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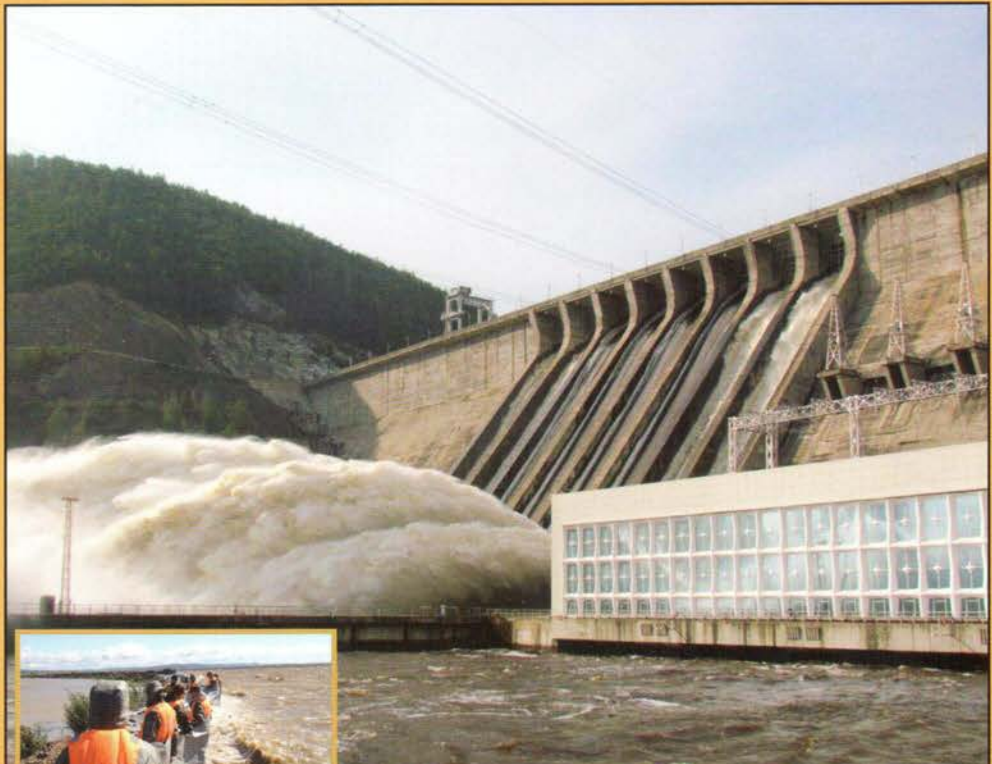

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Innovative sealing materials for butterfly and spherical ball valves

C. Rodriguez, Repack-S SAS, France

The outcome of a research project is reported into alternative, low friction/wear seal designs and materials which are better able to cope with the effect of high pressures experienced by trunnion seals. Using a dedicated test rig designed to simulate valve operation, a double acting composite seal design has been developed.

Dam ball and butterfly trunnion valve seals are subject to great forces because the weight of the trunnion assembly, and the effects of very high water pressures on the valve shaft. These forces can significantly increase compression of the valve seals, resulting in high levels of friction and seal wear, and eventually, costly-to-repair water leaks.

These forces include the weight of the trunnion assembly itself, and the effect of very high pressures on the shaft and seals when the valve is operated. The pressure significantly increases seal compression, leading to higher levels of friction with the valve shaft and trunnion, and thus seal wear. The rate of seal wear is accelerated by the abrasive effect of high pressure sand particles.

Traditional sealing materials for large (> 500 mm) butterfly and spherical ball valves such as polyurethane (PU), thermoplastic polyurethane (TPU), hydrogenated nitrile butadiene rubber (HNBR) and nitrile butadiene rubber (NBR), can struggle to cope with the stresses resulting from these distorting forces and higher wear rates. Leaking valves are difficult to maintain and, in the worst case, the seals will need replacing, which is a costly and highly disruptive exercise, as the turbine may have to be taken out of service for up to six months.

In a research project by Repack-S, using a dedicated test rig designed to simulate valve operation, a double acting composite seal design has been developed. It comprises an inner dynamic sealing ring (pad) with multiple sealing grooves and a static elastomer O-ring energizer, providing the initial sealing force (supplemented by the pressure generated when the valve is operated).

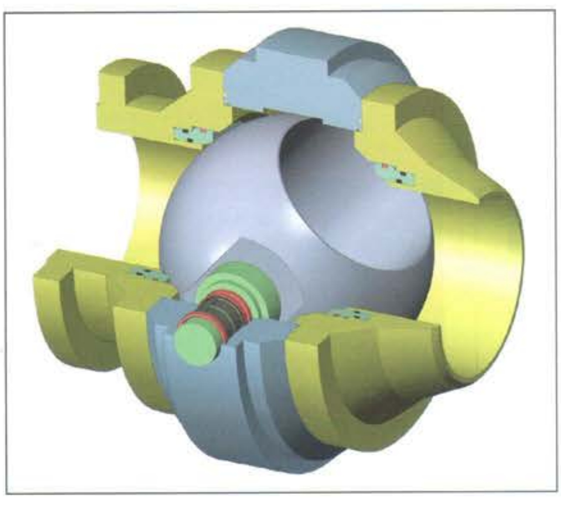


Fig. 1. A ball valve showing the spigot and seals. Note: hydropower ball valves are normally configured in pairs.

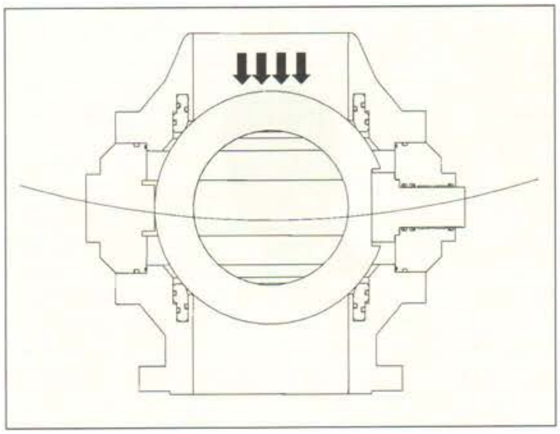


Fig. 2. The flexing or 'sag' (exaggerated) of the trunnion and spigot during valve operation.

The research project compared the performance of traditional polyurethane (PU and TPU) -based seals with a new composite seal design. The seal test conditions involved alternating rotation: +90° per minute, at room temperature and 105 bar pressure, with eccentricity, 1 mm, and surface roughness ranging from Ra 0.79 micron (Rz = 12.3) to Ra 1.08 micron (Rz = 11.9) for 28 062 cycles (equivalent to ten years of daily service).

The test results showed that the new composite seal design out-performed traditional valve seal designs, with no leakage during the simulated 10 years of service.

1. Background

Butterfly and spherical ball valves are widely used in hydropower plants to control the flow of water to turbines (Fig. 1). Trunnion-mounted ball valve designs are favoured for these types of high-pressure applications in excess of 40 bar. Trunnion-mounted valves are designed typically with sets of seals on the valve's rotational shaft or spigot to prevent water leakage.

The high-pressure water flow, together with the weight of the trunnions, causes the valve to deform slightly. For large ball valves, it can be difficult to predict accurately the degree of deformation using finite element analysis techniques.

Increasing the volume of the surrounding metal can help to reduce the deformation of large diameter valves. However, some valves can have up to 4 m diameter bore, and trunnion diameters exceeding 1.5 m. In such cases, valve deformation cannot be avoided, and is experienced as 'sag' or flexing across the valve's rotational axis. As a result the trunnion seals are heavily deformed under the applied load (see Fig. 2).

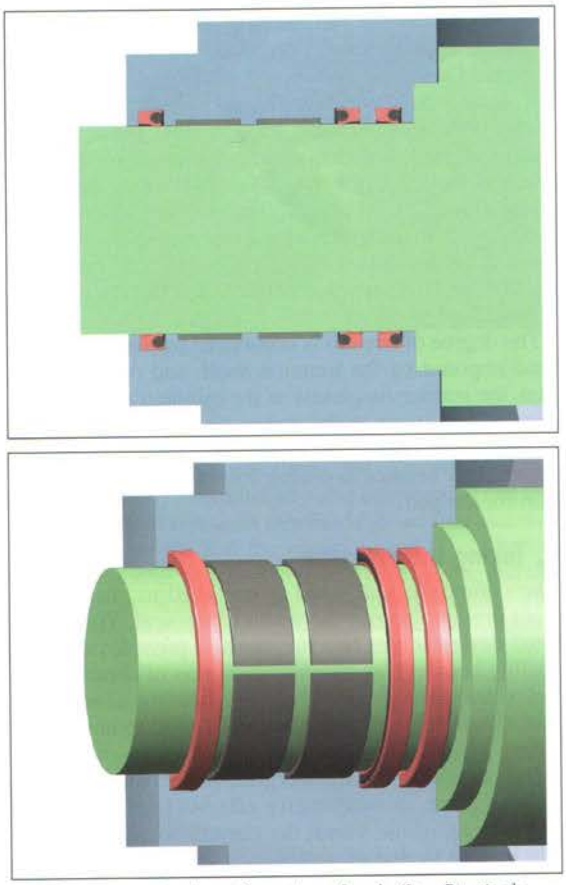


Fig. 3. A conventional configuration of seals (L to R): single effect seal, phosphor bronze pads and double effect tandem seal.

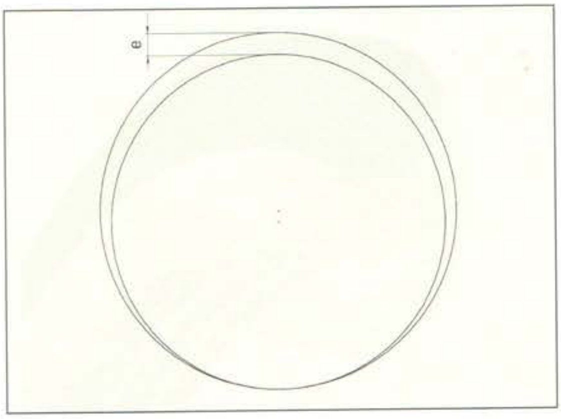


Fig. 4. The eccentricity of the valve seal trunnion.

The deformation is experienced as eccentricity (defined as the degree of displacement of the geometric centre of a rotating part from the true centre, especially of the axis of rotation of a wheel or shaft causing distortion of the spigot seal). Specifically, the seal is compressed to a greater degree on the lower part of the groove, resulting in higher, non-uniform stresses on these large diameter parts.

In an effort to cope with the effects of eccentricity, ball valve seals are traditionally configured with a double effect sealing arrangement. The complete sealing arrangement comprises a single effect outer seal, phosphor bronze pad(s) and a double effect inner seal, lubricated by either oil or grease. The seals serve two purposes: the outer single effect seal prevents the lubricant leaking into the atmosphere, while the inner double effect seal prevents both lubricant leakage and sediment from entering the space between the inner and outer seals and contaminating the pad and shaft bearings (see Fig. 3). However, leaks are still a common occurrence.

2. Overcoming eccentricity effects

The degree of seal distortion under pressure will vary by material compressive modulus, diameter, cross section profile, and load applied on the seal. For example, a 1.2 m trunnion will move in its housing, once the system pressure has been applied, typically resulting in 1 mm eccentricity and different levels of seal compression at the top and bottom of the spigot (see Fig. 4).

For illustrative purposes, consider a 12 mm nominal cross-section O-ring seal installed in a groove with a 9.5 mm nominal groove depth.

Assuming that when fitted the seal is subject to 15 per cent (1.8 mm) compression to provide the required sealing force (this takes into account the clearance gap between the trunnion and the housing bore, and it assumes the trunnion is perfectly centered).

As a result, the seal cross-section height is:

$12 - 1.8 = 10.2$ mm.

Now, when the trunnion is operated it experiences eccentricity of 1 mm. Then:

- At the top of the trunnion, the seal cross-section height becomes $10.2 + 1.0 = 11.2$ mm => $(12 - 11.2)/120 = 6.7$ per cent compression. The reduction in compression from 15 per cent to 6.7 per cent could cause the seal to leak.
- At the bottom of the trunnion, the seal cross-section becomes $10.2 - 1 = 9.2$ mm => $(12 - 9.2)/ 12 = 23.3$ per cent compression. This could be considered as excessive squeeze (compression) against the trunnion shaft, resulting in higher friction force, and thus accelerated seal wear.

In practice, gauging the correct sealing force is very difficult. Is there enough sealing force at the top of the seal where the clearance gap is largest at this level of compression? If there is, can an effective seal be maintained? Is there enough contact force? The degree of loss of sealing force is largely material dependent. For example, polyurethane (PU), thermoplastic polyurethane (TPU) and hydrogenated nitrile butadiene rubber (HNBR) generally exhibit more 'compressive stress relaxing' than nitrile butadiene rubber (NBR), leading to problems in maintaining sealing contact force at the top of the seal. One solution to compensate for these effects is to use a larger cross section seal. However, this can exacerbate the problem. The larger surface area in contact with the valve shaft will increase friction and rate of seal wear.

3. New composite seal design

Conventional trunnion seals use a U or V-shaped outer polyurethane seal, and sometimes an elastomer O-ring energizer to provide the necessary sealing force, compensating for the effects of eccentricity. The seals are configured as shown in Fig. 3.

A new composite seal design has been developed by Repack-S to achieve the optimum sealing force by improving wear resistance, thus extending seal life and overall reliability. The performance of the seal is such that it allows the inner tandem seals to be replaced with a single seal.

The new design uses an inner polymer pad with multiple radial sealing grooves in contact with the rotating shaft, and an elastomer O-ring energizer installed on

Fig. 5. New trunnion composite seal design.

the outer diameter in the seal groove (see Fig. 5). Designed specifically for rotary movements, the pad has a castellated profile.

The pad profile reduces the surface area in contact with the shaft to ensure lower contact friction. It also allows increased contact pressure, and therefore achieves better sealing. The surface profile of the interface between the thermoplastic pad and rubber energizer is recessed to optimize surface contact. The degree of friction (albeit the friction force) between the pad and the rotating shaft is:

$$F\mu = \mu \times R$$

where μ is the coefficient of friction of the inner seal pad material and R is the reaction force (which is equal and opposite to the applied radial load, the latter being the sum of the ball assembly weight with the force resulting from the applied water pressure on the exposed part of the sphere, as well as the radial force from the applied system pressure distributed over the exposed O-ring face).

It should be noted that the composite seal experiences both static sealing friction ($F\mu$) static (on the energizer) and dynamic sealing friction ($F\mu$) dynamic (on the pad), for the new composite seal design to work $(F\mu)_{static} > (F\mu)_{dynamic}$. In essence, the friction force between the trunnion and thermoplastic pad must exceed the latter and the O-ring, which in turn must exceed the friction force between the O-ring and bottom surface of the groove.

The degree of friction is influenced by the mechanical load imposed by the trunnion itself, and during operation, the surface roughness of the trunnion and the presence of sediments in the water. An important outcome of the research project has been the ability to achieve a satisfactory balance in sealing forces and material selection for the pad.

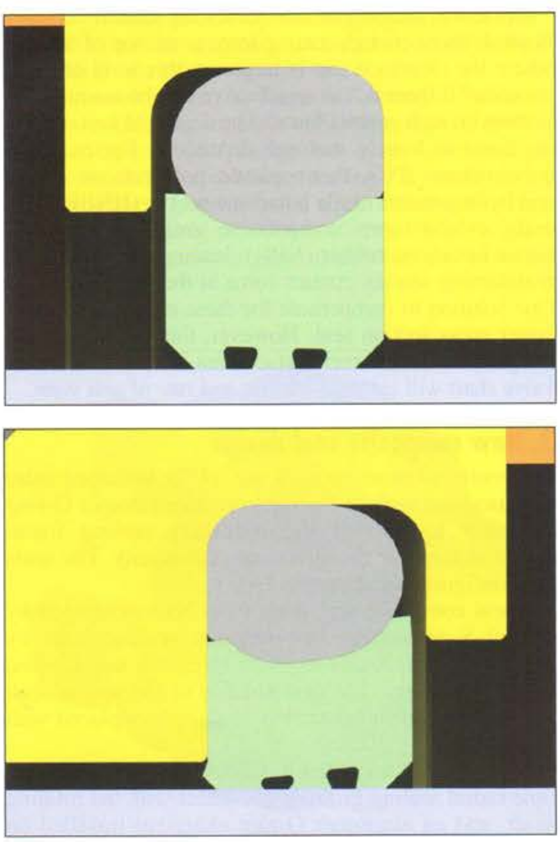


Fig. 6. The seal profile in normal use (top), and during valve closure as pressure increases (bottom).

4. Taking the pressure

The composite seal's pad is designed to ensure constant pressure across the width of the seal. The castellated design serves two functions: it provides multiple sealing barriers, preventing the ingress of abrasive particles from reaching the shaft's bearing assemblies; and, the castellated recesses can be used to hold lubricating grease, if required.

The elastomer O-ring energizer makes the seal highly responsive to eccentricity effects. During opening and closing of the valve, the elastomer's circular profile is able to distort and absorb the pressure change within the confines of the seal groove, as well as coping with an uneven loading and therefore uneven deformation and distribution of compressive forces (see Fig. 6).

5. Materials selection

A major benefit of the new composite seal design is the opportunity to customize the performance of both sealing elements. As the composite seal's O-ring is not subjected to abrasion, it is possible to choose the optimum material for compression resistance over time. The potential presence of mineral oil rules out EPDM (ethylene propylene diene monomer), therefore, a low compression set NBR compound is preferred. It is better able to cope with the level of squeeze generated during valve operation, and compression recovery is better.

For the pad material, various polyurethane materials were tested but they experienced significant friction wear. A proprietary grade of Ultra High Molecular Weight Polyethylene (UHMW-PE), on the other hand, was shown to offer the same sealing performance but with less wear, and thus longer sealing life.

6. Seal testing

Tests were conducted on two seal designs (Fig. 8).

Table 1: Seal designs

Seal design	Materials used
Conventional U-cup seal	Polyurethane pad
New composite design	Polyurethane pad Thermoplastic pad UHMW-PE (P91 grade) pad

Fig. 7. The seal test rig.

6.1 Sealing test bench

The test equipment is designed specifically for hydropower sealing applications, for example, simulating (accelerated) trunnion ball valve operation. It can test the behaviour of two seals mounted face-to-face, according to their profile and the material used. The rotation axis is horizontal, as found in most hydro valves, and the hollow inner seal (akin to a trunnion) rotates. The

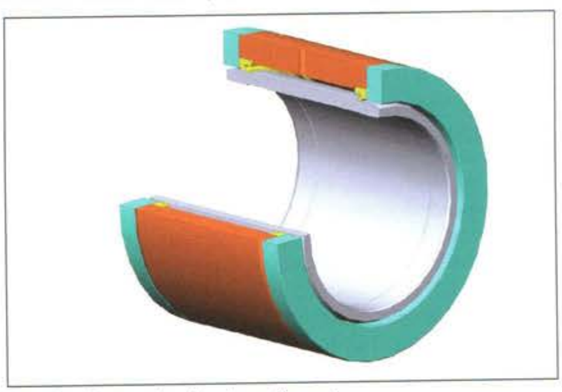


Fig. 8a. Conventional seal configuration

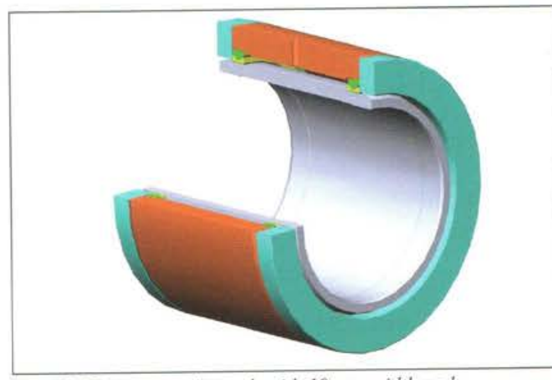


Fig. 8b. New composite seal, with 19 mm width pad

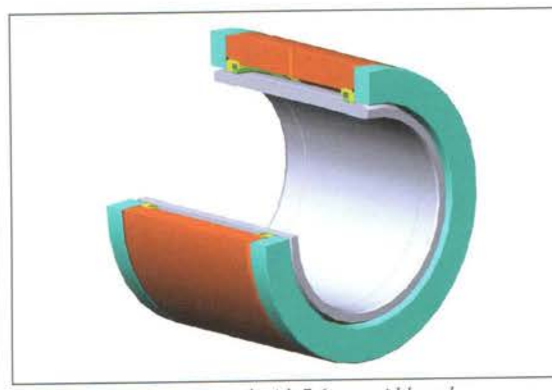


Fig. 8c. New composite seal with 7.6 mm width pad

uneven, compressive seal loading due to eccentricity is achieved by means of an adjustable mechanism that allows the outer non-rotating sleeve to be moved up in a vertical plane.

The hollow inner sleeve rotates on a Repkot composite bush-bearing located along the rotation axis just outside the seal trunnion assembly (Fig 7).

Table 2: Testing of the seal designs

Seal design	Pad material	Number of cycles	Number of hours	Seal wear	Notes	Comments
U-shaped convential composite seal design	TPU	900	15	N/A	Seal leaks	Wear of the lip is caused by too much friction on the shaft and excessive temperature rise
New composite seal (Danaroto) design	TPU	2400	40	The Danaroto in TPU causes the energiser to rotate with the pad because the frictional torque is too great	Seal leaks	O-ring energiser severly damaged - solution cannot be used
New composite seal (Danaroto) design with 19 mm width pad	UHMW-PE	38820	647	No rotation of pad in the groove. Wear of front pad is 0.1mm and the rear pad is tapered 0.1 to 0.35mm.	No leakage at high pressure. The roughness of the shaft has not changed Ra=1μm	Danaroto ensured a tight seal for the duration of the trials. The tapered pad wear would be less on a shaft with a better surface finish (Ra=0.4, HRC> 40)
New composite seal (Danaroto) design with 7.6 mm width pad, and nylon adaptor ring	UHMW-PE	38820	647	The seal wear is very small	No leakage. The shaft Ra surface finish has been improved by the sealing action	This new Danaroto section 15 × 20 gave completely satisfactory test results with P91 grade pad

PU - polyurethane; TPU - thermoplastic polyurethane; UHMW-PE - ultra high molecular weight polyethylene

6.2 Test conditions

The testing conditions were:

- alternating rotation, ± 90° per minute;
- test pressure, 105 bar;
- eccentricity, 1 mm;
- test fluid, industrial water; and,
- working temperature: 27 to 32°C.

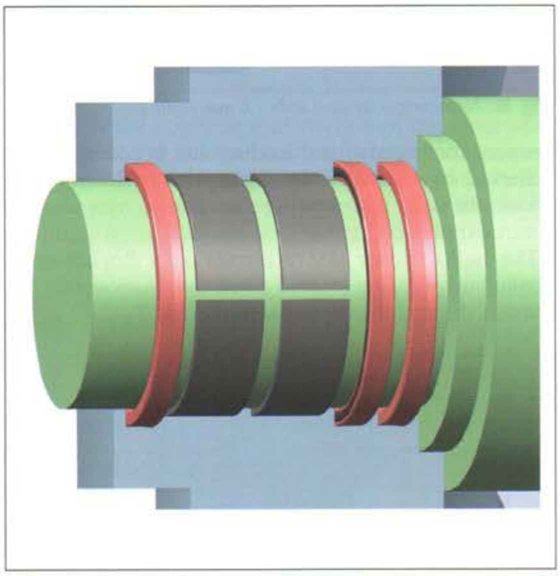
The characteristics of the inner shaft sleeve were:

- stainless steel, 316L;
- diameter, 250 mm;
- surface roughness, Ra = 0.79 μm (Rz = 12.3) to Ra = 1.08 μm (Rz = 11.9).

7. Comments

The tests showed that conventional trunnion seals based on PU / TPU quickly fail at 105 bar, because of the high levels of friction between the seal and shaft causing excessive seal wear.

Using the new composite design, with the castellated pad in polyurethane, was shown to be impractical: the frictional torque between the pad and energizer is too great causing the energizer, and thus the pad, to rotate within the seal groove.



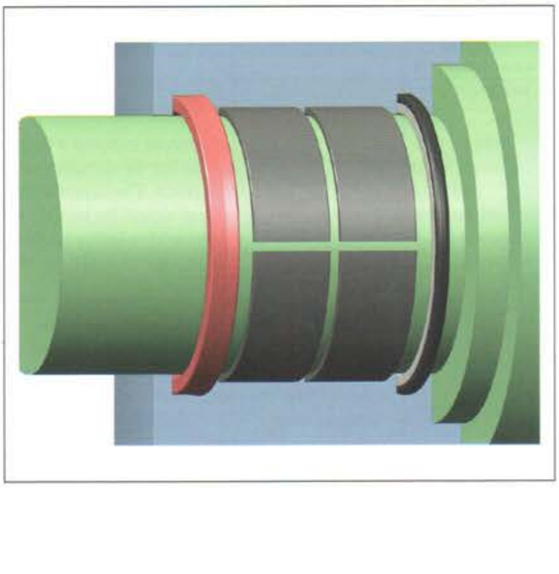


Fig. 9. The conventional tandem seal arrangement (top) can be replaced with a single Repack-S seal (bottom) to provide leak-free performance.

The composite seal design based on a UHMW-PE inner pad has been shown to work successfully at 105 bar. The seal achieved a simulated 10 year operation period without significant wear, and no leakage was observed.

Tests with a narrower UHMW-PE inner pad showed a similar performance to the wider UHMW-PE pad, demonstrating the suitability of a UHMW-PE pad in this type of application.

8. Conclusion

Conventional seal designs for trunnions in hydropower butterfly and spherical ball valves are subject to eccentricity arising from a combination of trunnion load and high water pressure, causing the seals to leak ahead of scheduled preventative maintenance.

The only sealing configuration currently available to handle pressure from both sides is tandem inner seals. The tandem seals are needed to prevent lubricants leaking into the water, and sediment from entering the space between inner and outer seals which could contaminate the pad shaft guide element. However, experience has shown that the tandem seals fail to prevent leakage.

The Danaroto composite design, based on an inner UHMW-PE P91 grade polymer pad with multiple radial sealing grooves in contact with the rotating shaft, is proposed as a replacement for the current tandem seals arrangement (see Fig. 9). The polymer pad has been shown to withstand the high pressures that can be encountered by trunnion seals, demonstrating the robustness of the seal design. The new composite seal design has also been shown to work even in a smaller cross section, demonstrating the repeatability and scalability of the seal design.

Replacing the current tandem seals with a single UHMW-PE (P91 grade) composite seal design will increase the time between scheduled seal maintenance intervals, as well as ensuring the seal lasts for the full 10 years service life without leakage. ◊

C. Rodriguez

Christophe Rodriguez is Chief Executive Officer at Repack-S SAS, a French seals manufacturer. He is a professional mechanical engineer with more than 10 years of experience of complex and technically advanced engineering composite sealing solutions in the aerospace, food and pharmaceutical, oil and gas, semiconductor, power generation and steel manufacturing industries.

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