Condition monitoring of reciprocating seals

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The condition monitoring (or 'health monitoring') of systems or plants enables data acquisition of a component by sensors at any time and thus the connection and processing of data in accordance with the idea of Industry 4.0; it offers many advantages such as condition-based maintenance or reduced stuff costs in maintenance procedures. Regarding a sealing system, the implementation of a measurement system is a challenge, as it is difficult to attach external sensors directly to the sealing gap of the housing. Monitoring the failure of a seal is desirable to reduce unplanned machine downtimes and avoid environmental damages from leaking fluids; or vice versa product contamination - as shown by food recall cases in the past.

This contribution shows the approach from Freudenberg Sealing Technologies: Instead of using indirect machine parameters and modelling the expected lifetime, the seal becomes 'smart' thanks to a special design: The sensing seal provides the same sealing functionality as a conventional one but can additionally become a sensing element by combining different materials to a two-component part. In that way, this seal does not require any external sensor components in the sealing system, which usually impair the sealing function. Measurements on real valves and cylinders show how the progressive wear of a sealing lip can be measured in translatory applications. The correlation of the dimensional change caused by wear to the leak test of the seal shows that the developed sensor seal system is more sensitive than the leakage detection and a measurable signal increase always occurs before, which has also been verified in contact with different fluids.

Possible intervention limits can be set by the user himself or the system can calibrate itself; in consequence the system provides self-learning capabilities. This solution significantly increases the overall system reliability and thus the system efficiency.

1 Introduction

The system health monitoring has become more into the focus of machine and plant constructors. The reliability of machines for sure has always been an important factor, but meanwhile during digitalization of machine parameters the potential to predict when a failure *will* happen becomes very attractive. And the advantages in terms of economic benefits become clearly apparent: Proactively plan maintenance intervals helps to avoid unplanned and expensive downtimes, an implementation into a digital logistic chain might enable to supply spare parts in time to reduce warehouse costs and finally the a reduction of personnel costs for maintenance can also be a further aspect. And finally, the usage of a component like a seal till the end-of-life, prolonging maintenance intervals clearly fits into the thought of sustainability and helps to reduce the CO2 handprint of the products.

The condition monitoring requires sensors, this is clear. The current activities focus on the use of already available sensors as pressure, temperature and acceleration sensors. With this input data, empirical models are fed; they are supposed to predict a mechanical or structural breakdown which leads to a failure. Some approaches have successfully proven their suitability for a variety of systems (e.g., bearings with the help of acoustic noise evaluation). There are attempts for leakage prediction through a digital twin based on machine parameters, too. This is an extrapolation of laboratory test values, which, however, ignore special field influences.

Therefore, it is still a challenge to predict the end-of-life of a seal based on models since in the field applications lot of effects can influence the seal failure which might be hard to be captured in models, such as char coal formation or change of a lubricant. Seals are parts in the machine or plants which might catch in the overall system health evaluation not the highest attention, however the follow-up costs of a failed seal might be enormous. Higher loads, heavier contamination and similar factors favor early failure and increase the risk of estimating the time of failure too optimistically through purely static statistical predictions. On the other side there are no sensor systems so far which can measure directly the condition of a seal, even more it is hard to place a sensor in addition to a seal on a groove A direct correlation as to when the leakage will occur in the field is difficult to achieve due to the sometimes very different conditions. Checking for leaks in the field is usually done by visual checks, e.g., oil drop formation on the drive shaft or on the hydraulic cylinder. Existing sensor solutions digitally map these optical failure root causes. In consequence, the idea has been born to develop a seal system which seals in a primary function and which is able to measure the condition of the seal at every moment of the application to allow an intelligent algorithm a prediction when it will fail.

2 Smart Seal

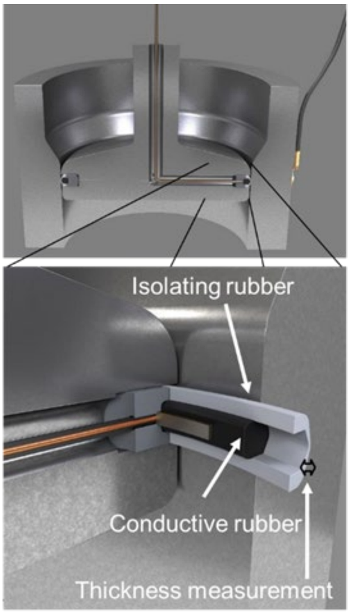
2.1 Root cause for sealing failures

Initially it was analyzed which effects and changes lead to failures of seal. Basically, all failure of a seal can be reduced to the loss of contact pressure which allows the sealed media to pass through the barrier of the seal and to leak. The loss of the contact force can be caused by different effects – either by mechanical changes or physico-chemical changes of the material. Mechanical changes are: Abrasion/Wear and Extrusion. Physico-chemical changes are swelling, shrinkage, setting, aging, fatigue.

The task of dynamic seals is to seal two components that move against each other in a liquid, gas and dust-tight manner. Due to the relative movement, they are exposed to high stresses and are therefore subject to wear, which becomes noticeable through slow erosion of the sealing material. If the material removal is too great, the sealing function is no longer guaranteed and leaks occur, such as oil escaping from hydraulic cylinders. A wear evaluation depends on various factors and above all external environmental conditions, so that an aggregation from machine data is usually not possible. In this development we focused on the effect of wear of a dynamic seal, which leads to a dimensional change and with that a loss of contact force. The approach to the solution is how to measure the wear of the sealing lip of a dynamic seal

2.2 Wear detection

To provide a solution for this concept the Freudenberg Smart Seal approach is as



follows:

In figure 1 there is the cross-section of a valve as it is used for bottling facilities in the food & beverage segment.

Figure 1: Measurement principle of Freudenberg Smart Seal

The radial seal in the outer diameter of the valve moves in translator direction. Behind the seal there is a back-up-ring which is connected by a wire to a cable which brings the signal to the outside. The seal is manufactured by using an electrically conductive rubber and an isolating rubber as a two-layer part. Physically, the conductive rubber and the metal housing form a capacitor with the isolating rubber in the middle. During the application the outer, isolating layer wears off, the distance becomes smaller and therefore the capacity signal increased. Furthermore it is important that the back-up ring is isolating otherwise an short-circuit is received. This development was patented [1].

2.3 Simulation

For the realization of the idea, it was necessary, at first to simulate the range of the capacity changes to ensure that the effects of changes. Also, the question of which shape is necessary to provide a most effective capacity measurement should be answered. The simulation was performed with COMSOL. The results show that the optimized shape of the inner conductive layer, which is the electrode 1, is triangular with one point pointing towards the metal counter face (electroce2, Figure 2). This provides an increase of capacity on the sealing tip and reduction of parasitic noise in the measurement. This development has patented as well [2].

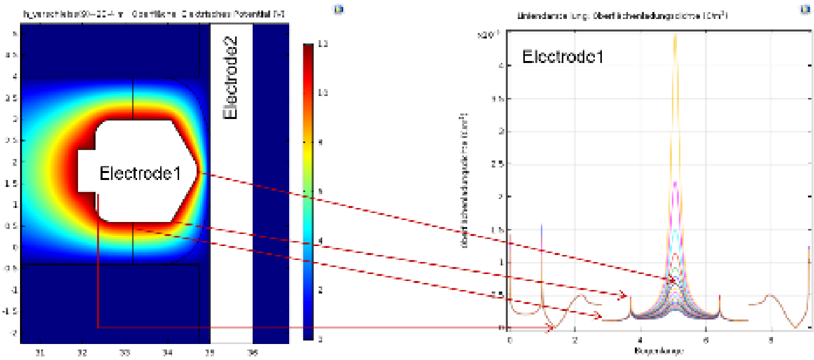


Figure 2: Shape of the electrode in the inner conductive rubber layer

Using this design and the equation of the plate capacitor the correlation between wear /abrasion of the outer (isolating) layer could be simulated, as the isolating layer wears off and the electrode (conductive rubber) comes closer to the electrode 2 (metal hosing). Figure 3

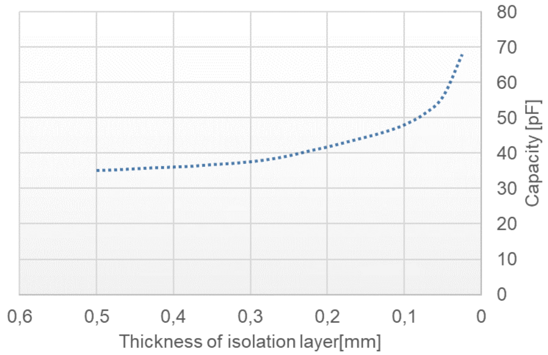


Figure 3: Shape of the electrode in the inner conductive rubber layer

2.4 Material development

The sensor system uses two different rubber material types which are bonded to each other in the manufacturing process. The challenge for the electrically conductive material (inner diameter) was basically to provide a material with a sufficient high electrically conductivity and good setting behavior. For the isolating rubber material, a good setting behavior and wear resistance is necessary. For both types acid and base resistance, as they are required in the process industry as cleaning fluids, and FDA / EU2004/1935 conformity is demanded. All values should be comparable to the EPDM 292 as reference materials. Furthermore, a good processability for manufacturing in the given tolerances and precision is mandatory and a good self-bonding from the outer layer to the inner layer is also key.

Finally, the development of the rubber material was successful: Two materials have been developed which fulfills the specification which has been defined. Even more, the processing was after several optimization successful: Good bonding, constant layer thickness of the two layer system as well as overall dimensional robustness could be achieved with a special tooling concept in a customer specific design which is in serial applications.

Figure 4: Freudenberg Smart Seal using two different rubber layers

2.5 Testing

2.5.1 Test-rig for dry runs

The testing of the manufactured seal was performed in a market available valve with a cooperation partner (figure 5). It has been modified in terms for suitability for testing under lab conditions considering also internal safety standards. A leakage measurement has been installed by using compressed air as reference: When applying 6 bar, closing the pressure supply line, and no pressure difference can be observed for 120 sec, the system is considered as tight.

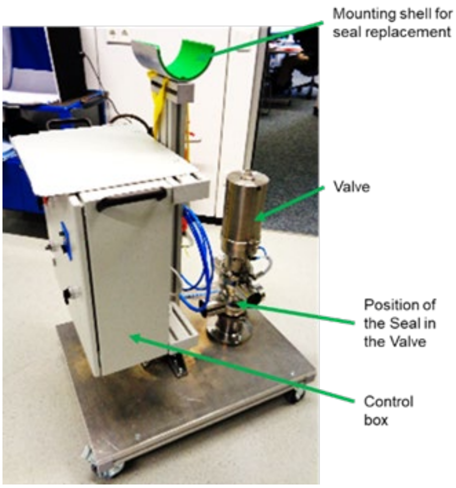


Figure 5: Set-up of the test-rig for the dry run

A further key for success is the measurement card and electronics. Several systems have been evaluated, however only one system was suitable to provide the capacity signal in an evaluable way. The test rig measurements and the signal evaluation has been optimized with the help of external partners. Several optimizations in the whole electronic systems have been made to reduce parasitic capacities and to increase the signal-noise ratio. The automatization of the test rig enabled continuous long-term measurements to measure the wear of the seal in a dry run which increased the efficiency. Test runs up to 100.00 cycles were performed.

2.5.2Results for dry runs

Figure 6 indicates the results of the dry runs. With the automatization and the optimization of the measurement equipment, it is possible to measure the capacity increase as the previous simulation (2.1) has shown (figure 3). It meets completely the expectation that the initial increase for the first 10.000 cycles is minor while the further increase becomes significant when the wear (which correlates to the cycle numbers) further increases. It can also be noticed that the leakage in this system occurs after the capacity increase. This indicated that the capacity increase is more sensitive to the dimensional changes and provides the correct sensitivity. All repetitive measurements proved that the capacity increase was detected always before the leakage of the system, no leakage before a signal increase was observed. An overall scattering of the wear was observed which is to be expected and correlates to the behavior of the serial seal.

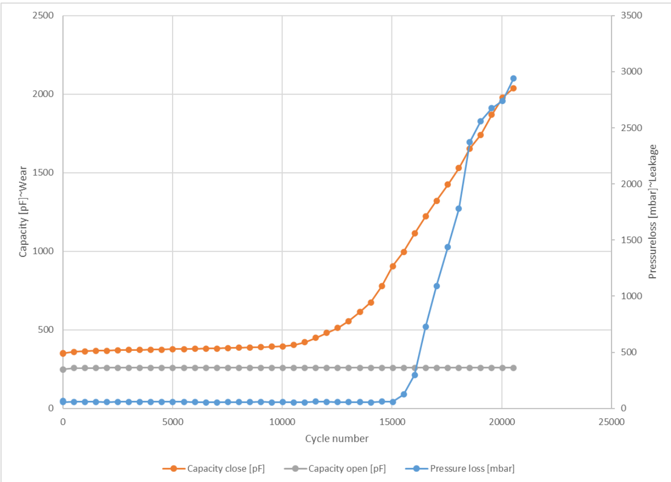


Figure 6: Set-up of the test-rig for the dry run

This results proofs the concept for a real-time condition monitoring of the wear of a sealing lip.

Furthermore, the reproducibility of the start signal of different seals was investigated: 11 different Smart Seals with the two layer set-up were tested on the valve test rig, the results are displayed in figure 7: The deviations in the start capacities are neglectable, the start capacity is 350 pF in this evaluation.

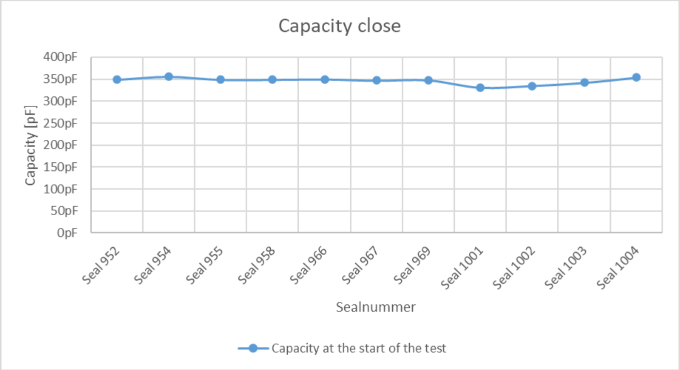


Figure 7: Set-up of the test-rig for the dry run

2.5.3 Test-rig for wet runs

After the results in the dry run showed that the correlation between wear of the sealing lip and the increase of the capacity signal is given, the next step in the evaluation is to test in fluid. For applications in the process industry, water is the most relevant fluid, but also for the evaluation of capacity measurement as suitable measurable, water is interesting because of its electrically conductive properties. In other words: The question is, if the contact of water during the capacity measurement has a negative impact or would even make any measurements impossible. Therefore, the test valve has been reconstructed and installed in a wet-room environment. The automatization and steering electronics have been adjusted accordingly, so that a continuous measurement under field-related conditions could been started (figure 8).

Figure 8: Set-up of the valve test-rig for wet runs in water

Smart Seals tested in valve with 517.000 cycles in deionized water. Over this run time, only a slight increase of wear could be detected on the seal after optical evaluation after the test has been finished. This is explained in the context of the lubrication effect of water. However, the measurement in itself was consistent to the expectations. The wear of the seal was homogeneous and no delamination of the 2 rubber bonding layer could be detected.

Further testing has been performed in deionized water, however, to accelerate the wear of the seal, a test protocol which alternates the dry run and wet run was set up. Now the wear on the sealing lip was found as homogeneous on the 4 quarters of the ring (Figure 9), accordingly a constant signal increase in water could be measured. So, the correlation between wear (dimensional change) and capacity increase also in water is given.

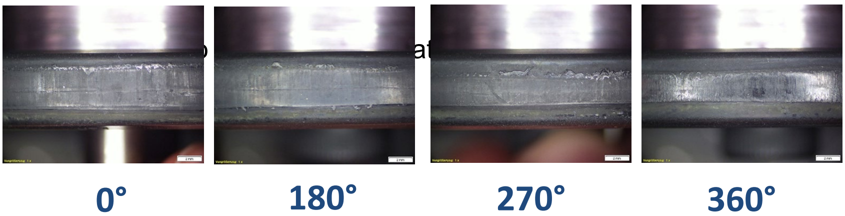


Figure 9: Sealing front after 218.850 cycles in water

For a full life-time evaluation, the testing in tab water was repeated. The initial capacity values are comparable to the dry (figure 6), over 40.000 cycles an more or less linear increase of capacity can be recognized, the spreading between the lower and upper band is explained by the open and closed valve and consequently to two different capacities which leads to an unchanged capacity in the baseline and refers to the open valve (figure 10). Similar as in the dry run a quasi-exponential increase of the capacity signal can be measured (> 40.000 cycles) , at the end of life also circuits be detected (> 80.000 cycles). This is indicated by bars which hit the 0 pF axis. This is the case, when the isolating layer is wears off and the conductive layer contacts the metal housing.

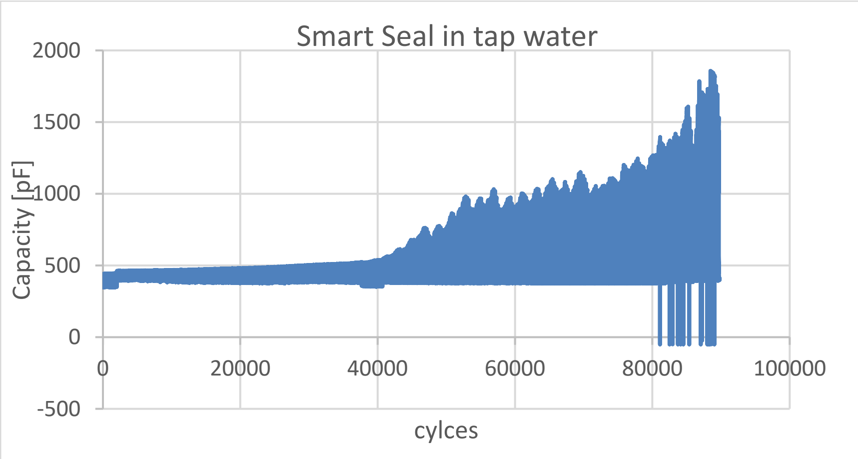


Figure 10 : Set-up of the test-rig for the wet run in water

Testing in water is regarded was successful: No negative influence, or distrubance even with tab water, to the measurement system could be found, also no delamination or impact on the sealing function. No significant leakage of tab water could be observed in that test run, however, it must be mentioned that the water was circulated without applying a pressure to the seal.

So the proof of concept in water was according to our findings very positive, in our opinion a real condition monitoring based on the dimensional change of the seal is possible.

2.6 Transfer to other reciprocal sealing systems

Further reciprocal systems has been investigated. High interest has been recognized for the primary sealing lip of a hydraulic cylinder. For this type of seals PTFE seals are in the focus, especially for high pressure applications. As in the previous example also the wear of the PTFE lip is in the focus and in conjunction with failure and leakage of the seal in the field. Typical applications are hydraulic cylinders in a variety of general industry applications (like excavator, sluice, foundry etc.). So the same approach like in the first valve example was used: The wear of the sealing lip was supposed to be measured by an capacity measurement, the capacity increases as the electrode come closer to the metal rod. In this case as electrode material a conductive PTFE was used. However, since PTFE is manufactured differently than rubber and taking the sintering tubular process into account, a different design was necessary, because a core-shell concept is not producible in that manner.

Therefore a three-layer concept where the layers are placed next to each other seems to be most suitable: For a design study a PTFE seal used a conductive PTFE which is displayed in figure 9 as light brown middle layer, the two outer and inner layer uses the standard, wear optimized PTFE material B602. The design uses an standard lip design and an additional sealing edge to avoid any tilt and with that any artefacts during the application. To transfer the signals to the outside, a conductive O-Ring is installed as an energizer (in here it is a electrically conductive HNBR, behind the O-Ring a cable transfers the signals to the outside). For the electrical functionality, an isolation to the metal housing is necessary. It must be constructed in that way that leakage though the cable gland is avoided. For our feasibility study, PU as isolating materials was chosen.

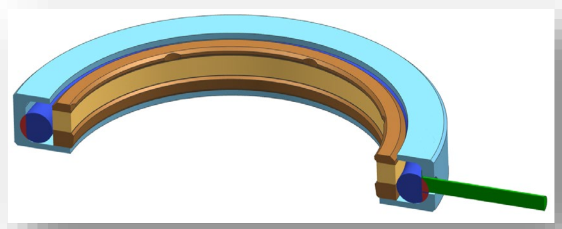


Figure 11: Design of the Freudenberg Smart Seal using PTFE and an O-Ring as energizer

The complete installation is shown in figure 12. During the reciprocal application, the PTFE seal wears off, so that the conductive layer, representing the electrode which comes closer to the metal rod, representing the counter electrode, which forms a capacitor. In the same manner like in 2.2-2.5 described, a continuous capacity measurement shows an increase of the signal during a testing.[3]

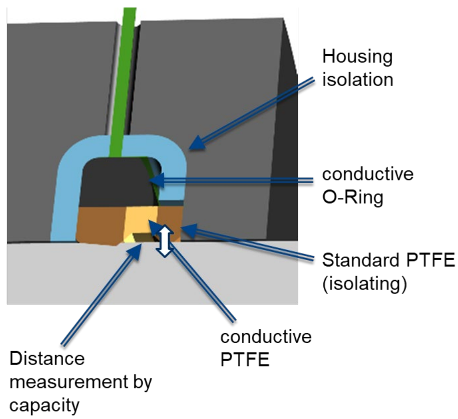


Figure 12 : Measurement principle of Freudenberg Smart Seal using PTFE

In Figure 13 the results from a lab testing set up is shown: Here the Smart Seal system was installed in a rod and a tensile testing machine was used to perform the dry test run. It is noticeable that the capacity significantly increases after 150 strokes.

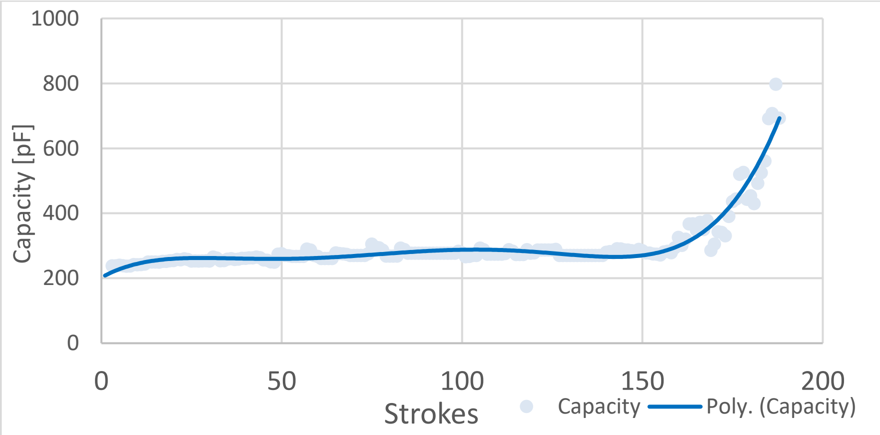


Figure 13 : Dry test run of a Smart Seal for dynamic applications

This clearly correlates with the dimensional change caused by wear (figure 12) which shortens the distance of the electrode to the metal rod. At the end of life the sealing edge is almost flat.

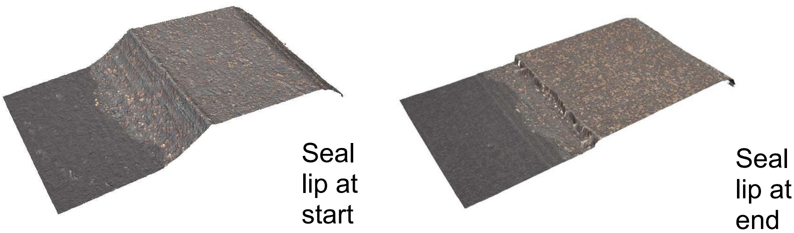


Figure 14 : Dry test run of a Smart Seal for dynamic applications

This clearly indicated that the principal of capacity measurement to measure dimensional changes can be also transferred to hydraulic PTFE seals. Currently, test rig trials on hydraulic wet cylinders are ongoing to proof the applicability also in lubricated applications.

2.7 Patents

[1] DE102016012552

[2] DE 102017008314

[3] US 2020370653

3 Summary and Conclusion

It could be shown that the first sealing system (Freudenberg Smart Seal) has been developed which is able to measure its own lifetime by using electrically conductive and electrically isolating layers to form a capacitor. With this transducer system it is possibly by a continuous capacity measurement to measure dimensional changes of a sealing lip which are caused by wear. In that way, a continuous measurement is possible and also a self-adjustment and machine intrinsic definitions of intervention limits are possible. Further, the validity of the sensor system has been proven in lab testing as well as in prototyping tests on market available valves for the food and beverage industry in dry testing as well as in wet runs using water as fluid. In all cases the sensor system turned out to be more sensitive and indicated changes before leakage occurred.

As a next step the Freudenberg Smart Seal System is supposed to be tested in real time field applications to evaluate the scope and the limits of the measurement system.

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