Wicket Gate Bushings
Grease vs. Greaseless

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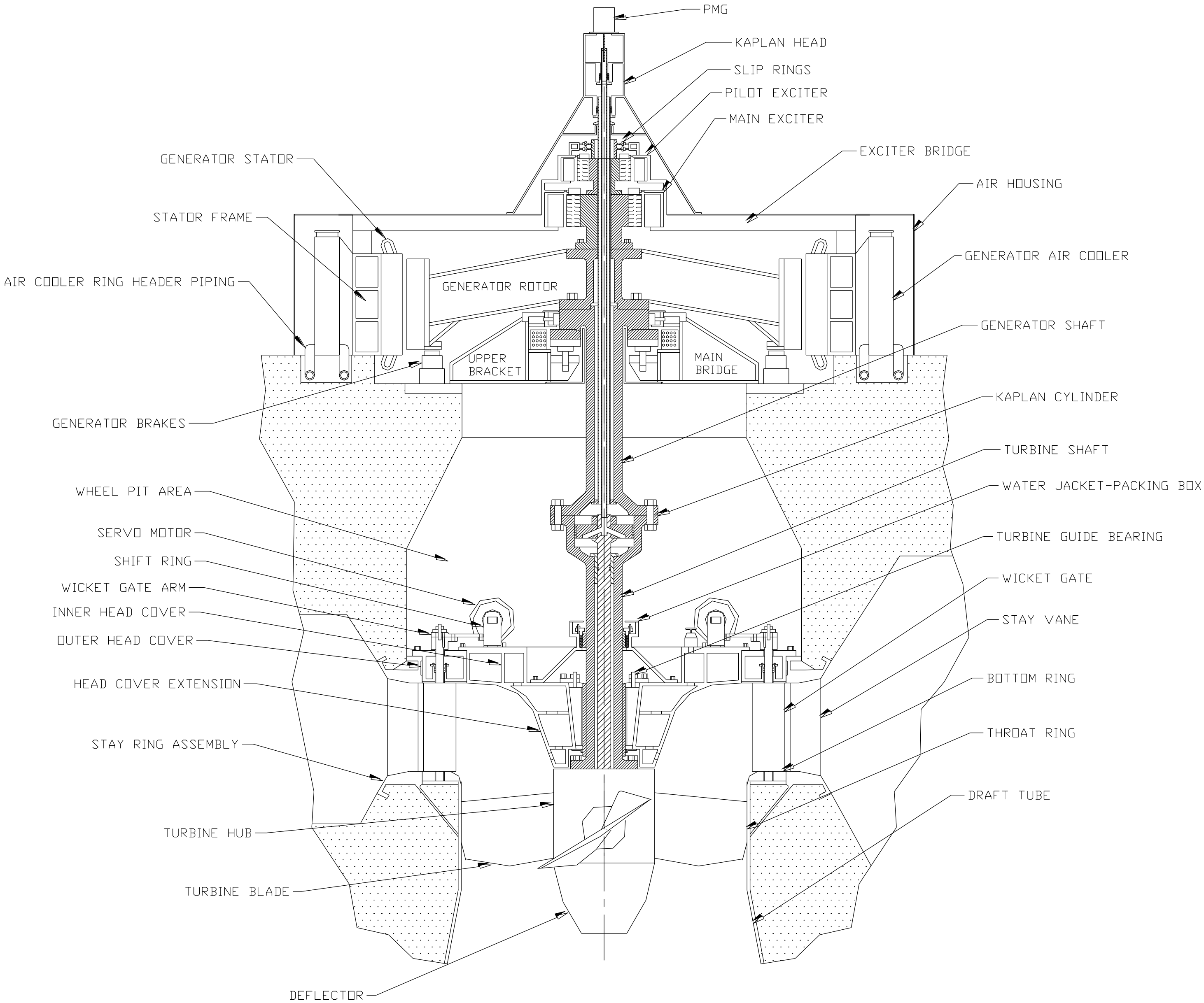

INTRODUCTION

The hydro system of the Tennessee Valley Authority (TVA) contains 30 plants and 113 units providing 5,905 MW of TVA's 29,413 MW total system capacity. In 1992 , TVA began an aggressive hydro modernization program (HMOD) to rehabilitate , upgrade , and modernize 92 of the 113 units by the year 2013. The HMOD scope includes much of the equipment in the generator, turbine, and balance of the power train. The turbine scope includes replacement of the turbine runner and rehabilitation of other turbine components, such as, the wicket gate mechanism. The early conception of the program included removal of the turbine's automatic greasing system and use of latest greaseless bushing technology in order to minimize grease discharge into the waterway. To date, 32 turbines have been converted to complete use of greaseless bushings. At the beginning of the HMOD program, greaseless bushing technology was relatively new but promising. Laboratory tests and experience from other utilities showed that our choices of greaseless materials were the best in the market at that time. In our opinion, after 8 years of field experience, their performance in our turbines has not met expectations. New advances in greaseless bearing materials and the latest laboratory tests show other greaseless bearing materials to be superior to our original choices. However, we have found that laboratory tests do not always fully represent the true material performance in the field.

USES OF BUSHINGS AND WEAR PADS IN HYDRO UNITS

Bushings, bearings, and wearing pads (all hereafter know just as "bushings") are typically used in the wicket gate mechanism of a hydro turbine. Many of the bushings are exposed to the waterways due to the flow of water through the turbine. Over one hundred years ago, many of these bushings were simply cast iron (cast iron contains embedded graphite) rubbing against steel with water aiding lubrication. Later grease was added as a lubricant and then anti-friction bronze was used to further reduce wear. Greased bronze has proven to be very reliable.

BRONZE BUSHINGS

The bronzes used for bushings are typically of the tin bronze family. Bronzes are softer than the contact journals which are typically steel or stainless steel. They have a low tendency to adhere to steel, high load carrying capacity, corrosion resistance, and provide excellent journal protection. To reduce friction and wear and ensure long life of the bronze bushings, lubrication must be provided using oil, grease, or solid lubricants. Grease has proven to be the lubricant of choice for wicket gates due to its high resistance to water washout, high load carrying capacity, and vibration damping.

GREASE

Lubricating greases are not simply very viscous oils. Greases consist of lubricating oil (usually mineral oils), which have been thickened by means of finely dispersed solids called thickeners. These thickeners bind the oil together resulting in a gel like substance with good lubricating properties. The most commonly used thickeners are soaps containing either calcium, lithium, or aluminum. The soaps are fibrous and tend to interlock to give stiffness, thickening, and adhesion. Under pressure between two contacting surfaces, the grease will give up its lubricating oil momentarily providing lubrication. The oil then returns to its bound state in grease. The periodic greasing of the bushings also provides a mechanism of removing debris by pushing out the contamination from the contact areas as the new grease enters.

A large hydro unit the size of TVA's Raccoon Mountain pump-turbine unit uses approximately one barrel or 400 pounds of grease per year with smaller units using a corresponding lesser amount of grease. In addition, only about 40 percent of the bushings using grease in the wheel pit ever come in contact with the water passage. Therefore, it is estimated that less than one half of this grease ever reaches the waterway . Current environmental laws do not regulate the use of grease for lubrication of components in a waterway. The laws are centered on the production of a "visible sheen" of oil on the water. Lubricating greases currently being used have a high resistance to washout and therefore; detecting a visible sheen has not been an issue for wicket gate grease.

Environmentally friendly ("green") greases are becoming available for use in hydro turbines. These "green" greases typically have two main characteristics: low toxicity and high biodegradability. In the past many of these greases did not have the mechanical properties necessary to carry the loads seen in a hydro unit. However, recent tests by others, show some "green" greases have proven performances similar to standard lithium based greases. The major arguments opposing "green" greases, are their environmental benefits are not recognized by the regulatory agencies and their high costs. As stated above, a sheen on the water surface from any source is a sheen in the eyes of the regulators, regardless of it's "green" status. However, these regulatory perceptions may change in the future as more attention is drawn to this issue.

REHABILITATION AND MODERNIZATION

During the past 25 years many hydro units have undergone rehabilitation and modernization which includes replacement of wicket gate bushings. Environmental concerns and fear of future regulations concerning grease discharge into the waterways prompted many in the hydro industry to begin addressing discharge of lubricating greases. TVA and others began to take the opportunity to remove the grease from their hydro turbines during these HMOD outages. Since the beginning of the HMOD program in 1992, 32 of TVA hydro turbines have been converted to complete use of greaseless bushings during their HMOD upgrades. However, this new technology has not been implemented by the hydro industry without growing pains.

GREASELESS BUSHINGS

Greaseless or "self-lub" bushings are a relatively new technology that has matured over the past 25 years. They are designed to have a low coefficient of friction utilizing a built-in solid lubricant and/or low friction material instead of using grease.

When TVA began using greaseless bushings in 1992, neither TVA or the hydro industry, had much long term experience with the performance of the various products on the market. Based on early studies and contacts with other utilities, we selected two different types of greaseless bushings to install. One was a polymer lined (plastic) material (liner in bronze sleeve) and the other was a plugged bronze material (PTFE based plugs in a bronze bushing). Hereafter, these will be called "PL" for polymer lined bushings and "PB-1" for the plugged bronze material. Both of these materials were well known leaders in the greaseless bushing material market at this time. The PL bushing is a plastic based material of low friction, whereas, the PB-1 bushing is a bronze material with plugs of solid lubricant scattered across about 30% of its surface. We chose to use the PL material primarily for wicket gate stem bushings on the main river units due to its resistance to wear from silt. The PB-1 material has primarily been used for stem bushings on wicket gates in the high head units, and linkages, as well as shifting rings on all units due to its high load capacity.

Laboratory tests and experience from other utilities showed that our choices of greaseless materials were the best in the market at that time. In our opinion, after 8 years of field experience, their performance in our turbines has not met expectations. New advances in greaseless bearing materials and the latest laboratory tests show other greaseless bearing materials to be superior to our original choices. However, we have found that laboratory tests do not always fully represent the true material performance in the field.

Several TVA units with PB-1 bushings are now experiencing "stalling" of the wicket gates, particularly at high heads (summer pools) as bushing friction has increased to a point greater than the servomotor's capability. Losing control of the wicket gates is an unsafe operating condition and can not be tolerated under any circumstance. Note, that the only indication that the Plant Operators have that the unit's wicket gates are stalled, is that the gate indication (movement) does not track an increase in speed setting (change in load). There is no differential pressure indication in the control room to show the Operator there is a wicket gate opening or closing problem.

The PL bushings in some TVA units have experienced delamination of the plastic wear material from the bronze backing sleeve. This is similar to failures at the US Corps of Engineers' (COE) Hartwell hydro plant and Ontario Hydro's Canyon hydro plant.

The greaseless bushing materials on the market today can be broken into two groups:

1. Metallic: These are usually bronze based through the full thickness with anti-friction and dry lubricant compounds (PTFE and/or moly-disulfide) dispersed on the bearing surface.
2. Non-metallic: These are usually plastic or composite materials with anti-friction compounds on the bearing surface. PTFE is the most prevalent material used for anti-friction. Moly-disulfide, graphite, and plastics are also used. Some of the thinner materials use a bronze or fiberglass backing or filler material to make up the bulk of the wall thickness. The anti-friction material is laminated onto the backing material. Some types of composite bushings have the anti-friction compounds interwoven with fibers throughout the full width the wall thickness.

Keep in mind, that both groups of greaseless bushings do not exhibit any form of hydrodynamic or boundary layer lubrication as can be found in a greased bronze design. The plugged bronze bushings have to wear the plug material off in order to supply the dry lubrication which means the bronze must wear too. Polymer / composite materials depend mainly on the low coefficient of friction of the PTFE material. The greaseless bushings are predestined to wear.

In addition to the PB and PL bushings, we have installed some composite (CP) materials on a limited basis. CP bushings were installed in Wilbur unit 1 as wicket gate bushings (small bushings: 1.5" dia. bore) in the spring of 1998 and as the Wilson 15 and 18 shift ring pads in 2000 and 2001; no reported problems to date.

Both greaseless groups have their strengths and weaknesses. The bronze based materials are stronger, creep resistant, and easier to install in a unit's rehabilitation, whereas, the polymer / composite materials are weaker, subject to creep, but have lower coefficients of friction.

LABORATORY TESTS

Greaseless bushings are a relatively new technology. Prior to 1990, there were no known independent laboratory tests available and users were forced to rely on manufacturer's tests and recommendations. In the early 1990's , Powertech Laboratories (BC Hydro) conducted the first test of several types of greaseless bushings. Later, Voith Hydro and TVA co-funded a test of a selected group of greaseless bushings at LeeHigh University. TVA based its decision to use the PL and PB-1 materials was based on these two laboratory tests and research that showed their favorable use at other utilities.

Recently (Dec. 1999), the COE released their laboratory study that was performed by Powertech Laboratories. This is the most thorough study that has been done to date and will most certainly be the standard for conducting all future tests. The report studied friction (dry and wet), wear rates, creep, and swell (volume change). The report also defined many new standards for conducting these tests. Significant findings from the report are as follows:

- The report stated, "There is strong resistance at the projects to being the first to use greaseless bushings. This reluctance is because everyone knows the bronze bushings work, and there have been problems with specific greaseless bushings they have tried."
- The COE studied the movement of wicket gates on several units and determined that "75 to 90 percent of all wicket gate motions are less than 0.2 percent of full gate motion. This percentage amounts to approximately 0.11 degrees of rotation per motion on these units".
- Their tests represented approximately 14 years of actual turbine operation.
- Based on the motion of wicket gates and their experience, the COE stated that bushings with lubricant plugs (PB) perform poorly in small movement applications. "This is almost the only kind of motion that occurs in hydropower applications."

- Between 90 to 95 percent of full swell occurs by the end of the 8th month after exposed to water or turbine oil. Full swell of most materials occur by the 14th month. Some composite materials, have "negative" swell or decrease in volume slightly when exposed to water or turbine oil.
- Shaft journal finishes should be at 16 micro-inches or better for all applications except the bronze bushings using plug type lubricant. Hardness of journal should be between 28-32 RC. (Note, TVA does not allow stainless sleeve hardness over 30 RC to prevent corrosion cracking (occurred in Chickamauga unit 3)).
- Stick-Slip or "stiction" is caused by differences between static and dynamic coefficients of friction when a system is moved from rest. If these coefficients are noticeably different there will be stick-slip, resulting in vibration, noise, and possibly damage to the equipment. The closer the static and dynamics friction coefficients are, the smoother the system will operate, even if actual friction is high.
- Preliminary testing indicates that most initial set and creep occurs within the first 48 hours of the test period if the bushing is not loaded beyond its service capability. Note, they indicate that long term creep is undetermined and should be studied.
- "In the absence of specific test information, and with the knowledge that a greased bronze bushing is able to partially exclude and purge dirt through frequent greasing, the use of seals on every greaseless bushing exposed to water or the outside atmosphere is strongly recommended. If the bushings are submerged, they will be operating wet very soon, even with seals. Seals are to exclude sand, silt, wind-blown dirt, etc." Note, there are no long term data regarding the use of seals; good or bad. (TVA does not have seals on any PL bushing installation, but did seal the PB bushings).
- They developed a rating system which assigns a number to each material based on its performance in all the tests (see their report referenced below).

This excellent report is available at:
http://www.cecer.army.mil/techreports/webgrease.less/webgrease.less.pdf

TVA's CONVENTIONAL HYDRO UNITS

TVA has operating experience with 31 conventional hydro turbines that have been converted to greaseless during their HMOD upgrades. To date, 7 out of 31 or 23 per cent have experienced significant problems with greaseless wicket gate bushings. The PL bushings have started delaminating from their bronze backing and is extruding out of the head cover of Chickamauga unit 4. Based on this failure, and failures at other utilities, we decided not to use the PL bushings in any future projects. An even larger problem has resulted from the use of the PB-1 bushings. After about 2 years of operation, Norris units 1 and 2, Fort Patrick units 1 and 2, Kentucky unit 5, and Wilson unit 15 began experiencing increases of friction in the wicket gate mechanisms. All of these units have shown signs of "stick-slipping". The frictional forces have increased to the degree that during last summer's high headwater elevation (which adds more load and friction), several of the units had times that the wicket gates would stall in operation or would not move. Governor pressures had to be manually increased above normal settings in order to bring the units back under the Operator's control. An investigation of the problem revealed that the solid lubricant plugs in the PB-1 bushings were swelling and closing the bushing's designed clearance. Theory is that the high epoxy content in the plugs is the cause of the swelling. Further evidence of this was found when we discovered that the plugs in spare bushings in dry storage had swelled. As the clearance closes, the friction increases. It is believed that the wear material from the bushings, being trapped with the bushing seals, is contributing to the tight clearances and increased friction. Increasing the governor operating pressure and lowering headwater elevations has reduced the problem for the time being, but this is only a temporary solution.

We decided not to continue installing the PB-1 bushings in new projects due to the swelling problem. A similar plugged bronze product without the epoxy content in the lubricant plugs (PB-2) was installed in Fontana unit 2 and Guntersville unit 4 in 2000. In these units, PB-2 was used as wicket gate stem and linkage bushings. Another material based on powder metallurgy (PM) technology was used as shifting ring wear pads. This material has bronze powder and dry lubricant mixture pressed onto a stainless steel backing plate. So far there are no reported problems with these two units, however, our experience shows that problems usually do not appear for several years. There is no long term data showing that these PB-2 or PM bushings are the right choice. Note, based on recent laboratory testing, the COE will no longer specify or recommend any bronze based greaseless bushings due to high wear rates and high coefficients of friction.

The service life of greaseless bushings in conventional units is estimated to be from 15 to 25 years. This estimate is partially based on the current industry experience with greaseless bushings in actual field applications which is limited to about 25 years. At best this is approximately one-half of the recorded service life of greased bushings in the same application.

TVA's PUMP-TURBINE UNITS

The Hiwassee unit 2 pump-turbine had PB-1 bushings installed in 1998. Last summer, after about 18 months of operation, the unit started experiencing wicket gate stall at 5 per cent opening during peak headwater elevation. The wicket gates would not pass 5 per cent open; therefore, the unit could not generate. The wicket gates stalled in the 5 to 10 per cent range that commonly requires the greatest servomotor pressure (pressure spike) to move the gates in a pump-turbine. A pump-turbines' wicket gates are designed to be held closed by headwater pressure (pivot point shifted toward toe of gate which is opposite conventional units); otherwise, in pump prime to pump mode, they might not open. For this reason pump-turbines in turbine mode, have a high pressure "spike" in the lower gate positions (Raccoon Mountain's is at 8%). Factors that affect this pressure "spike" include headwater elevation in the reservoir, friction in the wicket gate mechanism (bushings, pads, gate seals, etc.), and servomotor oil pressure. The problem usually shows up during high headwater levels as the head pressure on the gates increases. The accepted root cause of the wicket gate problem at Hiwassee is the extra friction developed by the reduced clearance as the PB-1 bushing plugs swell, in addition to possible accumulation of bushing wear material.

The Raccoon Mountain pump-turbines have experienced similar wicket gate stalling many times in the past even though they still have greased bushings. This stalling usually occurs when the automatic greasing system malfunctions along with a high headwater elevation. In order to generate with the unit in this condition, the greasing system is run manually, the governor pressure is raised manually, and the gates are moved closed to open until they break free. Based on this past experience and since high headwater elevations occur almost daily at Raccoon Mountain from nightly pumping, a conversion to greaseless wicket gate stem bushings will almost guarantee wicket gate stall problems. For this reason, we decided to retain the original bushing design at Raccoon Mountain during the HMOD upgrades.

In Raccoon Mountain's current bushing configuration, the wicket gate stem bushings and shift ring pads are greased bronze and typically last about 15 years. The linkage bushings are a composite bushing (CP-SE) and usually last around 8 years. Unlike conventional hydro turbines, pump-turbines commonly have problems with high wicket gate flutter or vibration which shortens the bushing life. For these reasons, one should be cautious of installing greaseless bushings in pump-turbines.

OUTSIDE TVA

Several contacts were made with other utilities in North American, to determine if similar problems were occurring outside of TVA. Reports on greaseless bushing performance were mixed. Some reported successes, others failures, and some horror stories.

In our opinion, no one is replacing greased bushings with greaseless bushings at the rate that we have been progressing. Certainly, due to the HMOD program and the large number of unit modernizations per year.

THE FUTURE OF GREASELESS BUSHINGS IN TVA

Several units with greaseless bushings are now experiencing "stalling" of the wicket gates, particularly at high heads (summer pools) as the hydraulic force and bushing friction has increased to a point greater than the servomotor's capability. This has lead TVA to the point of reconsidering its position toward greaseless bearing materials in order to ensure the reliability of the power system. Many options were considered, including trying different greaseless materials, "green" grease, and returning to proven standard greased technology. We have found that problems with the greaseless bushings may not be discovered until after 3 to 4 years of service. The fast pace of TVA's HMOD program which modernizes 5 or more units per year could result in an huge accumulated liability before a bushing problem is known. In consideration of this unacceptable potential liability, we decided to limit its magnitude by returning to the use of standard greased bronze bushings in those applications which normally require disassembly of a unit, such as wicket gate stem bushings. Testing of greaseless bushings will continue in those applications, such as wicket gate linkages, that would be less costly to replace. Testing of environmentally friendly "green" greases will also be performed in the future. We may consider returning to completely greaseless unit installations in the future, once field tests both inside and outside TVA have proven the reliability of the product/s.

All of the units with PB-1 bushings are being considered for bushing replacements in the next couple of years. Four of the most severe cases will have their bushings replaced this year. The wicket gate stem bushings and shift ring pads will be changed to greased bronze. Automatic greasing systems will be reinstalled. The linkage bushings will be changed to another type of greaseless bushing. Various types of greaseless bushings will be installed in linkages in these and new projects for field testing.

We are currently installing a continuous monitoring system on suspect unit's servomotors, to monitor maximum differential servomotor pressure. This will be done by installing a differential pressure transducer (Rosemount) on a servomotor and transmitting that signal to the Waterview system (TVA's WAN based hydro system monitor). The Waterview program will be configured to display the actual real-time differential servomotor pressure and the maximum differential pressure over the past 24 hours. The data will be stored in the Waterview system. The Waterview system will also give us headwater elevations and gate positions relative to the differential pressure. From this data we will be able to determine the severity of the problem, trend data, and schedule bushing replacements accordingly.

CONCLUSIONS

Over the past 25 years many hydro units in the world have been converted to fully greaseless. Obviously, many are working satisfactorily. Why some are successful and others are not? We believe the answer is as simple as "force" ,"friction", and "fatigue". Is the friction (which is the result of the coefficient of friction of the bushing and contact force from the maximum hydraulic head) less than the maximum moving force from the servomotors at the low end of their pressure range? Will the greaseless bushing hold up to the conditions seen in the unit or will it fatigue too rapidly due to vibration or water quality?

We suggest considering the following guidelines for choosing and using greaseless bushings:

1. Pick a material that is strong and will hold together under harsh conditions.
2. Material should have a low coefficient of friction. Ideally, the static and dynamic coefficients of friction should be close together to avoid "stick-slipping".
3. Material should have a low wear rate. Note, a material that is good in the wet may not be so good in the dry.
4. Material should have low or no swell. At the very least , the swell must be predictable and allowances made.
5. Don't skimp on bushing clearances. Follow manufacturer's recommendations.
6. If your water quality is poor, consider installing seals. Silt and debris will accelerate wear.
7. Study your unit. Take dry differential pressure readings and wet running readings at maximum head. Assume the friction will increase regardless of manufacturer's

data or laboratory tests. Are the servomotors strong enough for a 25% increase in friction? If not, continue using greased bronze or consider installing stronger servomotors.

8. Accept that the life of the greaseless bushings will be less than the greased bronze.

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