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A Method of Comparing Recurring Observations of Leakage in Rotary Shaft Seals under Accelerated Tests

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1 Abstract

Accelerated testing of rotary shaft seals as an integrated part of a hydraulic system, coupled with advanced methods of measuring and recording leakage, is challenging existing notions of zero-leakage evaluations of time-to-failure and rotary shaft seal comparisons. This is due to the fact that, when conducting accelerated tests of orbital motors; observations of leakage between the seal and shaft do not always imply defects in the rotary shaft seal itself. A spontaneously applied radial load, particles caught between the rotary shaft seal's sealing-lip and the output-shaft, instant variations in a motor's case-pressure or the quick reversal of output-shaft rotation can all cause, individually or in combination, a temporary break in the viscous sealing membrane between an otherwise, perfectly functioning sealing-lip and output-shaft, resulting in, seemingly, arbitrary leakage occurrences.

Considering these arbitrary occurrences of leakage, one can conclude that a rotary shaft seal's ability to eject particles which are trapped between the output-shaft and rotary shaft seal or to quickly re-stabilize the sealing membrane between the output-shaft and sealing-lip (which has been temporarily broken, for any number of the aforementioned reasons) are among the most desirable characteristics a rotary shaft seal can possess and that furthermore, these characteristics are counterintuitive to the information which can be obtained from zero-leakage evaluations of time-to-failure experiments.

This paper will explore a possible method of comparing and evaluating recurring observations of leakage in rotary shaft seals, as an integrated part of a hydraulic system, under accelerated tests.

2 Introduction

In an orbital motor, the rotary shaft seal, output shaft, housing bore and hydraulic lubricant form a complex sealing subsystem in an even more complex power generating system [1]. Though plunge ground shafts, bore tolerances in the magnitude of microns and sealing and lubrication technologies from industry leaders have all been implemented into standard orbital motors, achieving zero-leakage performance over total lifetimes has proven evasive in applications where customers show a willingness to continuously employ an orbital motor at the intermittent pressure, speed and load-bearing boundaries of its specifications. For these customers, operating in a niche market, it is an orbital motor’s ability to withstand the adverse effects of an extreme duty-cycle, which differentiates their product from those of their competitors. In addition to elevated magnitudes of attrition on the power generating system’s rotating components, adverse effects can include recurring leakage occurrences between the orbital motor’s output shaft and sealing lip.

In order to accommodate the needs of customers operating in this challenging market, it was decided to conduct tests on four types of high-pressure rotary shaft seals, with the intention of identifying and implementing the most suitable seal design. The four shaft-seal types were specially designed, for a specific orbital motor, by three different industry leaders in sealing technologies. Upon receiving the seals, a test which closely resembled an accelerated version of a customer provided duty-cycle was designed and a test-rig was constructed. A brief description of the test-specification itself, considerations associated with preliminary test results, a method for evaluating these results and finally, how these results were interpreted in order to find the most suitable seal for the customer application, are the subjects of the following sections.

3 The Accelerated Test Specification

Having closely examined a customer provided duty-cycle; an accelerated test specification was developed, under the premise:

> *“Acceleration requires that there be a stress dependent physical process causing change or degradation that leads to failure”*, whilst keeping in mind that, “*[i]n general, different failure modes will be affected differently by stress and have different acceleration factors”*, and *“[t]herefore, it is unlikely that a single acceleration factor will apply to more than one failure mechanism“* [2].

The failure mechanism to be examined was *Measured Leakage,* where failure (*Time to Breakdown)* was identified as Measured Leakage exceeding 20 milliliters within a 24 hour period. In order to accommodate production and assembly tolerances in the testing (thus ensuring a statistically representative data set) a test-sample size of 20 pieces orbital motors, for each shaft seal type, was chosen.

When examining the Test Specification in Table 1, it is important to note that *Maximum Peak Pressure* and *Maximum Peak Speed* parameters, in unison, fall outside of the Maximum Power Output specification for the orbital motor in question. Likewise, the *Maximum Radial Shaft Load* being applied; here defined as the maximum permissible load, located 80 millimeters from the front flange of the orbital motor, at 100 revolutions per minute, also falls outside of the orbital motor's load limitations [3]. In combination, these factors will promote particle generation as the internal components wear. In order to allow for the free passage of particles caught between the sealing-lip and output-shaft, applied radial load is momentarily released every 60th second. This sudden reapplication of radial load, coinciding with shaft reversals, also serves to effectively break the sealing membrane between the output-shaft and sealing-lip and to further provoke leakage occurrences.

Table 1: The Test Specification

Parameters	**Description**	**Remarks**
Motor type	*O-Series*	Test 20 pieces of each seal type
Case Pressure (low level)	100 bar	10 seconds
Case Pressure (peak level)	Max. Peak Pressure [bar]: according to the Technical Brochure	2 seconds
Shaft Speed	Max. Continuous Speed [rpm]: according to the Technical Brochure	Constant
Direction of Rotation	Reversing	Every 60 seconds
Radial Shaft Load	Max. Permissible Shaft Load [kN], placed 80 mm from flange: Load according to the Technical Brochure	Constant, but with instant release at each reversal
Duration of Test	Time to Breakdown [hours]: Defined as Leakage > 20 [ml/day]	Record hours and leakage
Oil Type	Tellus 68	Filtered reservoir
Oil Temperature	90 degrees C	Constant
Oil Viscosity	10 cSt	Constant

4 Preliminary Results

When testing of 15 pieces each of two different shaft seal types had been completed, a method of comparison was considered. Here, it became apparent that determining the marginal differences between the two shaft seal types would require more than the standard statistical methods with which we were familiar. A simplified overview of the preliminary results can be seen in Figure 1, which shows the leakage histograms for Shaft Seal Types *A* and *B*. By *Leakage* is meant the daily sums of leakage occurrences, for every tested orbital motor, for each of the shaft seal types.

The first histogram shows that orbital motors tested with Shaft Seal Type A, had six occurrences of a daily leakage, equal to approximately 3 milliliters of magnitude. Note that the histogram does not specify when the leakage occurred, or which of the orbital motors had “3 ml leakage”, but rather expresses that measured leakage, with a magnitude of approximately 3 ml, occurred six times, over the course of testing.

In order to compare the two shaft seal types, from this preliminary data, it would appear necessary to determine whether it is the magnitudes of leakage occurrences, the number of leakage occurrences or a combination of both (possibly in relation to hours of operation), which are to be examined. However, when reconsidering the original intent of the test specification to provoke arbitrary leakage occurrences through wear, particle generation and dynamic loading, it becomes clear that; magnitudes of leakage will greatly depend upon the size of the generated particles which are caught between the sealing-lip and output shaft, and that leakage occurrences will likewise be compounded by the spontaneously applied radial load, aforementioned particles, variations in case-pressure and the immediate reversal of output-shaft rotation. It was therefore concluded, an ideal method of comparison would enable the evaluator to determine if the leakage occurrences are truly arbitrary and to compare rotary shaft seal performance accordingly.

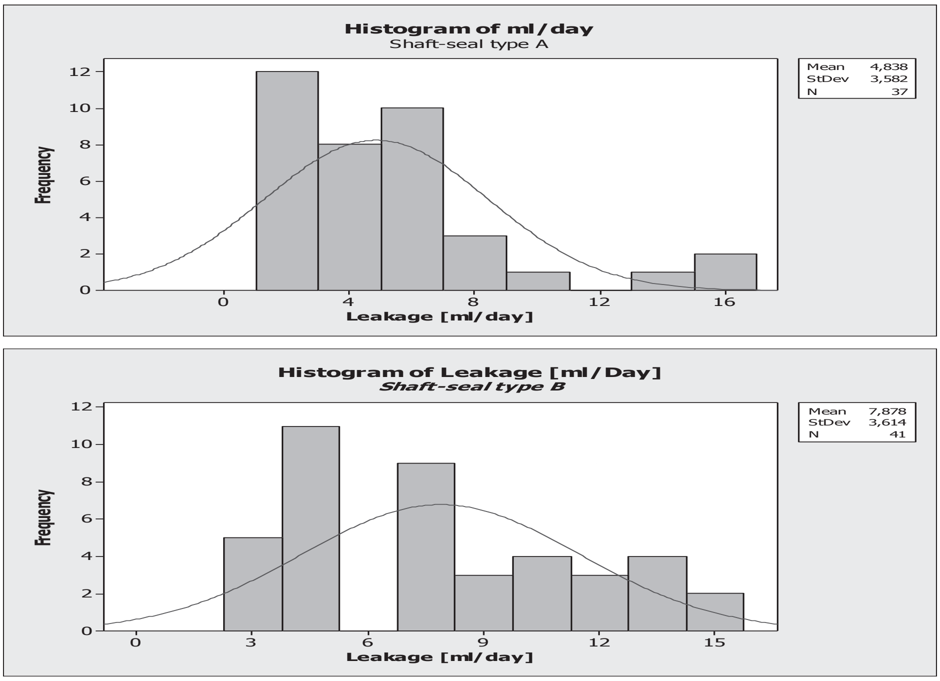


Figure 1: Histograms of Leakage for 2 different shaft seal types, where *Leakage* <> 0

5 A Possible Method of Comparison

In order to identify eventual relationships between individual orbital motors and leakage occurrences measured over time, the preliminary data was plotted three-dimensionally, where *Mean Times to Failure* for both the shaft seal and the bearing[1] were also referenced. Figure 2 shows the topographic plot[2] of leakage occurrences for Shaft Seal Type A, where the motor numbers were re-ordered according to their Time to Failure (from smallest to largest, where Motor No. 20 had the longest lifetime).

The Author was also examining three-dimensional surface roughness standards when the preliminary test results became available and upon a closer examination of Figure 2, it became apparent that it might be possible to consider the topographic plot as if it were a measured surface; in which the 20 pieces of orbital motors and *Time [Hours]* = 3*T* would demarcate the *X* and *Y* axes respectively (where 3*T* is equal to L90% for all shaft seals being compared[3]). This type of plot will hereafter be referred to as the *Performance Topography* of a given seal.

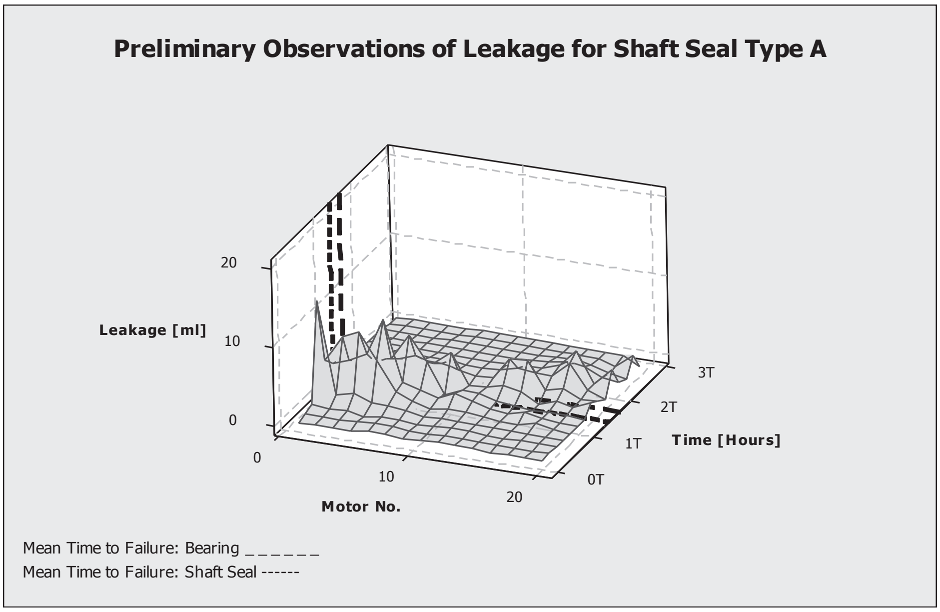


Figure 2: Topographic plot showing occurrences of *Leakage* for Shaft Seal Type A

[1] Why consider bearing lifetimes? Bearing failure under accelerated testing will inevitably generate sufficiently many large particles, that the shaft seal will also be destroyed. The bearing is therefore typically dimensioned to have an L20% lifetime corresponding to that of the shaft seal.
[2] Topographic plots were created using the *Minitab Distance Method*, with a Distance Power of 2 [5].
[3] Unless otherwise noted, L90% implies the time to failure, where no more than 90% of the shaft seals will have failed, using 95% Confidence Intervals [4] for the percentiles, assuming that the data is normally distributed, and examining the results for all shaft seal types as separate data sets.

This would imply that existing methods of evaluating the characteristics of a measured surface could also be used to evaluate and compare the Performance Topographies of different shaft seal types. Pursuing this implication required that those 3D surface roughness parameters which could best evaluate the arbitrary characteristics of the observed leakage occurrences be identified.

5.1 Identifying 3D surface roughness parameters for use in the evaluation

Two of the surface roughness parameters defined by the University of Huddersfield's Centre for Ultra Precision Technologies[4] (University of Huddersfield, hereafter) could directly evaluate the characteristics of a measured surface in relation to a Gaussian surface [6]. These parameters are known as the *Kurtosis of a Topography Height Distribution* and the *Skewness of a Topography Height Distribution* (see the following subsection). Examining these two parameters, one could ask: If an ideal Gaussian surface can be considered to be a symmetrical pattern of observations, could a data set also be evaluated and compared, in regards to an "absence of symmetry", in the data set's recorded leakage observations?

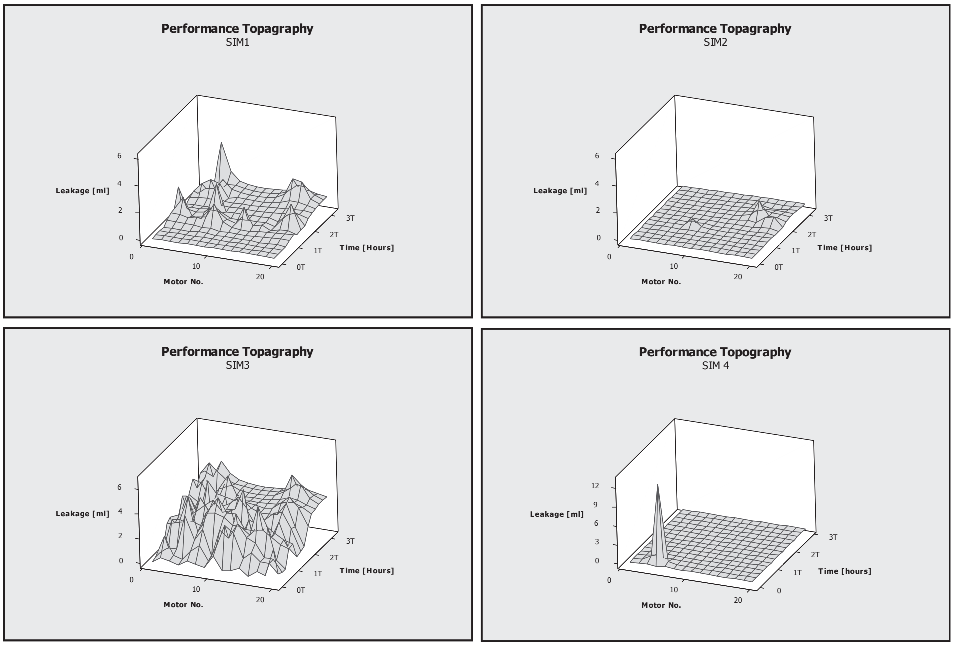


Figure 3: Performance Topographies for four different simulated test results

In order to address this question, the Author created four different, simulated data sets of shaft seal leakage over time. The simulated data sets each included 20

[4] At the time of this activity, the Author was unaware of efforts associated with the publication of ISO 25178. Therefore, all surface roughness considerations described in this subsection were based on the work of the Centre for Ultra Precision Technologies at the University of Huddersfield.

pieces orbital motors and differed in: the number of leakage occurrences; the magnitude of the leakage occurrences; and the time-position of the leakage occurrences. The number of measurement samples, *N*, in time, *3T,* was designated as 220. The Performance Topographies for the 4 simulated data sets can be seen in Figure 3.

These Performance Topographies clearly show the different leakage characteristics of the four simulations (note that Simulation 3, with 120 leakage occurrences, appears to resemble a Gaussian surface), but in order to make an objective evaluation of differences between the simulated data sets, the Author now needed to identify the surface roughness parameters which were to be utilized in the analysis. The Author so chose to consider the *Root-Mean-Square Deviation*, *Skewness and Kurtosis* parameters as defined by the University of Huddersfield [6]. For the sake of brevity, these equations can be expressed as equivalent to: the square root of the first moment about the mean; the third moment about the mean; and the fourth moment about the mean. Brief descriptions of the parameters are following.

5.1.1 Root-Mean-Square Deviation of the Surface Sq

> *"This is a dispersion parameter defined as the root mean square value of the surface departures within the sampling area. Sq is a very general and widely used parameter. […]In statistics, it is the sample standard deviation"* [6].

5.1.2 Skewness of Topography Height Distribution Ssk

> *"This is the measure of asymmetry of surface deviations about the mean plane. This parameter can effectively be used to describe the shape of the topography height distribution. For a Gaussian surface which has a symmetrical shape for the surface height distribution, the Skewness is zero.* […]*This parameter can give some indication of the existence of "spiky" features"* [6].

5.1.3 Kurtosis of Topography Height Distribution Sku

> *"This is a measure of the peakedness or sharpness of the surface height distribution. This parameter characterizes the spread of the height distribution. A Gaussian surface has a Kurtosis value of 3. A centrally distributed surface has a Kurtosis value larger than 3, whereas the Kurtosis of a well spread distribution is smaller than 3"* [6].

5.2 Utilizing the three 3D surface roughness parameters in an evaluation

Having now considered the aforementioned surface roughness parameters, the Author concluded that these three parameters could be a suitable basis for examining the simulated data sets. Unfortunately however, attempts at using these parameters, in their true mathematical form, failed. The primary difficulty lay in uncertainty regarding how to utilize (and eventually filter) the Z-axis, X-axis and Y-axis values (*Leakage*, *Motor No.* and *Time*, respectively), according to the integrals defined by the University of Huddersfield. It was therefore decided to limit the Skewness, Kurtosis and Root-Mean-Square Deviation (RMSD) evaluations to the Leakage parameter, where the position of leakage occurrences, with regards to time and motor number, would be ignored in the calculations. Single dimension versions of these statistical measures are shown below, in spreadsheet pseudo-code.

(1)

RSMD = SQRT(1/(*N* - 1)*(SUM (*'Leakage [ml]'* - AVERAGE (*'Leakage [ml*))^2))

It is important to remember that it is possible for many leakage observations in a Performance Topography to give a smaller RSMD than fewer leakage observations in another Performance Topography. RSMD is therefore only considered here as a component of the Skewness and Kurtosis parameters.

(2)

Skewness = 1/(N****Sq***^3)*(SUM(*'Leakage [ml]'*^3)))

The higher the Skewness: the more "spiky" the topography. A high Skewness implies fewer, random leakage observations. One observation of leakage in any group of *N* measurements will give the largest possible Skewness. A high Skewness is thus desirable when Skewness <> 0 and *N* >3.

(3)

Kurtosis = 1/(N****Sq***^4)*(SUM(*'Leakage [ml]'*^4)))

One summit in any group of observations (where *N > 3),* will give a Kurtosis equal to *N*. A high Kurtosis is thus desirable when Kurtosis <> 0.

Having limited the examination to the measured leakage occurrences, simulated data sets could now be compared. The results of these comparisons can be seen in Table 2. Table 2 shows that the four simulated data sets had 25, 5, 120 and 1 leakage occurrences (L_N) over the course of 220 measurements (*N*), with varying sums of leakage ($\sum L_N$). The table also shows that simulation number 4, with only one leakage occurrence, has the highest Skewness and Kurtosis values, whereas simulation number 3, with 120 leakage occurrences, has the lowest Skewness and Kurtosis values. These conclusions are certainly in agreement with the Central Limit Theorem and Law of Large Numbers [7], but for these simulated data sets, the advantages of using the Skewness and Kurtosis parameters as a rating system (as opposed to just using the counts of leakage occurrences directly) are not readily apparent. Reasoning that this could be due to the logarithmic differences between the count of leakage occurrences for each of the data sets, it was decided to pursue the assumption that an absence of symmetry in leakage observations is to be preferred to symmetrically patterned leakage observations, by evaluating measured leakage results for the four different shaft seal types which were already provided.

Table 2: *N*, L_N, $\sum L_N$, *Skewness*, *Kurtosis* and *RMSD* values for the simulated data sets

Simulation	N [number of measurements in time 3T]	L_N [number of leakage observations in time 3T]	$\sum L_N$ [sum of leakage occurrences, in ml]	Skewness	Kurtosis	RMSD
1	220	25	25,1	4,2	19,2	0,4
2	220	5	9,6	12,5	167,7	0,4
3	220	120	352,5	1,5	2,4	2,3
4	220	1	13,0	14,8	220,0	0,9

6 Results of Comparisons

Figure 4 shows the Performance Topographies[5] for Shaft Seal Types A and B, where the motor numbers where re-ordered according to their Time to Failure (from smallest to largest, where Motor No. 20 had the longest lifetime). Likewise, Figure 4 shows the Performance Topographies for Shaft Seal Types C and D, where the motor numbers were also re-ordered. A visual examination of these figures clearly reveals the strengths of examining the data topographically: it is apparent that the Mean Time to Failure values of all the shaft seal types are just under the Mean Time to Failure value of the bearings and that Shaft Seal Types A and B have significantly less leakage occurrences than Shaft Seal Types C and D. However, if the examination were limited to either Shaft Seal Types A and B, or Shaft Seal Types C and D, a visual examination would fall short of revealing which of the two shaft seal types, in the given pairs, is to be preferred.

Table 3 shows that the four data sets had 147, 161, 134 and 153 leakage occurrences (L_N) over the course of time *3T*, with varying sums of leakage ($\sum L_N$). The Skewness measures for Shaft Seal Types C and D are, respectively, 2,8 and 2,1. The Kurtosis measures are likewise 9,9 and 5,8. This would imply that leakage occurrences and magnitudes for Shaft Seal Type C are more arbitrarily distributed than the leakage occurrences and magnitudes of Shaft Seal Type D. If the Author's assumption that an, "absence of symmetry in leakage observations is to be preferred to symmetrically patterned leakage observations" is correct, then Shaft Seal Type C is to be preferred to Shaft Seal Type D.

Repeating this analysis for Shaft Seal Types A and B, where Skewness measures are respectively, 4,4 and 9,7 and Kurtosis measures are respectively, 19,8 and 128,4: Shaft Seal Type B is to be preferred to Shaft Seal Type A (under the same

[5] Performance Topographies were (also) created using the *Minitab Distance Method*, with a Distance Power of 2 [5].

assumptions). Likewise, Shaft Seal Type B is to be preferred to Shaft Seal Type C. That Shaft Seal Type B is to be preferred to Shaft Seal Types A and C is particularly interesting, when one considers that type B had more leakage occurrences than both types A and C (albeit with lower magnitudes of leakage per occurrence).

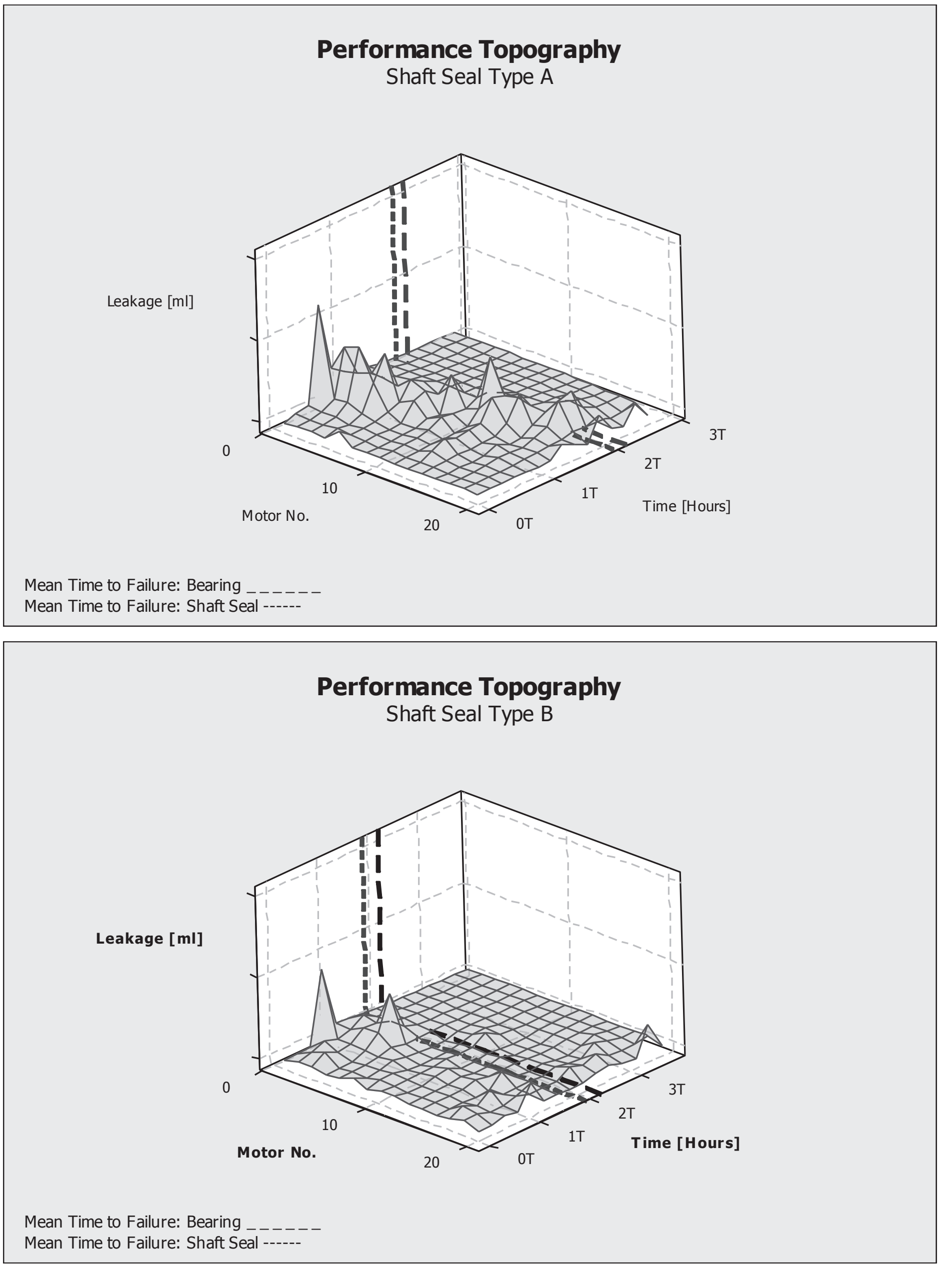
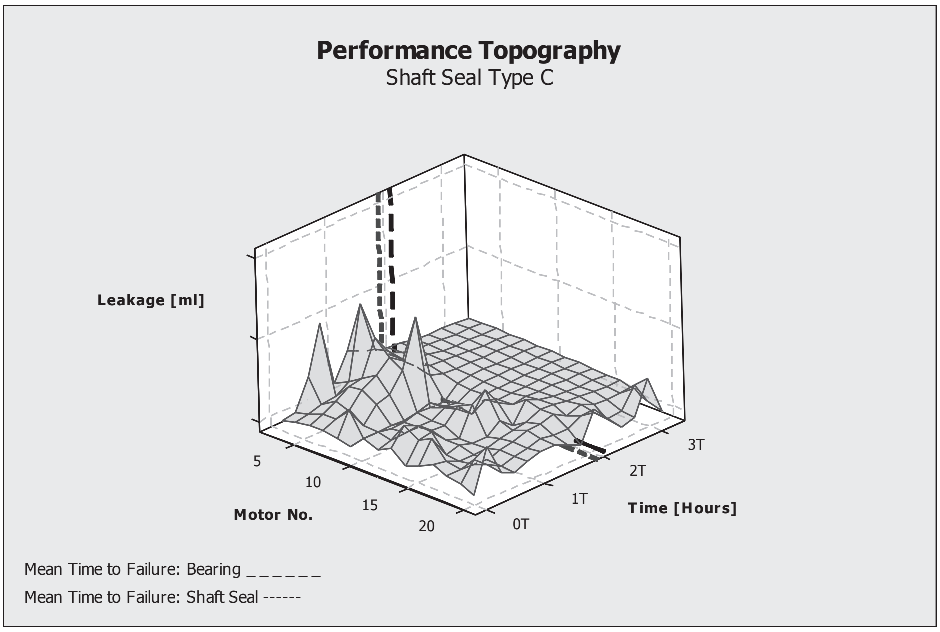


Figure 4: Performance Topographies for Shaft Seal Type A and Shaft Seal Type B



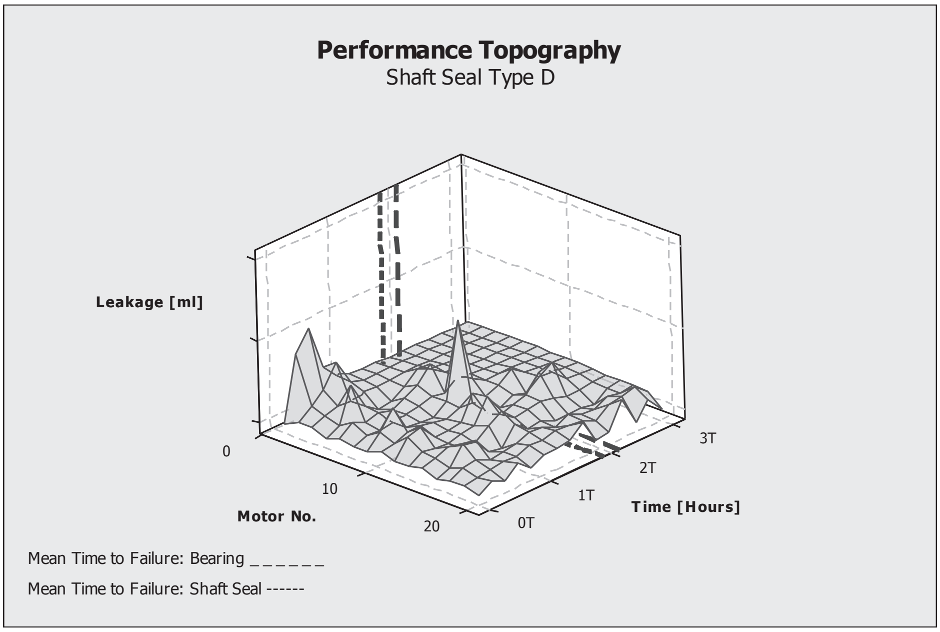


Figure 5: Performance Topographies for Shaft Seal Type C and Shaft Seal Type D

Table 3: L_N, $\sum L_N$, *Skewness*, *Kurtosis* and *RMSD* for Shaft Seal Types A, B, C and D

Shaft Seal Type	L_N [number of leakage observations in time 3T]	$\sum L_N$ [sum of leakage occurrences, in ml]	Skewness	Kurtosis	RMSD
A	147	486	4,4	19,8	3,5
B	161	186	9,7	123,4	1,4
C	134	937	2,8	9,9	3,4
D	153	935	2,1	5,8	3,4

7 Summary

In order to compare different types of shaft seals, which had similar occurrences and magnitudes of leakage under accelerated tests, where the tests were specifically designed to provoke arbitrary leakage; the Author proposed that an, “absence of symmetry in leakage observations is to be preferred to symmetrically patterned leakage observations”.

In an attempt to characterize this “absence of symmetry” in simulated and experimental data sets, the Author tried to examine the data sets as *Performance Topographies*, using 3D Surface Roughness Parameters specified by the University of Huddersfield. Failing to implement the *Number of Motor* and *Time* parameters of the data sets into the specified 3D surface roughness integrals, the Author had to suffice with visual examinations of the Surface Topographies and single dimension methods of calculating the following statistical measures: the square root of the first moment about the mean; the third moment about the mean; and the fourth moment about the mean, of the examined data sets.

Using this method to compare recurring observations of leakage in rotary shaft seals under accelerated tests, the author was able to rank the different types of shaft seals, by their performance over time, according to the aforementioned statistical measures and visual evaluations of their Performance Topographies; under the assumption that these measures did indeed evaluate an absence of symmetry in the examined data sets. Though promising, this assumption has not been mathematically proven by the Author (to date).

In extension of this endeavor, the Author is open to future collaboration with any individual wishing to pursue either: a more rigorous mathematical examination of the assumptions made in this paper; or an effort to implement the *Leakage*, *Number of Motor* and *Time* parameters into the 3D surface roughness integrals which were discussed in this paper.

8 Acknowledgements

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9 References

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