Characterization of radial shaft seal performance in contaminated environments

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1 Introduction

Radial shaft seals (RSS) are typically used to avoid leakage of a lubricant from the lubricated interior of a machine, while allowing for the transmission of power to the outside through a rotating shaft. Their secondary function is to prevent ingress of environmental substances such as water or dirt/dust particles into the machine. While water ingress would substantially inhibit the proper function of the lubricant and possibly cause corrosion, ingress of dirt particles can damage the functional surfaces of gear flanks and bearing raceways. Both effects would drastically decrease the service life of the machine.

To guarantee reliable sealing, the RSS must be able to pump oil present at the air side end of the sealing contact towards the oil side /1/. The presence of this reverse pumping action is typically explained by the interaction of several effects, which require the presence of a rough sealing lip /2/ and an asymmetric contact pressure distribution in the sealing contact with its maximum closer to the oil side (see Figure 1) /3/.

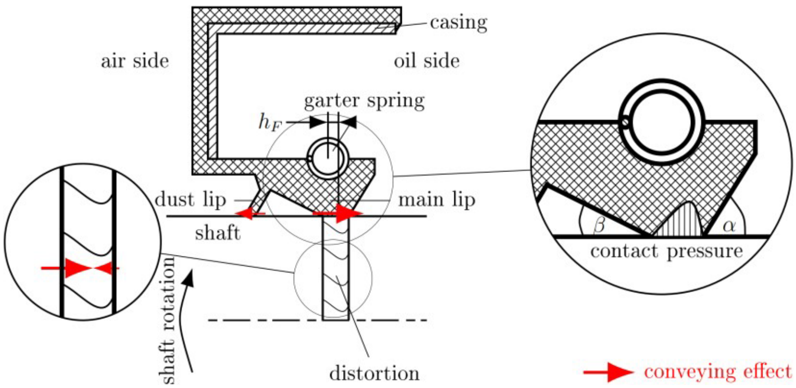

Figure 1: Cross section of RSS with dust lip and visual representation of the lip distortion and resulting conveying effects in the sealing contact.

During shaft rotation, a small fluid film (~1 µm) will form between shaft and sealing lip because the shaft will drag oil in the contact /4/. The friction in the contact causes the sealing lip to deform circumferentially, creating a distortion pattern which is more pronounced on the air side end due to the asymmetric contact pressure distribution.

Oil being dragged in circumferential direction due to the shaft rotation will partly be deflected axially from the distorted sealing topography. The resulting axial oil conveyance dominates towards the oil side. While this effect guarantees reliable sealing, the combination of a small lubricant film in the sealing contact and oil conveyance towards the inside of the machine can potentially also transport small particles or unwanted fluids from the environment through the sealing contact /1/. In many applications, seals are used in contaminated environments. Examples are seals in utility vehicles used for construction work or in mining, where dusty air or abrasive slurries (water containing dirt particles) can reach the seal. Industrial gearboxes in food processing, where regular cleaning with hot water or steam and aggressive media is required are further examples.

Therefore, in environments with problematic contaminants, RSS are usually equipped with an additional dust lip (see Figure 1) to prevent dirt particles and fluids from reaching the main sealing lip. The dust lip can either have a small clearance with respect to the shaft or be in contact with it. In the latter case, due to the dust lip geometry, a small conveying effect towards the air side is present. Since the lubricant at the inside of the machine can only reach and lubricate the main sealing lip, the cavity between main lip and dust lip is usually lubricated with grease. A major disadvantage of RSS with contacting dust lip is that the conveying effect of main and dust lip both transport fluid, grease or air out of the cavity between both lips /5, 6/. This can cause a significant negative pressure inside the cavity. Higher contact pressures and increased friction torque result /7, 1/. In extremely contaminated environments and applications, special sealing solutions like cassette seals with multiple axial or radial dust lips and other repelling features are applied, which typically cause even more friction torque.

Several standards for testing sealing systems in contaminated environments exist /8, 9, 10/. However, they only describe static tests and were not designed to include the typical conditions for radial shaft seals. The patent US 6276194 B1 /11/ presents a test apparatus for RSS in environments contaminated with dusty air. This apparatus does not allow testing with contaminated water reaching the RSS. In most available publications investigating radial shaft seals, contaminated air is used /6, 12, 13/. HARTL however investigated the effect of abrasive slurry and recorded the dirt migration under the sealing lip through a quartz shaft /14, 15/. OTTINK and PESCHKE investigated seals for rolling bearings in contaminated conditions /7, 16/. While PESCHKE does not provide information about the intensity and duration of dust application, OTTINK conducted tests where the air side of the seal was filled with contaminated oil. SHORE presents two different test setups for testing rolling bearing seals in contaminated environments /17/.

Although such applications are widespread, until now no universal guideline or standard defining uniform, reproducible testing of the overall performance of RSS in contaminated environments exist. This fact forces companies manufacturing products with potential use in contaminated environments to either define their own internal test procedures and test benches or do without such tests. Especially small and medium enterprises (SME) are not able to develop their own test procedures and test equipment. Furthermore, a development of proprietary test procedures leads to limited comparability of results and an unreasonably high effort for seal manufacturers due to the multitude of necessary tests their seals must pass.

In this contribution, an attempt at developing standardized investigations of the influence of dirt on an RSS-system is presented. A standardized test cell for test with contaminated air and also contaminated liquids is proposed. The influence of the operation conditions and sliding distance on the performance of seals is evaluated based on wear progress, leakage and contamination progression in grease and lubricant. Results of investigations with nitrile rubber (NBR) and fluoro rubber (FKM) based seals are presented.

2 Definition of standardized tests in contaminated environments

2.1 Definition of a standardized test cell

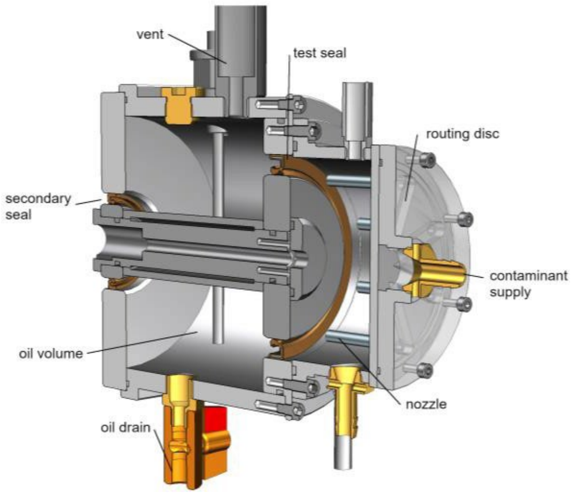

Figure 2: Standardized test cell for radial shaft seals in contaminated environments

A standardized test cell has been developed for testing radial shaft seals in contaminated environments (Figure 2) /18, 19/. It consists of an oil volume with temperature control which is sealed by a secondary seal towards the drive side (left) and by the test seal on the free side (right). The test seal is covered by the application head, designed to apply contaminated air or water directly onto the sealing contact through eight equidistantly spaced nozzles. The contaminated media is supplied through a central bore from the outside and distributed to the nozzles through a routing disc. By exchanging the routing disc, the nozzle diameter can be adjusted to seals with different shaft diameters. The supply of contaminated media can either occur using a brush dispenser and pressurized air or using a water reservoir with agitator and a pump. To allow for the quick investigation of enough seals for determining the statistical deviation of characteristics like wear or contact width change, six test cells have been manufactured. In the investigations presented here, each parameter set was applied on five cells, while one cell was used as uncontaminated reference.

A grease application device was constructed to allow for a constant, reproducible application of grease to the cavity (Figure 3).

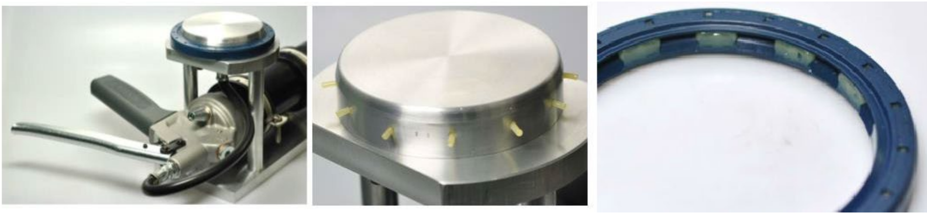

Figure 3: L./m.: Grease application device. R.: Greased RSS.

2.2 Definition of a standardized test procedure and evaluation methods

To define a standardized test procedure, different dirt substances (glass beads, silicon carbide, aluminium oxide, quartz, Arizona Dust, salt), particle sizes, particle concentrations, contamination durations, intervals, and media (air, water) have been investigated and compared in tests with 5,000 km sliding distance in previous investigations /18/. It was found that the wear in the system increases with increasing sharpness of the particles (evaluated as described in /20, 21, 22, 23/), particle concentration and contamination load (contamination interval time and duration) and also when water is used as transport medium. The reproducibility of the results was increased when using water and also when particles < 5 µm were present.

A representative collective of operation conditions and contamination has been selected based on the overall reproducibility and expressiveness of the previous tests (Table 1).

Table 1: Collective and parameters selected for tests

shaft material	42CrMo4 (55 HRC)	**oil sump temperature**	70 °C
oil	FVA PAO 2 (Gargoyle Arctic SHC 226E)	**sliding velocity**	6 m/s
grease	Petamo GHY133N	**grease amount**	40%, 0.46g
seal type	AS 80-100-12/8 /24/		
oil level	mid shaft	**contamination interval**	5 h
dirt medium	water	**contamination duration**	10 s
dirt substance	Arizona Dust A2 (A4) /25/	**dust concentration**	30 g/l

In subsequent tests, the influence of sliding distance (7,500 – 20,000 km) and relative motion (constant speed 6 m/s, increasing speed with average of 6 m/s, and change of rotational direction +-6 m/s every 5 h) was investigated for seals made from NBR and FKM with a sliding distance of 7,500 km. In order to investigate the influence of particle size distribution on the particle migration through the sealing contact, selected tests were also repeated using Arizona Dust A4.

The evaluation of wear and contact width was performed using a profilometric laser scanning measurement device at 5,000 positions along the circumference /26/ (Figure 4). By evaluating the luminance signal of the sensor, a monochrome image of the sealing lip can be recorded, which can be used to identify damage on the lip (Figure 6).

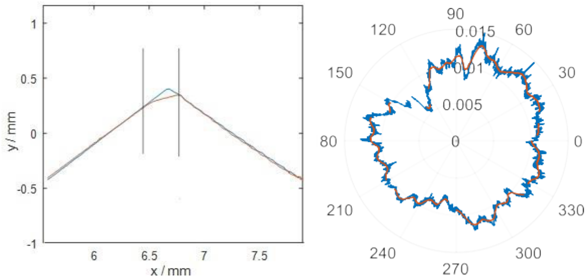

Figure 4: Wear evaluation of a NBR seal after 20,000 km sliding distance. L.: Main lip profile in new (blue) and worn (red) condition at random position along the circumference. R.: Polar plot of planimetric wear / mm² around the circumference of a FKM seal.

The particle contamination in oil and grease after the test was measured at an external laboratory using Atomic emission spectroscopy (AES) (grease) and Inductively coupled plasma atomic emission spectroscopy (ICP) (oil), water content was measured using KARL FISCHER titration.

3 Investigation of seal performance under different scenarios

The investigations with Arizona Dust A2 up to 20,000 km sliding distance show significant differences of the sealing performance of NBR and FKM seals. Data for 5,000 km was taken from previous investigations /18/.

The FKM seals remain tight during all investigations, while for the NBR seals, leakage can be identified in all tests from 7,500 km onwards. For the lower sliding distances, leakage is identified by the presence of oil in the water reservoir and cannot be assigned to individual seals. At a sliding distance of 20,000 km, all test cells with NBR seals lost 50 to 80 % of the initial oil volume due to leakage. Reference seals run without contamination were leak tight in all investigations.

Figure 5 shows the progress of wear and interference at dust and main lip for NBR and FKM seals. The wear at the dust lip increases continuously with sliding distance, while the interference of the dust lip decreases. The interference of the dust lip of the NBR seals reaches almost zero at 20,000 km sliding distance, indicating a failure of the dust lip due to wear. At the main lip, no significant increase of wear can be found for FKM, while the wear of the main lip of the NBR seals increases drastically between 15,000 and 20,000 km. This is coherent with the loss of interference for the NBR seals. Probably, the dust lip of the NBR seals failed between 15,000 and 20,000 km, allowing high amounts of the abrasive slurry to enter the cavity, wash out the grease and reach the main lip, causing increased wear. This could possibly be avoided by using a grease that is wash-out proof.

The interference of the main lip did not change drastically during the tests (max. -14,5% for NBR and -18,8 % for FKM).

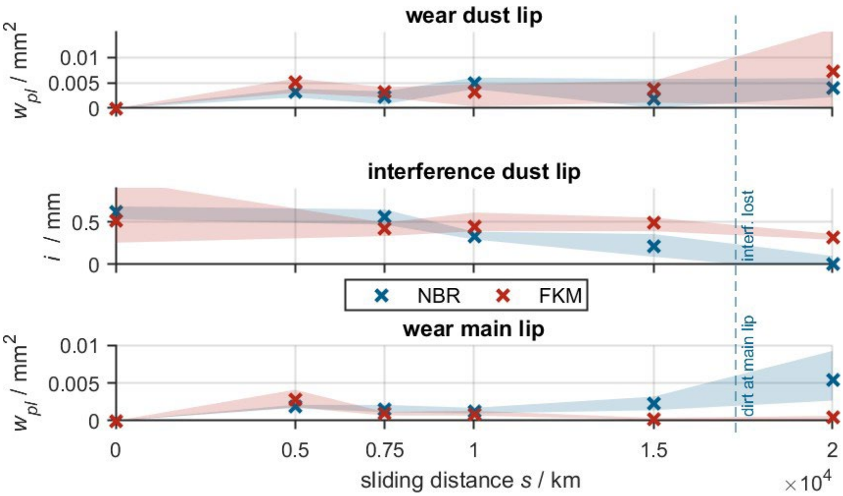

Figure 5: Progress of wear at dust and main lip for NBR (blue) and FKM (red) for a sliding distance up to 20,000 km with Arizona Dust A2. The shaded areas represent the min and max values of the five investigated RSS per sliding distance and material. When determining the wear of the dust lip of the FKM seal at 15,000 km, three invalid data points (wear < 0, probably due to residual particles on the dust lip) have been neglected in the evaluation.

The 360° monochrome images of the RSS show similar results. While for NBR seals, wear is clearly visible on both lips after 20,000 km (Figure 6), the FKM seal looks almost as in the new condition (not depicted).

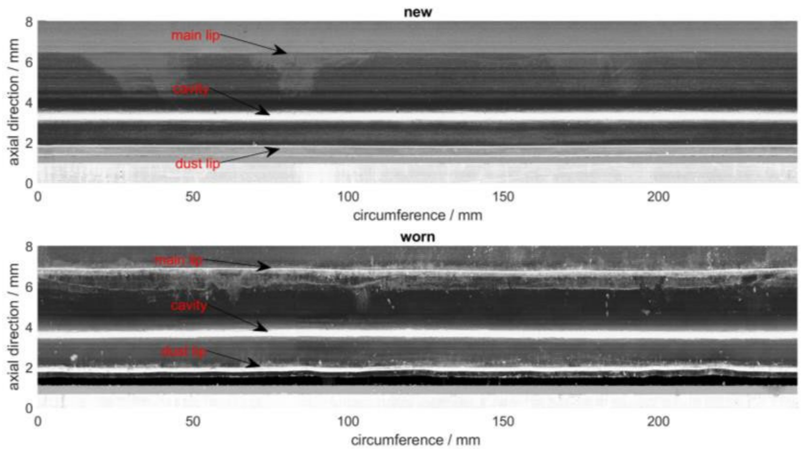

Figure 6: Main lip of a NBR seal before (t.) and after (b.) test with 20,000 km sliding distance. Damage and deformation are clearly identifiable on the worn seal.

After each test, grease and oil samples were extracted and analyzed as described in Section 2.2. Figure 7 shows the change of the extracted grease from 0 to 20,000 km. It can be clearly seen that the grease darkens and is covered by black, crystalline deposits, which probably contain contaminants that were able to pass the dust lip. When investigating the grease of the RSS run in clean environment, no such dark crystalline structures can be identified. However, this grease has also darkened – probably due to a combination of wear particles and thermal influence.

Due to the increasing leakage of the NBR seals, grease was washed out and only a limited sample amount could be retrieved after each test.

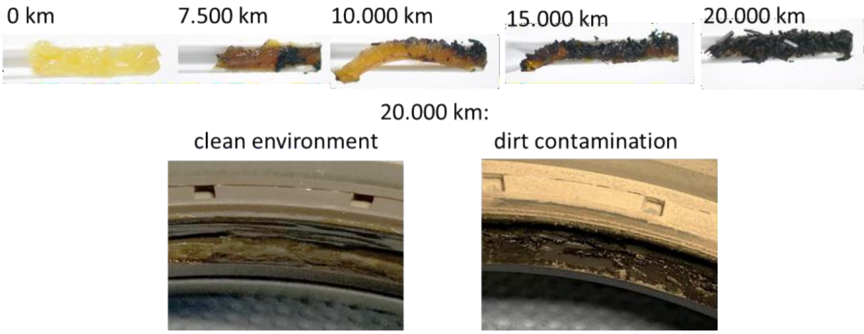

Figure 7: T: Evolution of grease between main and dust lip over 20,000 km sliding distance for FKM seals. B.: Grease in the inter-lip space after 20,000 km sliding distance in a clean (l.) and contaminated (r.) environment. It can be clearly seen, that grease was washed out in the contaminated test.

Selected results of the grease analysis can be found in Figure 8. The contents of chemical elements that can be attributed to Arizona Dust (SiO_2, Al_2O_3, CaO, Fe_2O_3, K_2O, NaO_2, MgO, TiO_2 /18, 25/) and the water content in the grease increase compared to the new condition. For the NBR seals, a maximum of contaminants is reached at 15,000 km and a decrease is found at 20,000 km. This is probably due to the massive oil leakage and failure of the dust lip, allowing the grease to be washed out. The grease samples from the FKM seals show an increase of contaminants up to 10,000 km and after that a stagnation of the contents. The analysis of the oil samples shows only faint traces of Si and Na (1 ppm) and no significant changes in water content and viscosity, indicating, that both NBR and FKM seals reliably prevented contamination of the oil, even though the dust lip of the NBR seal failed and leakage occurred.

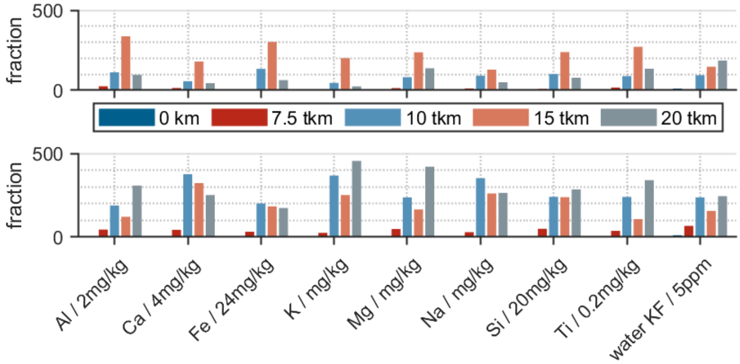

Figure 8: Change of grease contamination during the investigations. T.: NBR, B.: FKM. Please note that some of the categories have been scaled (as given in the category name) to allow for a uniform bar length and better visibility of the differences in each category.

The influence of a different dust size (Arizona Dust A4) and different relative motions (constant incremental increase of speed from 0 to 12 m/s and change of rotational direction with +-6 m/s every 5 h) has also been investigated. Leakage was observed for the NBR seals in all tests.

For the coarser Arizona Dust A4, less particle contamination in the grease can be found for both NBR and FKM seals, indicating a better protection of the dust lip against coarser particles. Due to the leakage of the NBR seals, only a limited amount of grease samples could be extracted from the NBR seals.

Mixed results are obtained for wear and interference at the dust lip (Figure 9).

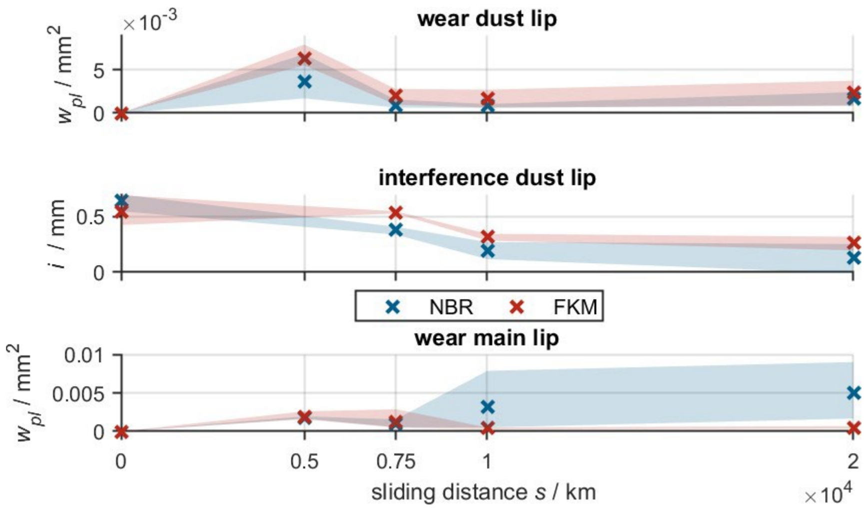

Figure 9: Progress of wear at dust and main lip for NBR (blue) and FKM (red) for a sliding distance up to 20,000 km with Arizona Dust A4. The shaded areas represent the min and max values of the five investigated RSS per sliding distance and material.

While the interference loss at the dust lip of the NBR seal seems to be slightly lower compared to the test with A2, the opposite can be found for the FKM seals. This indicates that coarser particles might cause more wear with FKM dust lips. Wear and interference of the main lip show no influence of the dust particle size for both NBR and FKM seals.

Using non-stationary shaft speeds increases the particle ingress into the grease. A profile with changing rotational direction causes more dust ingress compared to a profile with increasing shaft speed. On the other hand, the wear of the dust lip is significantly lower for an increasing speed profile and slightly lower for a profile with change of rotational direction.

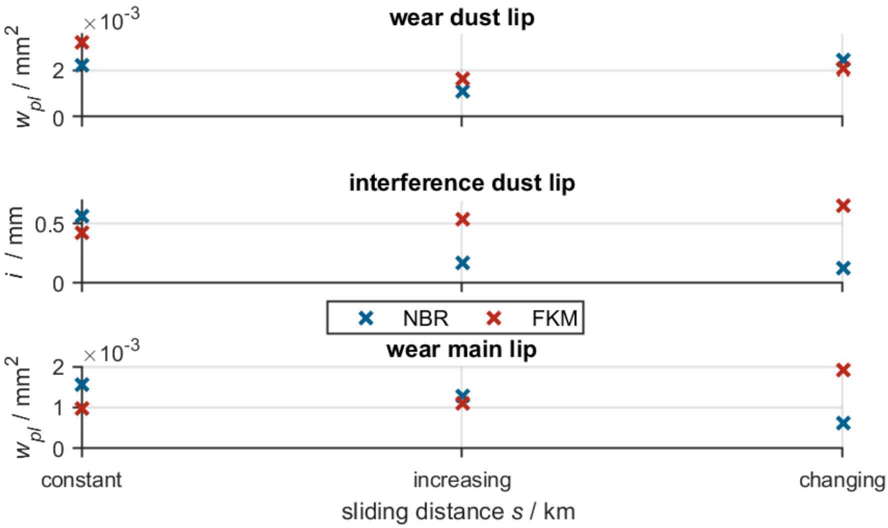

Figure 10: Comparison of relative velocity (stationary, increasing speed and change of rotational direction) for NBR (blue) and FKM (red) for a sliding distance of 7.500 km with Arizona Dust A2.

4 Summary and Conclusion

Although some investigations and test procedures for the performance of RSS in contaminated environment exist, until now, no standardized test method and test environment has been defined. Therefore, a standardized system for the investigation of RSS performance in contaminated environments has been developed. This includes the definition of a standard test cell for tests with water and air as dirt medium and the definition of investigations to be performed on the seal and the lubricants after each test to determine the sealing performance. Based on previous investigations, a test protocol, and an exemplary load collective for conducting such tests have been developed on seals with contacting dust lip.

Comparative investigations of the influence of seal material, test duration, dirt particle size distribution and type of shaft movement have been conducted. The investigations show that the seals made from NBR failed in the test and showed significant leakage, while the FKM seal remained tight with respect to oil leakage and contaminant penetration into the oil volume. Based on the investigations with different sliding distance, the failure mechanism of the NBR seals could be identified: The dust lip showed increased wear leading to loss of interference thus allowing the abrasive slurry to enter the cavity, wash out the grease and reach the main lip.

The investigations also show that changes in the operational conditions or the type of contaminant influence the behavior of the seal. This illustrates the need for a standardized dust test for radial shaft seals, allowing to take into account the relevant application conditions. Based on the investigation method and standardized test cell presented in this contribution, the creation of a standard or guideline for such tests will be pursued in future efforts.

5 Acknowledgements

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6 Nomenclature

Abbrev.	***Meaning***
AES	Atomic emission spectroscopy
FKM	Fluoro rubber
ICP	Inductively coupled plasma atomic emission spectroscopy
NBR	Nitrile rubber
RSS	Radial shaft seal
SME	Small and medium enterprises

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