts would not contact the housing (approximately ¼" clearance) Calculations showed that the heat generated from the nuts against this housing could result in enough horsepower loss to cause overheating of the coupling guard. Consequently, the coupling guard was redesigned to use threaded inserts instead of nuts in order to reduce the horsepower losses and keep the guard temperature at acceptable levels. These design modifications are illustrated in Example Figure 4.

Example Figure 4



The table below shows the comparison of the mass elastic properties for the gear coupling, the initially proposed coupling, and the final coupling as installed in the application.

Example Figure 5

Characteristics	Original gear cplg	Retrofitted Diaphragm cplg	Retrofitted Dia. cplg
OD (inches)	8.2	10.94	8.97
Comp. weight @ CG both ends	34.3 lb @ 2.74 in.	55 lb @ 2.74 in.	31 lb @ 2.97 in.
Torsional stiff.	5.4×10^6 in.-lb/rad	6.7×10^6 in.-lb/rad	5.4×10^6 in.-lb/rad

This coupling was installed in 1986. No known operating problems have been reported. Initially the vibration levels were reported to be 25% below the gear coupling. The guard temperature was measured to be approximately 135^{o} F which is very close to the calculated value of approximately 140^{o} F.