Investigation of hydraulic fluid condition on seal performance

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This work investigates the impact of various hydraulic oil conditions on the performance of hydraulic rod seals - fresh, different aging conditions and cleaned with a special oil regeneration. Oil aging was introduced by so-called heavy-duty tests applying elevated temperature and pressure conditions to the oil and the seals. This test procedure accelerates aging of the hydraulic fluid by oxidation and particle formation. The test program was done with a commercial hydraulic oil grade and polyurethane rod seals on a hydraulic seal test rig. The aged oil was treated with the newly developed Double Separation Technology (DST) and tests were afterwards repeated with same procedure.

1 Introduction

Modern hydraulic fluid power applications are characterized by increasing power density and decreasing overall dimensions. They contain less and less hydraulic fluid, have smaller cooling systems, and operate at higher pressures. In consequence, the hydraulic oils experience increasingly difficult mechanical, thermal, and chemical conditions of operation, which leads to ageing and fast deterioration in functional properties of the oils [1]. In current state of the art hydraulic components, frequent service intervals and oil changes need to be conducted to ensure a proper functionality of the equipment and to counteract oil degradation. “Double Separation Technology” (DST) of SKF RecondOil is a new solution to increase lifetime of hydraulic oils as well as seals installed in hydraulic fluid power equipment. This newly developed and patented process is adding additives that are consumed during the operation and removes very small particles that catalyse oil oxidation, which offers an extended usage of the fluid and hydraulic components [2].

This study investigates the influence of different hydraulic fluid conditions on the performance of rod seals. The results show that the DST process was able to significantly improve the friction of seals without a negative effect on the seal material. In addition, it helps to extend the service life of the used mineral oil.

2 Theoretical Background

The primary function of a hydraulic oil in fluid power applications is to transfer power. The concept of fluid power is described by Blaise Pascal as: Pressure applied to an enclosed fluid is transmitted undiminished to every portion of that fluid and the walls of the containing vessel [3]. Beside this, it serves to maintain a smooth operation of the wider hydraulic system by lubricating moving parts, cooling the system by transporting heat from areas of high load, preventing corrosion of surrounding metal components, and removing contamination from critical surfaces.

All is starting with maintaining a smooth operation of the hydraulic system by keeping the properties of hydraulic oil in good condition. The service live of a hydraulic fluid is limited depending on how long the oil is used at its upper operating limit. It undergoes aging (degradation) because of the following: thermal-decomposition, UV-radiation impact, contamination by particles/water, oxidation and by a depletion of additives [4,5]. The most important catalysts for the oil aging process are shortly described in the following sections:

- Thermal decomposition

Thermal degradation of hydraulic oil is a result when temperatures rise above a specific point which occurs by different effects such as micro-dieseling, electrostatic spark discharge or extreme temperature zones in applications by a malfunction of valves.

- UV radiation

UV radiation during maintenance due to inappropriate oil storage can lead to a degradation in service. Oil which is stored outside tanks and exposed to sunlight can rapidly degrade.

- Hard particle contamination

Abrasive wear is typically found in mechanical systems, where two surfaces are in relative motion. The movement can be either reciprocating, oscillating or rotating. It is characterized by accelerated wear due to hard particles damaging the surfaces while in motion. Particle contamination like dust, metal particles, rubber and fibres can all act as abrasives in the system – accelerating the wear of mechanical components like pumps, bearings, rods, pistons, and seals. Removing these particles from the oil leads to a reduced wear rate and longer service life of the system [7]. Conventional filtration systems remove larger particles – from high-speed separators which are rated to >5 microns, to coated filters rated at >2 microns and electrostatic filters rated at >1 micron. Accumulation of smaller (<1 micron) particles over time is a result of conventional filtration systems, only removing larger particles. Latest internal investigations show that those smaller particles have a bigger role to play in oil degradation [8].

- Oxidation / Thermal degradation

Often viewed as the most prevalent mode of degradation, oxidation can lead to the formation of varnish which, if left unchecked, can cause issues like valve stiction, obstruction of heat transfer, blocked filters, and impaired lubrication properties. Oil oxidation is the chemical process where oxygen reacts with base oil and additives in the oil product. The process is accelerated at higher temperature, but also by the presence of water, acids and particle contamination. Even filtered oil contains particles in very small sizes and thereby accelerates the degeneration process. The surface area of the catalyst is a key parameter influencing the speed of reaction. 80% of the contaminant surface area is associated with very small particles [4]. Conventional filtration systems are designed to remove larger particles and standard lubricant condition monitoring systems does not monitor these smaller particles. To avoid this reaction, the industry standard is to supply oil with antioxidants. These additives release antioxidants to combat the free radicals associated with the oxidation reaction. But as the process continues, these additives will be depleted until eventually oxidation will proceed unhindered.

- Depletion of Additives

It is very important to understand that additives in the oil get consumed and depleted by decomposition, by adsorption onto metal, particles, water and separation due to settling or filtration. For many additives, the longer the oil remains in service, the less effective the remaining additive package is in protecting the equipment. When the additive package weakens, viscosity increases, sludge begins to form, corrosive acids start to attack bearings and metal surfaces, and/or wear begins to increase. If oils of low quality are used, the point at which these problems begin will occur much sooner [6].

2.1 Oil Treatment

The patented oil treatment process combines a liquid/liquid two-phase extraction technology with separation processes such as settling, centrifugation and filtration. The technology is based on the addition of a separation medium "separation booster" that is not soluble in the oil and forms a cloud of micron sized droplets with a large surface area. The contaminants in the oil are absorbed by the separation booster, the droplets coalesce into larger droplet and finally the dirt containing liquid phase can be removed. In this study, it is done by settling and filtration. The DST process allows to clean the oil, not only by removing micro sized contaminants, but also by removing even smaller contaminants that are not collected in conventional filter systems. These particles have a very large specific surface area, that can catalytically accelerate the oxidation and degradation of the oil. By removing these contaminants, the oxidation and aging process of the oil will slow down, and the service life of hydraulic fluids will increase [4].

3 Experimental

This study investigates the influence of oil aging and the effectiveness of an oil treatment process on the performance of rod seals by using:

- Static compatibility tests to evaluate the chemical compatibility of seal materials in treated oil,
- accompanying oil analysis for a deeper understanding and
- dynamic rod seal tests with extremely harsh testing procedure.

3.1 Static Compatibility Testing

Static compatibility tests were performed to understand the impact of the oil treatment process on the compatibility of the thermoplastic polyurethane with the respective hydraulic fluid. Tests have been carried out based on ASTM D471 in both the reference mineral oil and the DST-treated oil. The reference mineral oil was DST-treated in its virgin condition. Tests were done for an immersion period of up to 1000h at a temperature of 100°C and changes of Shore A hardness, volume and tensile properties were checked regularly.

3.2 Oil Analysis

In addition to the static compatibility tests on seals, an oil analysis was performed before and after the oil treatment. Particle content was measured both, with a direct imaging particle counter according to ASTM D7596 where the result is presented according to ISO 4406:99. Additionally microscope-based image analysis according to ISO 4407 was done, where the result is presented according to ISO 4406:87. The water content was measured according to ASTM D6304. The PQ-index measured according to ASTM D8184 stands for the “Particle Quantifier-index” and counts magnetizable iron abrasion in the fluid sample. The total acid number (TAN) according to ASTM D974 is used to detect the number of acidic components present within the oil sample. Finally, the oil oxidation stability was measured in a rotating pressure vessel oxidation stability test (RBOT) according to ASTM D2272. This method detects oxidized lubricants which can form sludge and varnish that prevents a proper cooling of equipment and bearings.

3.3 Dynamic Seal Testing

All dynamic seal tests were performed with commercially available rod seals, made of a premium grade thermoplastic polyurethane. Different oil aging conditions were introduced by a special and demanding seal test procedure. The test program was launched with an untreated commercial hydraulic oil of viscosity class 46 and compared against the same oil, regenerated with DST. The effects of the oil treatment technology on seal performance criteria such as seal friction, leakage and material properties were evaluated. To detect an improvement as service life extension of hydraulic systems (seals and oil), a highly sensorized test rig was used which continuously records all relevant data such as friction force of seals, system pressure in the test chamber, oil temperature, external leakage. Possible oil aging was detected by regular visual analysis after testing (discoloration, smelling of oil, etc.). A performance change because of degraded oil can be seen by a strongly varying friction force of seals, increasing leakage and a strong discoloration of the oil.

Therefore, seal testing was performed with the reciprocating seal test rig LP5 (see Figure 1) of SKF. It consists of one pressurized test chamber, one piston rod, an electrical drive unit and a hydraulic pressure unit. With this setup, it is possible to evaluate two rod seals at the same time. For simplicity, just one seal was used to present leakage, preload loss results and seal pictures in this report. The external leakage is continuously measured and recorded. The rod seal test rig is equipped with a load cell to be able to measure the friction force of two seals. The system pressure is verified and controlled with a pressure transducer, directly installed in the test chamber. The oil temperature is measured in the oil outlet port of the test chamber. The discoloration of the oil was evaluated after each single test by an optical investigation of an oil sample.

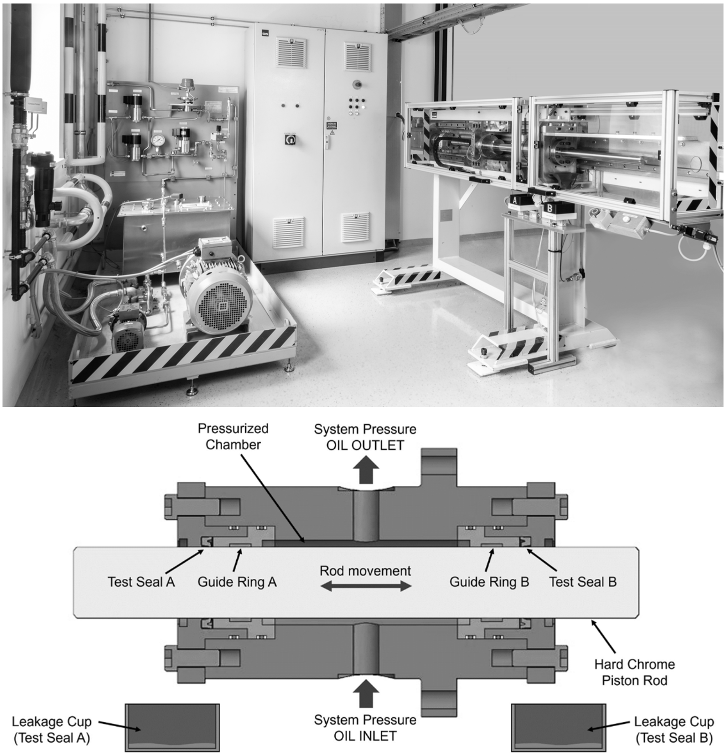

Figure 1: Reciprocating hydraulic seal test rig (LP5) and sectional view of the test cell

The seals tests were performed with asymmetric U-Cup seals (SKF S1S design), made of TPU with a rod diameter of 50mm. All seals were molded in Judenburg, the seal lips have been trimmed.

3.3.1 Test Program

An internal test procedure, referred to as “heavy-duty test”, is used to evaluate seal at elevated temperature and pressure levels, but also to accelerate the aging process of the hydraulic fluid which is stressed by oxidation (thermal degradation) and particle contamination.

The test, shown in Table 1, is divided in two test cycles where the seals are not dismantled in between. The first cycle is a moderate 10-day test with an operating temperature of 80°C and a system pressure of 200bar and is used to check the seal performance under common application conditions. The second test cycle with an increased operating temperature of 110°C and a system pressure of 315bar is used to evaluate the limits of the hydraulic system (seals and hydraulic oil).

Table 1: Test conditions

Seal type	Asymmetric U-Cup Seal (SKF S1S)	
Seal housing	ø50 x ø65 x 10 mm	
Seal material	Thermoplastic Polyurethane (ECOPUR®)	
Extrusion gap	0,15 mm (radial)	
Stroke speed	0,25 m/s	
Stroke length	400 mm	
Test medium	• Commercial mineral oil - HLP 46 • DST treated mineral oil - HLP 46	
	Test Cycle 1	Test Cycle 2
System pressure	200 bar (constant)	315 bar (constant)
Oil temperature	80 °C	110 °C
Test distance	200 km	60 km

Under standard testing operations, it is needed to change the oil regularly. If the oil is not changed periodically, test results such as friction force of seals and wear performance are worsening over time because lubrication capability of the oil is negatively impacted by degradation of the oil. The oil replacement intervals are different and vary depending on which test programs are applied. Typically, it is necessary to change the oil after every second to third heavy-duty test. Figure 2 shows an example of a fully degraded oil caused by a too long usage time.

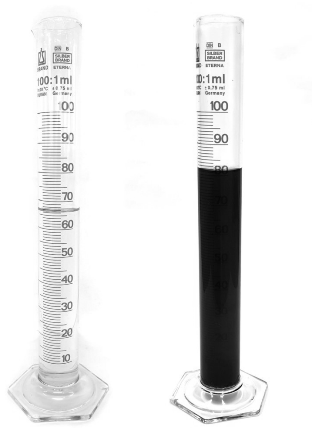

Figure 2: Degradation of the hydraulic oil results in a darkening of oil

To be able to evaluate the seal performance under different oil conditions, the heavy-duty test program was used several times without changing the oil (Baseline Tests) in between. After the third heavy-duty test, the oil would be latest removed and disposed due to reaching the end of its lifetime. In this investigation, only half of the oil was removed from the hydraulic tank and DST treated for further investigations.

The other half of the hydraulic oil was kept in the tank and used to continue the "Baseline test series" with a 4th heavy-duty test, to show the effect of degraded oil and to quantify the regenerating effect of the new DST technology. After this test, the residual oil in the tank was removed and disposed.

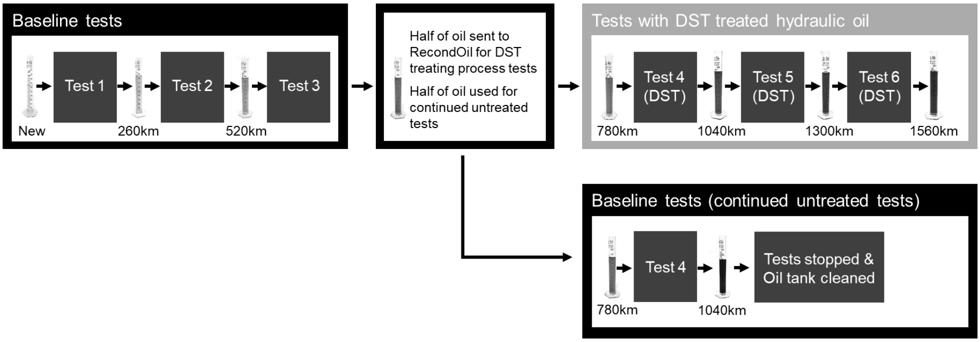

Figure 3: Test program

Once the pre-aged oil was cleaned and treated with the DST process, it was filled into the cleaned hydraulic tank and used again for another test series (DST treated Tests 4 to 6). This test series consists again of three heavy-duty tests. The results from the Baseline Tests (Test 1-3) were afterwards compared against results from Test 4 to 6 (DST). Figure 3 shows the overall procedure which was used for this paper. Each single heavy-duty test was started with new U-Cup seals and new piston rods to ensure constant testing conditions.

4 Results and Discussion

In the following section the most important test results, from static compatibility tests, oil analysis and dynamic rod seal tests including all relevant seal performance criteria, are summarized.

4.1 Static Compatibility Results

Table 2 shows the change of properties of the applied premium grade polyurethane after an immersion period of 1000h at 100°C temperature.

Table 2: Immersion test results after 1000h at 100°C

Property Change	Commercial oil	DST-treated oil
Volume (%)	+0.31	+0.44
Hardness (Shore A points)	+-0	-1
Tensile Strength (%)	+3	+2
Elongation at Break (%)	+11	+23

The change in properties demonstrates excellent compatibility of the polyurethane to mineral-oil based hydraulic fluids. Although tested at the elevated temperature of 100°C, no significant reduction in properties was observed during the 1000h immersion time for both, the commercial oil, and its DST-treated counterpart.

4.2 Results From Oil Investigation

Oil investigations were performed after Test 3 before and after DST treatment and the results are shown in Table 3. These investigations showed that with a single pass through the treatment system, the oil cleanliness was improved according to particle counter and image analysis and to some extent also the PQ index and water content. The cleanliness level according to ISO 4406:99 could be improved from a particle count of 21/19/16 to 13/12/8 – even cleaner than the virgin oil which was at 17/15/10. The RBOT measurement indicated some improvement in oil oxidation stability comparing the oil before and after DST treatment.

Table 3: Oil parameters before and after DST treatment compared to virgin oil reference

		Virgin	**Test 3**	**Test 3 after DST**
Particle Counter	ISO 4406:99	17/15/10	21/19/16	13/12/8
Image Analysis	ISO 4406:87	--	13/12/11	9/8/7
PQ Index	ASTM D8184	0	10	5
Water Content (ppm)	ASTM D6304	20	19	12
TAN (mg KOH/g)	ASTM D974	0.30	0.38	0.28
RBOT (min)	ASTM D2272	467	325	364

4.3 Dynamic Test Results

The leakage results of Test 1, 2 and 3 with the untreated oil are on a very similar level, even if the 3rd test showed the best overall performance. This is a usual scattering of test results, caused by the tough test procedure and could be often seen in previous test series, but all tests are below the internal leakage limit. The leakage as well as the seal pictures confirm that the oil was in an acceptable condition even after the 3rd heavy-duty test in row. As described in chapter 2, the oil is getting stressed by various external factors such as temperature, oxidation and depletion of additives when it is used beyond a certain point. This effect can be seen by analysing the leakage and the seal pictures of Test 4, which is shown in Figure 4 alongside the three preceding tests with untreated oil. Whilst the seal was working without any problems in the first test cycle, this changed significantly in the test cycle 2, where the leakage increased dramatically right from start. The total leakage after the test was 40g, which clearly exceeds the internal leakage specification.

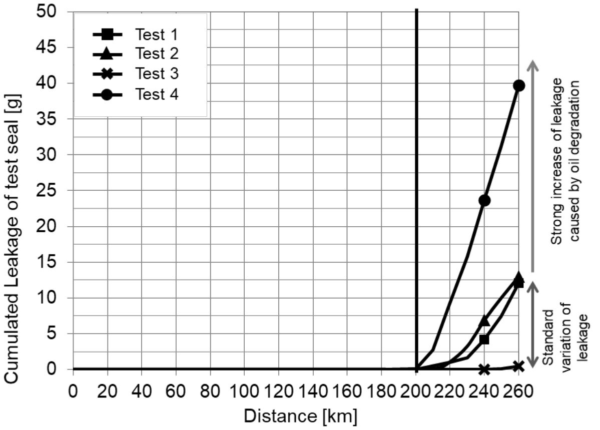

Figure 4: Leakage results of Test 1 to 4

Looking at the seal pictures after testing it was clear why the seal showed increased leakage. Figure 5 shows a comparison of tested seals from the Baseline Tests 1 to 4. The seal picture after the 4th Test clearly shows an extrusion damage with partially torn-off areas. This area of the dynamic seal lip is responsible for the back-pumping behaviour. If this area is strongly damaged it leads to leakage. Additionally, the strong discoloration of the dynamic sealing surface is an indication of increased temperature in the contact zone probably caused by decreasing lubrication capability of the oil.

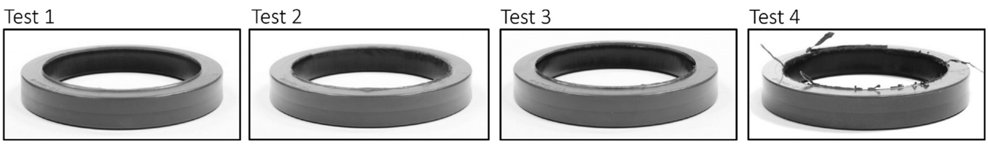

Figure 5: Seal pictures after testing with untreated oil

Figure 6 shows the leakage results of seals tested with DST treated oil. The leakage of all three tests was again on an excellent level and within the internal leakage specification. This is an excellent result as the 4th Test prior the cleaning process, showed the consequences of degraded oil. The leakage results indicates that the DST treated oil is able support and lubricate the sealing system again accordingly, even after 3 heavy-duty tests were already performed with the oil before the DST treatment was applied.

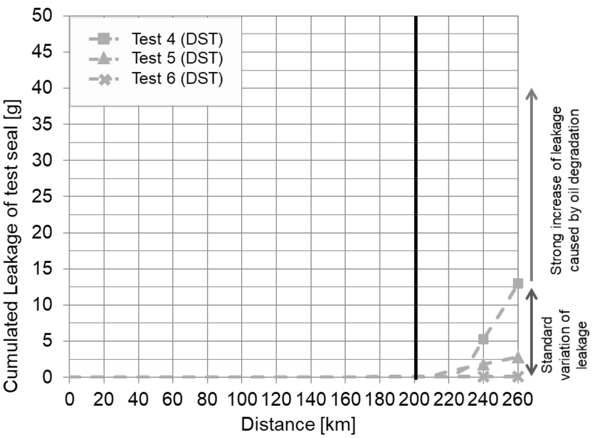

Figure 6: Leakage results of seals tested with DST treated oil

Figure 7 shows a visual comparison of seals from tests with the DST treated oil. The seals show an extrusion performance which is comparable to tests done with untreated oil. They do not show any severe damage as it could be seen at the Test 4 with the untreated oil. This excellent performance is remarkable, considering the usage time of the oil during the 3 heavy-duty tests prior the DST treatment.

Figure 7: Seal pictures after testing from Test 4 (DST) to Test 6 (DST)

Another important key performance criterion is the permanent deformation of the seal after testing. Figure 8 shows the preload loss of the outer diameter (∆OD) which is mainly caused by compression set of the seal material and the cross-sectional change of the seals (∆CS) which is caused by the compression set of the material and, to a minor extend, by the wear of the dynamic seal lip. They describe the change of the seal dimensions (OD and CS) in relation to the seal housing dimensions where they were installed during the heavy-duty test. Generally, the lower the preload loss values after testing, the better is the material quality. Aside the fact that all numbers are on a very low level considering the heavy-duty test program, there is no clear trend or difference in the performance between the tests run with the standard mineral oil and tests run with the DST treated oil.

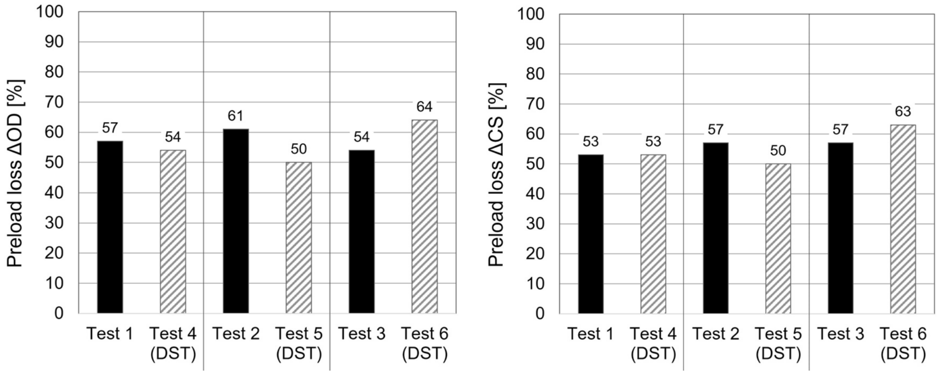

Figure 8: Permanent deformation of tested seals

The biggest and most noticeable difference could be seen in the seal friction. It is a result of the interaction between the sealing system (influenced by seal design and seal material), the test conditions, the hydraulic fluid and the counter surface. As the counter surface and seals were exchanged after each single test to exclude any possible variations, the improvement of the seal friction is demonstrating the positive impact of the oil treatment process.

The following friction charts show typical friction characteristics of seals when they are tested with the heavy-duty testing program. During the 1st test cycle the friction level is quite constant. Looking into the 2nd test cycle, the friction level and the friction band are usually increasing, which is caused by the significantly increased oil pressure and by the higher oil temperature. During the second part of the program the seals and the hydraulic fluid are extremely stressed.

The improvement in the seal friction could be seen when friction plots from different single tests are compared. Figure 9 shows the combined friction characteristic of two seals from Test 1 and Test 3 (untreated hydraulic oil) which are compared against Test 4 (DST) and Test 6 (DST).

The friction improvement of the seals operating in the treated and cleaned hydraulic oil can be seen in a reduced friction force and a narrow friction band. The improvement can be explained by the removal of very small particles, achieved with the DST process. This could also explain why the friction in Test 4 (DST) is even smaller as the friction from Test 1 with virgin mineral oil where larger particles were detected during particle counter investigations according to ISO 4406:99.

The second chart is showing the same trend. Even after three “Baseline Tests” and two “DST Tests” with the treated oil, the Test 6 (DST) shows a lower friction level compared to any test with the virgin hydraulic oil.

The friction force difference of the Test 4 (DST) and the Test 6 (DST) is in a similar scattering range of test results and could be seen as well in previous heavy-duty tests in past, performed with a standard non treated oil.

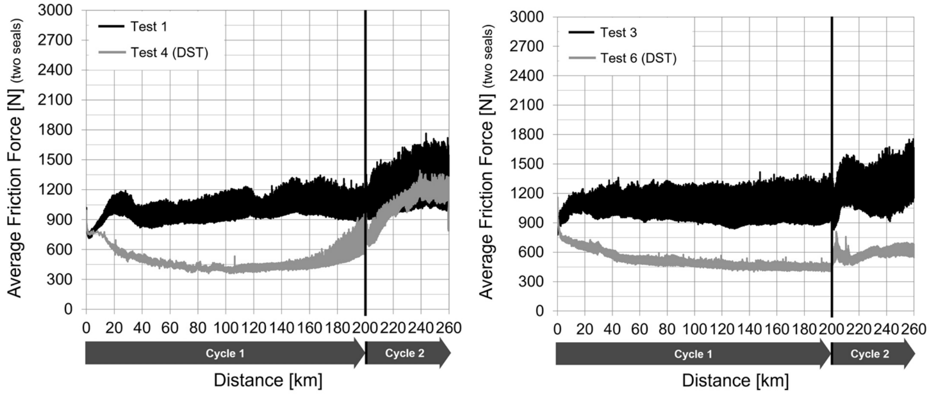

Figure 9: Friction characteristics

An even more impressive behaviour of the seal friction improvement could be seen when Test 4 (performed with the aged oil) is compared against the Test 4 (DST, the same oil being regenerated), as shown in Figure 10. Considering the same operating time of both oils at the beginning of the test, the friction improvement and the resulting lifetime extension of the oil by using the DST process is clearly visible. The strong degradation state of the oil in Test 4 causes a higher friction level and friction band.

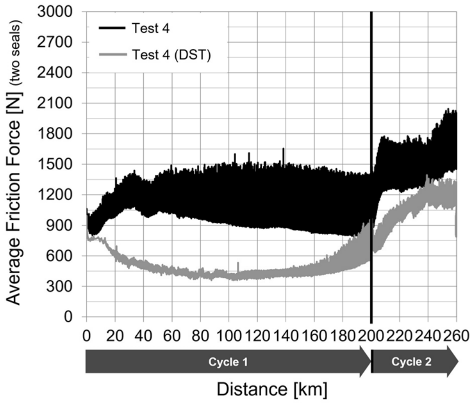

Figure 10: Friction force of seals Test 4 vs. Test 4 (DST)

5 Conclusions

The results of these investigations demonstrate a positive effect on the most important seal criteria as leakage, friction force and remaining deformation of seals when oil aging is prevented by treating it with the double separation technology process. It also outlines significant problems of seals when oil is aged due to heavy environmental conditions and when it is used beyond the usual service lifetime. The tests showed that the oil lifetime under the applied test conditions could be doubled when it was treated with the DST process. Comparing the test results and seal pictures of Test 4 (DST) against the Test 4 (virgin untreated oil) outlines the positive effect of the DST process which results in a lower friction force a better leakage and a better extrusion resistance. Removing very small contaminants with DST process leads to a slowdown of the oxidation and aging process and to an increase of the service lifetime of the oil. Another key finding was the clear correlation between oil aging and performance of seals when Baseline Tests 1 to 4 are compared against each other.

6 References

[1] Baczewski, K., Szczawinski, P.: Investigation of the process of ageing of hydraulic oil during its use, In: The Archives of Automotive Engineering – Archiwum Motoryzacji. 2016; 73(3): 5-18, http://dx.doi.org/10.14669/AM.VOL73.ART1

[2] N, N.: SKF RecondOil Q&A, https://skfgroup.sharepoint.com/sites/cs-recondoil/SitePages/de/RecondOIl.aspx, visited on April 27, 2022

[3] Totten, G., Westbrook, S., Shah, R.: Fuels and Lubricants Handbook, Technology Properties, Performance and Testing, American Society for Testing & Materials, 2003, ISBN 0803120966

[4] Ostberg, T., Fasching, M., Schwarz, T., Schreymayer, S., Rochford, I.: Managing Particulate Contamination in Hydraulic Oils, In: SKF Whitepaper, 2021

[5] Livingstone, G., Cavanaugh, G.: *The real reasons why hydraulic oil fail,* In: TLT Tribology & Lubrication Technology, 2015

[6] N, N.: Noria Corperation: Lubricant Additives - A Practical Guide, In: Machinery Lubrication, https://www.machinerylubrication.com/Read/31107/oil-lubricant-additives, visited on March 04, 2022

[7] Cen, H., Morina, A., Neville, A.: Effect of lubricant ageing on lubricants' physical and chemical properties and tribological performance; Part I: effect of lubricant chemistry, In: Industrial Lubrication and Tribology, 2018

[8] Fitch, J., Ghost Riders: Noria Corperation: That Haunt Your Oil, In: Machinery Lubrication, August 2018

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