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Service Life of NBR-, EPDM-, HNBR and FKM O-Rings

Presentation of the State-of-the-Art of O-Rings Taking into Consideration the Effects of the Installation Space (Sealing Gap and Deformation) and Operating Conditions (Temperatures, Media)

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1. Introduction

While the long-term behavior of O-rings is of great practical importance, it is almost impossible to find in the technical literature a guidance for a realistic assessment of the load limits for O-rings. This contribution has the goal to first demonstrate under which boundary conditions the long-term evaluation of O-rings according to Arrhenius method is meaningful and effective. For this purpose it is necessary to show what causes the failure of O-rings in order to define the realistic life span (service life) criterion. In doing so, based on various parameter studies, the effects of the cross section size (cord thickness), gap dimensions, media, temperature patterns, and of the degree of deformation will be discussed. After that, it will be explained how to specify O-rings in order to exploit available current technology and to what extent the new O-ring material standard ISO/DIS36011-5 (2013-07) offers useful guidance. With clearly defined boundary conditions, based on performed long-term experiments, it will then be possible to point out realistic service life limits for the use of NBR-, EPDM-, HNBR and FKM O-rings.

2. How, and More Specifically, How Long Do O-Rings Function?

In order to recognize under which conditions O-rings fail, it is necessary to understand the way O-rings function. The sealing effect of O-rings is a result of two significant effects (see Figure 1 [1]):

1. The O-ring establishes contact with the sealed area and at the same time, forms a seal because of its good ability to adapt.
2. The O-ring produces a restoring force (pressing of the sealed area) which increases with the increase of pressure (the O-ring is activated). This allows the O-ring to be able to seal off almost any high pressure. The actual limitations are given by the resistance of the materials to extrusion within the sealed area (in case of one-sided pressure application).

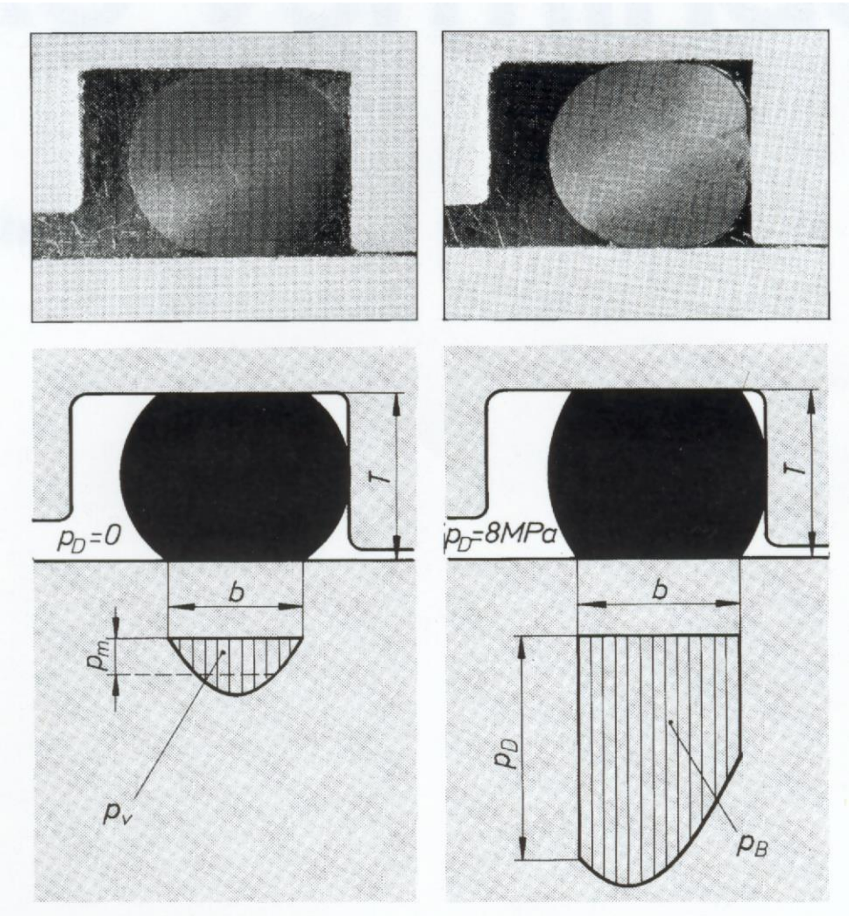

Figure 1 [1]: The O-ring as an active element

A leakage occurs only when both described effects no longer exist. This failure mechanism is particularly evident at low temperatures. First, during the continuous cooling of the O-ring the rubbery elasticity is lost and with this the O-ring loses its self-reinforcing effect; that is, the ability to be activated by pressure (see Point 2, above). However, as long as the O-ring still remains in contact with both sealing surfaces and if even a minute pressure exists, the O-ring will stay leak-proof, even when it lost its elastic recovery either completely or almost completely. A leakage will then only occur when additional cooling resulting from a relatively large thermal shrinkage of the O-ring causes its lifting off from the sealing surfaces. This leads to the formation of a gap. Since O-rings cool down much slower [2] below the glass transition temperature, it is possible to produce low temperature boundaries at very low pressures distinctly under glass transition temperature or even at freezing point (that is a complete loss of sealing force) as shown in Figure 2 [3]. This is also proven by experiments carried out at the DuPont Company [4].

Material designation	**Temp. [°C] (CS = 100%)**	**Temp. [°C] (leakage)**
FKM 1	-21	-35 ±2
FKM 2	-7	-20 ±2
FKM 3	-27	-31 ±2
FKM 5	-33	-44 ±2
FKM 7	-33	-41 ±2
FKM 8	-33	-41 ±2
EPDM	-47	-61 ±2
MVQ	-45	-63 ±2

Figure 2 [3]: Low temperature limits for O-ring seals (Flange sealing, 1 bar pressure)

The test method used in this case for the determination of the loss of rubbery elasticity is the TR-10 value [5, 6]. Low temperature boundaries for O-rings at high pressures have established that, in this case, the TR-10 value is a rather conservative criterion for the failure limit [7] as seen in Figure 3. The observation of the behavior of the O-ring within the cold region indicates that when evaluating the failure limit of O-rings, the operating conditions have a significant influence; in this case, it is the sealing pressure. For very low sealing pressures (e.g. 1 bar) we can definitely use 100% compression set as a realistic boundary criterion, while for higher pressures TR-10 value represents a rather conservative criterion. Experience shows that that the boundary criterion 80% of compression set represents an equally reliable criterion for the unrestricted functionality of an O-ring at low temperatures. These boundary criteria for the function of O-rings are valid certainly also for the loss of sealing force due to aging. In this case the change of properties, namely loss of restoring

	HNBR LT	**FKM LT**	**FKM ULT**
TR10-Value	-36°C	-31°C	-40°C
Minimum sealing temperature (test pressure 100 bar, applied only at the test temperature)	-41°C	-31°C	-41°C

Figure 3 [7]: Minimum sealing temperatures of pressurized O-rings (at the test temperature)

potential and embrittlement are irreversible in contrast to low temperatures, where they are reversible. This leads us to the subject of the long-term behavior, in which case the goal is to estimate at which thermal conditions the O-ring will fail. These predictions of the service life regarding the effects of heat and oxygen or air can only yield realistic results if after damaging mechanisms causing the failure such as abrasion, crack extrusion, explosive decomposition or a chemical attack by the surrounding oil are eliminated.

3. Effects of the Formulation Design

When undertaking long-term observation of O-rings, it certainly makes sense to define the O-rings under consideration with regard to the type of formulation (recipe) used and the degree of cross-linking of the base elastomer. With that the properties of the product represent one pan of the hoped for imbalance in favor of the life-span quality (durability) in comparison to service conditions (see Figure 4). This is clearly the weak point in so many elaborate tests of the O-rings, in which the life-span quality was not adequately defined. The Figures 5 and 6 reveal that there are decisive differences in the long-term behavior within the same polymer family; the Figures 7 and 8 demonstrate that a good characteristic value is not enough if the O-ring is not adequately vulcanized (cross-linked). The durability of an O-ring is then only defined when the properties of the formulation and the degree of cross-linking of the material used are sufficiently specified. It should be noted that the degree of cross-linking of the material can vary with the processing parameters relevant to performance (see Figure 9).

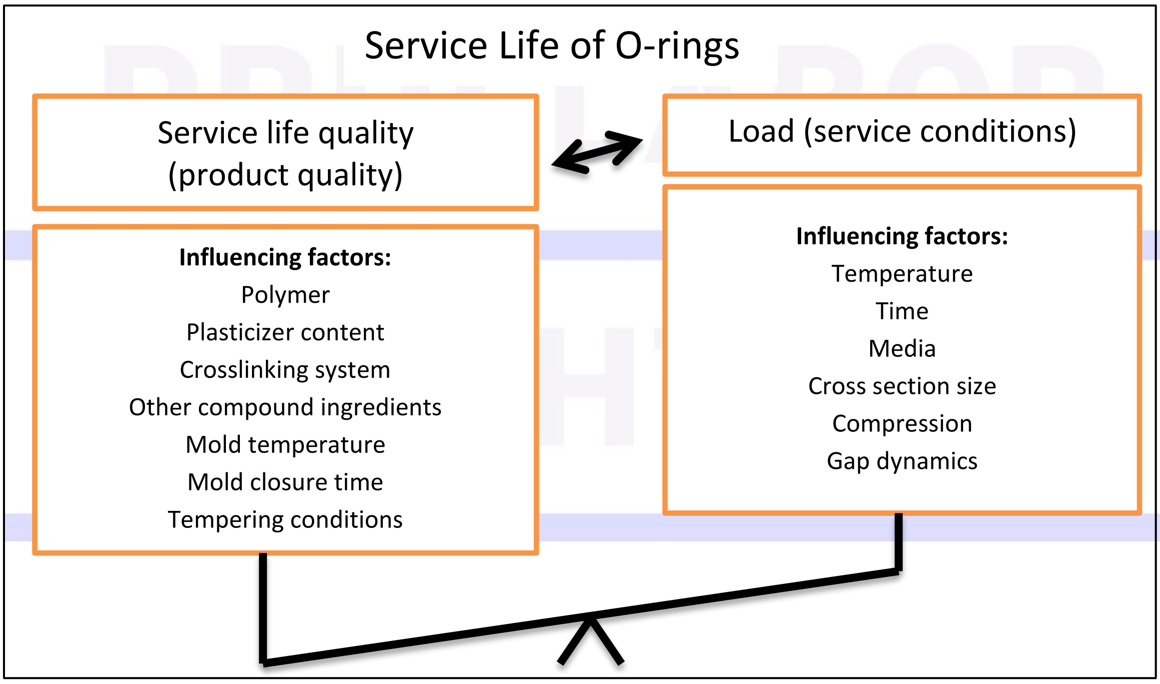

Figure 4: The imbalance between the O-ring quality and the load in favor of the ring ensures the sealing function

Long-term behavior of EPDM O-rings

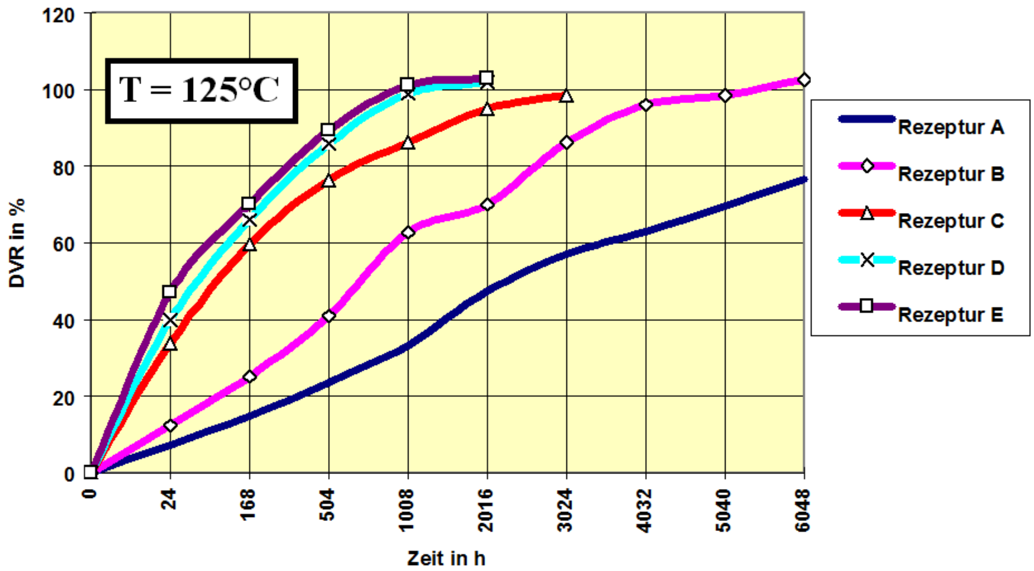

Figure 5: Long-term compression set (DVR) behavior of different EPDM O-rings (The Formulations A and B are cross-linked by peroxide, the formulations C, D and E by sulfur.)

(**Translation key:**

- *Rezeptur* = Formulation
- *DVR in %* = Compression set (CS) in %
- *Zeit in h* = Time in h)

Long-term compression set behavior of 2 different FKM formulations Measured on O-rings, d2 = 5,33 mm, T=200°C

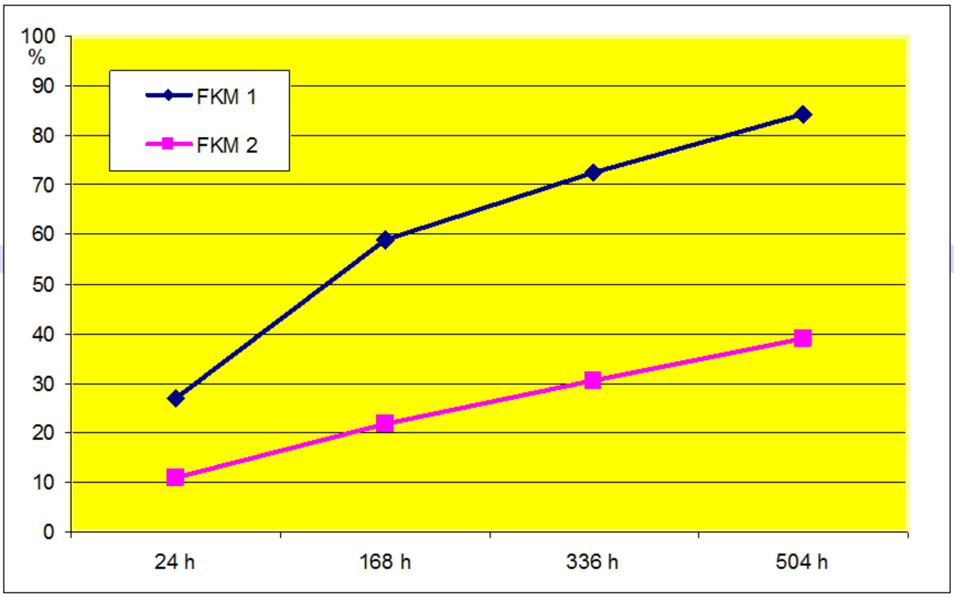

Figure 6: Long-term compression set behavior of two FKM O-rings

A) PHYSICAL PROPERTIES	REQUIREMENTS	TEST RESULT
PRESS CURE @ 170DEGREE C X 10 MIN		
POST CURE @ 120 DEGREE C X 1 HRS		
HARDNESS SHORE A	90+/-5	86
TENSILE STRENGTH,MPa	10	17
ELONGATION,%	200	332
SPECIFIC GRAVITY		1.513
B)HEAT AGING @ 150 DEGREE C X 70 HRS		
HARDNESS CHANGE, POINTS	+10	+3
TENSILE STRENGTH CHANGE ,%	-25	+4
ELONGATOIN CHANGE ,%	-30	-2
C)COMPRESSION SET		
HEAT AGING @ 150 DEGREE CX 22 HRS %	30	28
D)FLUID RESISTANCE,TEST METHOD NO.1.oil @ 150 DEGREE C X 70H		
HARDNESS CHANGE, POINTS	-5~+10	-3
TENSILE STRENGTH CHANGE , %	-20	-19
ELONGATION CHAGNE, %	-30	+13
VOLUME CHANGE, %	+/-5	+3
E) FLUID RESISTANCE,TEST METHOD NO.3.oil @ 150 DEGREE C X 70H		
HARDNESS CHANGE, POINTS	-15	-15
TENSILE STRENGTH CHANGE, %	-30	-18
ELONGATION CHANGE , %	-30	+48
VOLUME CHANGE, %	+25	+17

NOTE:THE ABOVE TESTS WAS TESTED WITH TEST PIECE AND FOR YOUR REFERENCE ONLY.

Figure 7: Excerpt from a Data Sheet of an HNBR 90 material

Härteprüfung IRHD Mikrohärte nach DIN ISO 48 M (in [IRHD])				
Einzelwerte: 85,3; 85,0; 86,5; 86,6; 86,0				
Mittelwert **85,9**	Median 86	Größtwert 86,6	Kleinstwert 85,0	Range 1,6
Dichtemessung nach ISO 2781 (in [g/cm³])				
Einzelwerte: 1,51; 1,52; 1,52				
Mittelwert **1,516**	Median 1,52	Größtwert 1,52	Kleinstwert 1,51	Range 0,01
Druckverformungsrestprüfung nach DIN ISO 815-1 (in [%]) Parameter: 24 h / 150°C				
Einzelwerte: 98,9; 99,2; 98,2				
Mittelwert **98,77**	Median 98,90	Größtwert 99,20	Kleinstwert 98,20	Range 1,00
Infrarot-Spektroskopie Prüfeinrichtung: FT-IR Spektrometer AVATAR-330 (Thermo-Nicolet) Prüfverfahren: Abgeschwächte Totalreflexion (ATR) mittels eines Germanium Kristalls				
Ergebnis: Das gefundene Spektrum ist typisch für ein HNBR -Elastomer Transmissionsspektrum anbei.				

Figure 8: Results determined from HNBR 90 O-ring, made from the material shown in Figure 7 (Translation key for the text in the red frame:

- Druckverformungsrestprüfung nach DIN ISO 815-1 = Testing of compression set according to DIN ISO 815-1
- Einzelwerte = Individual values
- Mittelwert = Average value
- Median = Median
- Größtwert = Largest value
- Kleinstwert = Smallest value)

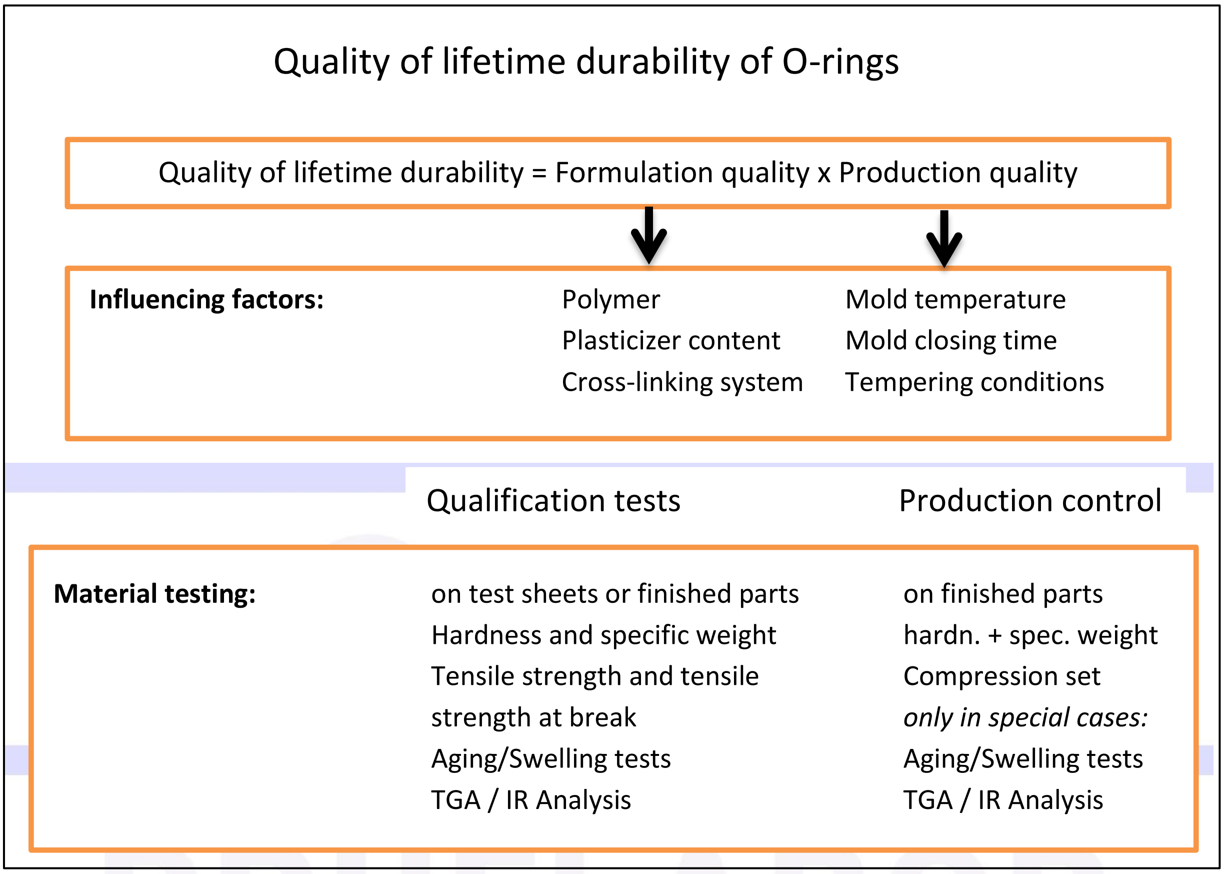

Figure 9: Factors influencing the durability of O-rings

This is exactly the approach in the Preliminary Standard ISO/OISI-5 (2013-7) [8]. The consistent implementation of this document presents to the end user a good industrial standard of the service life quality (durability). This also can define the long-term behavior. Of course, the manufacturers of premium O-rings can also go beyond that and by offering better properties score good marks from the end users.

4. Evaluation of the Long -Term Studies of Compression Set Using Arrhenius Method

When evaluating relaxation of O-rings after rather long-term testing, the loss of ability to retract can be explained by the influence of aging due to heat and oxygen. The “memory” of the O-ring regarding its original form, that is, the network of long molecular chains and wide-meshed cross-links is getting lost slowly and continuously due to secondary cross-linking and chain scission. Thus this damage is essentially a chemical reaction mechanism and it is possible, under certain conditions (see below), to apply Arrhenius Equation [9] in order to establish the relationship between the aging reaction and reaction rates (see also [10]). When presented in a certain form, the result is a straight line, called life line (or service life line). If the reaction rate cannot be established directly, a substitute method is used, namely plotting the time to attain a service life criterion on Y-axis, which of course has to depend directly on the reaction rate. In this case, as shown above, for O-rings, the compression set can be used as the criterion for the service life criterion. In order to prove the applicability of the Arrhenius Equation for the long-term compression set behavior, compression set measurement on NBR O-rings over a time span of 2 years were performed at the O-ring Test Laboratory. During this test program it was confirmed that this method is suitable for small cross sections (such as 1.78 mm). At the same time it was pointed out that long-term experiments with O-rings with larger cross section (such as 3.53 mm) cannot be evaluated at temperatures higher than 80°C using Arrhenius procedure since the reaction causing the changes is dependent on the geometry and cannot proceed due to deficiency of air or absence of partner for the reaction (see Figure 10). This also explains, for example, why results from long-term measurements of NBR materials on standard test buttons (dimensions 13x6.3 mm) [12] at temperatures higher than 80°C cannot be transferred to O-rings with a significantly higher ratio of free surface to volume. Figure 10 illustrates this way a secure

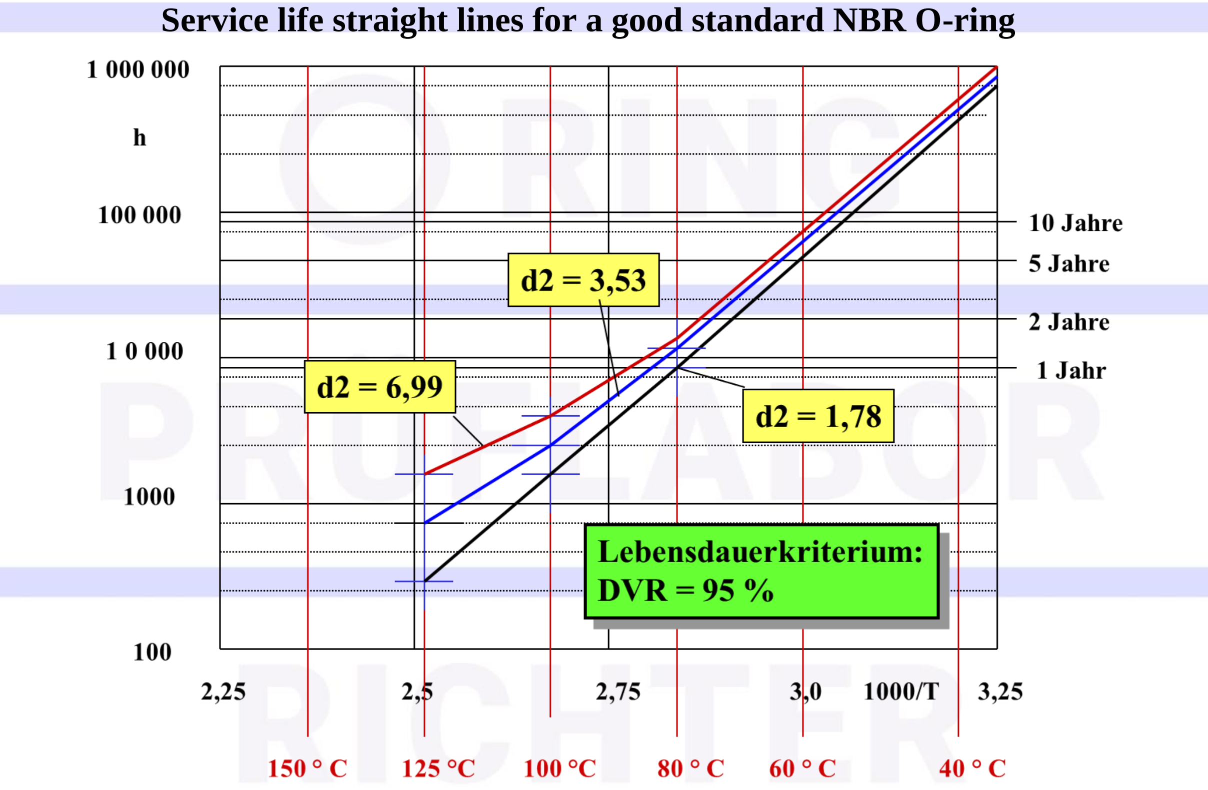

Figure 10: Service life straight line for the state of the art NBR O-ring
(**Translation key:**

- Lebensdauerkriterium: DVR = 95% = Service life criterion: Compression set = 95%
- 10, 5, 2 Jahre = 10, 5, 2 years
- 1 Jahr = 1 year)

thermal stress limit for the O-rings from the tested NBR formulation as long as the service life criterion of 95% compression set taken as basis represents the actual application. This will be met by typical O-ring installation spaces [13]. From the graphic evaluation it is possible to derive service life multiplicators within the experimental uncertainty (see Figure 11). Figures 12, 13 and 14 show such service life lines for HNBR, EPDM and FKM O-rings, which are clearly only from the tested formulations. In addition, in this case, it is necessary to mention (of course, with some qualifications) that these lines are based on measurements carried out over a period of 3000 hours (18 weeks). This in fact still appears long, but in comparison to the evaluations of NBR O-rings (2 years) mentioned earlier, the certainty of this statement is lower.

Temperature drop from/to [°C]	**Service life multiplicators** derived from a more *conservative assessment*	**Service life multiplicators** derived from a more *progressive assessment*
200 / 190	1,41	1,50
150 / 140	1,57	1,71
140 / 130	1,61	1,76
130 / 120	1,65	1,81
120 / 110	1,69	1,87
110 / 100	1,74	1,93
100 / 90	1,79	2,00
90 / 80	1,85	2,08
80 / 70	1,92	2,17
70 / 60	2,00	2,28
60 / 50	2,08	2,40
200 / 150	7,19	10,47
150 / 100	12,21	19,66
100 / 50	26,4	49,44

Figure 11: Service life multiplicators derived from the long-term experiments with NBR

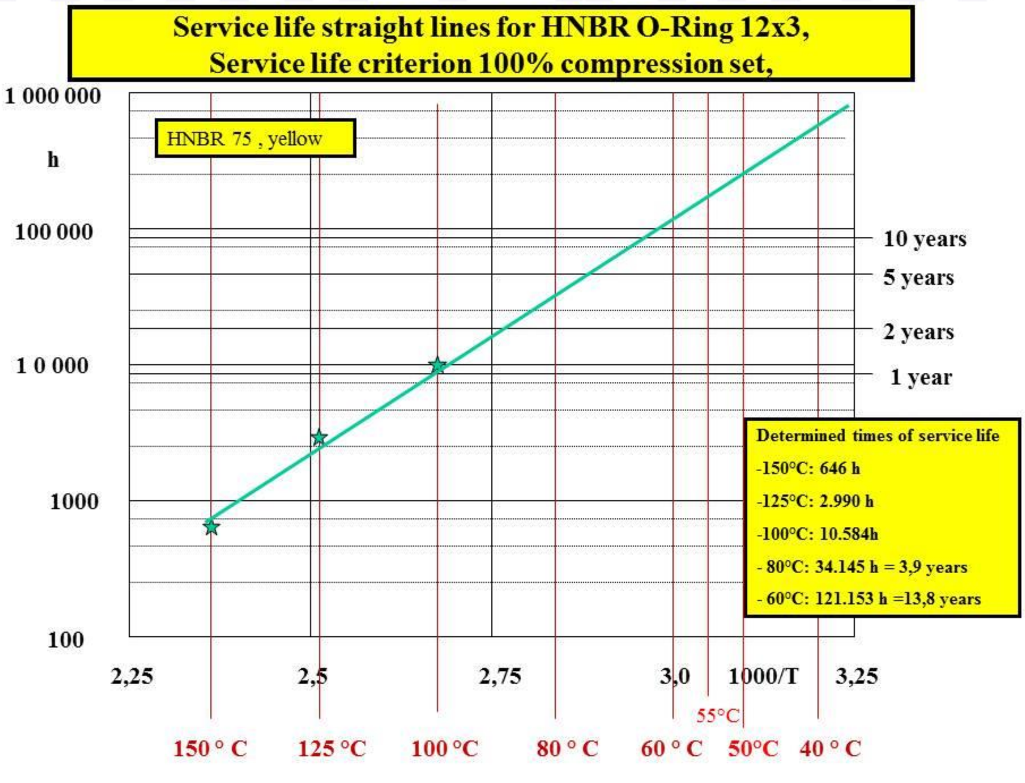

Figure 12: Service life straight line of an HNBR O-ring

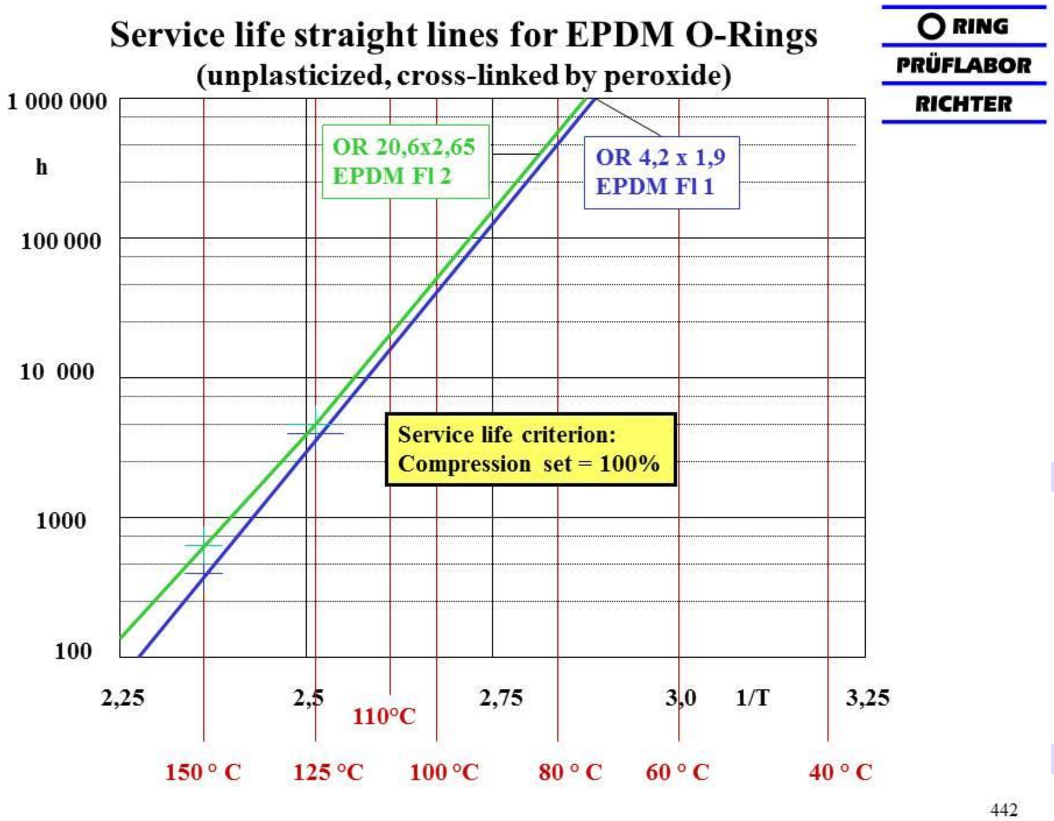

Figure 13: Service life straight line derived from the EPDM O-rings cross-linked with peroxide

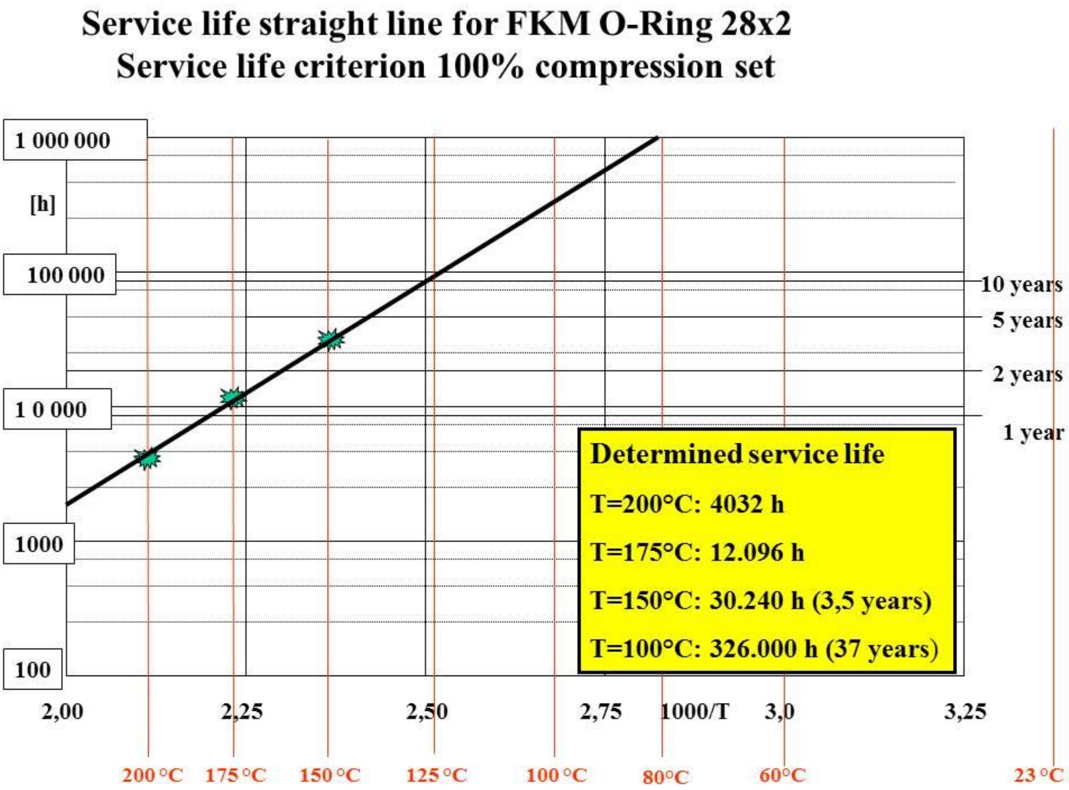

Figure 14: Service life straight lines from FKM O-rings

5. Effects of the Cross Section Size and Compression

The above observations show that the compression set can strongly depend on the geometry, that is, cross section size (see also Figure 15 [14]). The small cross section of 1.5 mm does so poorly, because its ratio of free surface to volume is so high, that the aging reaction on each particle of the material can only proceed hindered or restricted in spite of the progressively growing consumption of oxygen with the temperature even at 150°C. On the other hand, larger cross sections let less oxygen enter into the O-ring and the aging reaction is slowed down or even restricted with increasing temperature. The test temperature of 150°C is in the borderline region of the aging resistance of HNBR materials. At the test temperature of 120 °C the effect of the cross section size would be presumably negligible. Additionally, the effect of compression, that is, deformation of the cross section in the groove is shown in Figure 15.

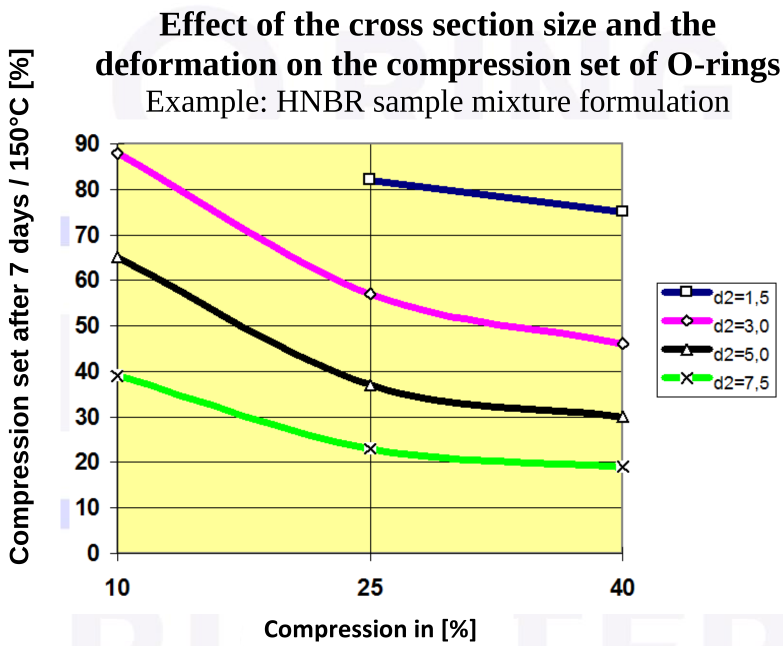

Figure 15: Effects of the cross section size and the deformation on the compression set

The elastic potential of an O-ring can be exhausted only by an adequate compression. Therefore, it is recommended for usual installation of O-rings [13] to set the average compression of about 25% for small cross-sections (such as 1.78 mm) and 15 to 20% compression for larger cross sections (such as 6.99 mm).

6. Effects of the Sealing Gap

In the O-ring design the compression of the O-rings by a plunger or rod mounting spaces besides centric as well as eccentric mounting position should be checked. Only this will aassure a reliable design. The larger is the play in diameter or the gap, the greater will be the demand on the bridging capability of the O-ring with the eccentrical force transmission to the components to be sealed as long as these components are not brought together. This is usually not the case. Therefore a large play in diameter means a sharper failure criterion with regard to compression set and this again leads to shorter service life (see Fig. 16 and 17).

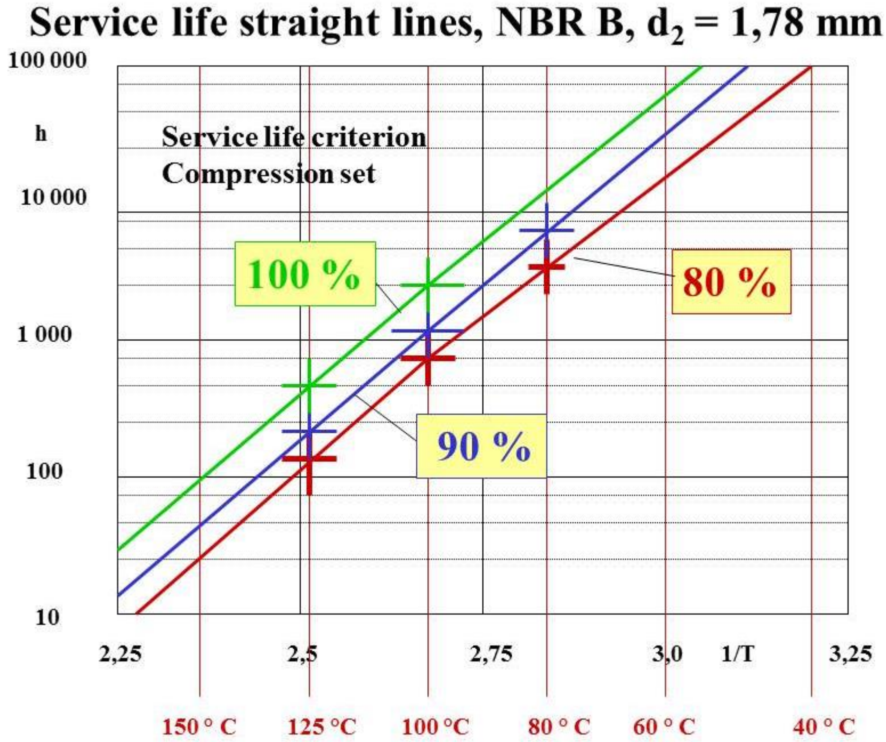

Figure 16: Service life as a function of the service life criterion (NBR O-ring)

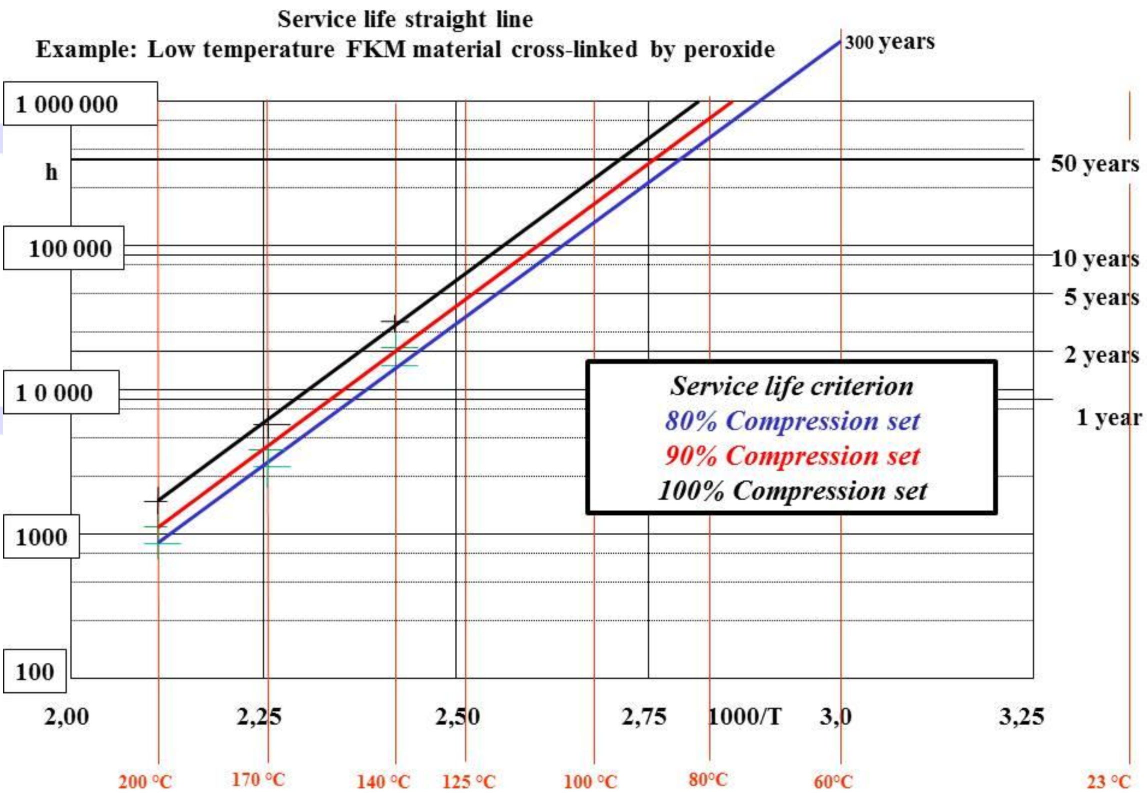

Figure 17: Service life as a function of the service life criterion (FKM O-ring)

7. Influence of a Medium

Oxygen in the air acts as a relatively aggressive medium for many elastomers. This means that when O-rings form a seal against a fluid to which they are resistant, the O-rings on the medium side are protected against aggressive oxygen and this can extend the service life of the O-rings considerably. This effect is particularly pronounced in the case of EPDM and aqueous media (See Figure 18). In the case of NBR O-rings, oils as a rule increase their service life. On the other hand, elastomers, which exhibit an outstanding aging resistance in air, such as FKM materials, can show an opposite effect when the surrounding media decrease the service life in comparison to that in air (see Figure 18). This significant effect has to be obviously considered in the evaluation of the durability of a material and it means that long-term experiments with EPDM and NBR O-rings in air more likely represent a rather conservative estimate of the service life.

OR 80x5 EPDM 70 Cross-linked by peroxide	**Air [%]**	**Water [%]**
24h / 125°C	4,6	--
1008h / 125°C	31,1	24,7
2016h / 125°C	47,5	26,2
3024h / 125°C	63,8	31,6
24h / 140°C	6,4	--
504h / 140°C	41,6	--
1008h / 140°C	70,3	23,7
2016h / 140°C	99,8	27,8
3024h / 140°C	102,9	32,3

Figure 18: Compression set values from an EPDM O-ring in air and water (acc. ISO 815-1, Method A)

Test pieces: O-rings with d_2 = 2,0mm Compression set 336h / 150°C	**EPDM 70 (cross-linked by peroxides)**	**FKM 70**
In air, DIN ISO 815-1, Method A [%]	62,8	14,7
In water, DIN ISO 815-1, Method A [%]	24,0	**94,4**

Figure 19: Compression set results in air and water (EPDM + FKM O-rings)

8. Summary

The above statements clearly indicate that the results from long-term investigations of O-rings under certain boundary conditions can be evaluated by the use of Arrhenius straight lines. The transferability of these experiments into practical situations is only possible when the formulation grade and the degree of cross-linking of the O-rings are sufficiently defined. At test temperatures up to 20K below the permissible continuous temperature (1000 hours criterion) for each material the cross section of the O-ring has only a slight effect; therefore these temperatures are preferred for long-term tests, or rather small cross sections (such as 1.78 mm) should be used as test pieces. Sealing gaps that are too large can have a considerable effect on shortening the service life. On the other hand, a good resistance of the O-ring material to the media that is being sealed off frequently brings about an increase of the service life.

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