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INVESTIGATION OF SEAL EFFECTS ACCORDING TO AXIAL COMPRESSION VARIATION OF METAL SEALS FOR TRANSPORT AND STORAGE CASKS

Ulrich Probst **Peter Hagenow** **Holger Völzke** **Dietmar Wolff**

Peter Wossidlo **Behboud Abbasi** **Andreas Achelpöhler-Schulte** **Sebastian Schulz**
Federal Institute for Materials Research and Testing (BAM)
D-12200 Berlin
Germany

ABSTRACT AND INTRODUCTION

Casks for the transport and storage of heat generating radioactive waste in Germany are normally provided with screwed lid systems, which are in most cases equipped with double jacket metal seals with an inner spring wire to provide long-term resistance to the seal compression force. Preservation of the high sealing quality of those seals under operational and accidental stress conditions is essentially important to the safety of those casks. Relative displacements of the lid system surfaces caused by specific impact scenarios cannot be excluded and have to be evaluated with respect to a possible increase in the leakage rate.

To get representative data for such metal sealed lid systems BAM has developed a special conceptualized flange system placed in an appropriate testing machine for relevant mechanical loading of the metal seals under static and dynamic conditions. Furthermore, the flange system enables continuous measurement of the standard helium leakage rate during each test.

The primary aim of the investigation is to identify the correlation between variation of installation conditions (axial displacements) caused by external loads and the standard helium leakage rate. An essential parameter in this case is the useable resilience r_u of a metal seal under relevant stress conditions. The useable resilience r_u is the vertical difference in the cross section between the seal's assembling status and the point where the leakage rate, by means of external load relieving, exceeds the specified value of 10^{-8} Pa·m^3/s. Load relieving can instantly occur due to modification of the seal groove dimension caused by accident impacts and deformation of the lid system. Furthermore, component specific basis data for the development of finite element calculation models should be collected. In the tests seals are subjected to static, cyclic and dynamic loads. All tests are performed at ambient temperature.
This paper presents the test configuration, different test series and results of the current experiments. Typical load – displacement – leakage rate correlations are presented and discussed. In the past, BAM had already done research and estimates regarding this type of seals, see e.g. [1,2]. Research of sealing behaviour due to vertical and side deviation has been done in Japan, see e.g. [3].

1. SEALS

In Germany so-called HELICOFLEX® double jacket seals with an internal helical spring [4] are very often used in the lid sealing system of transport and storage casks for radioactive materials. Silver and aluminium are used as materials for the outer seal jacket, and both types of seals were used for our test series.

Figure 1: Components of a double jacket metal seal

Seal dimensions and materials:

Inner diameter: 200 mm
Toroid diameter: 9.9 mm (Al) / 9.7 mm (Ag)
Spring material: Nimonic 90 (2.4969)
- Thickness: 1.1 mm (Al) / 1.2 mm (Ag)

Outer jacket: Al (3.0255) / Ag 99.99
- Thickness: 1.1 mm (Al) / 1.2 mm (Ag)

Inner jacket: Stainless steel (1.4307)
- Thickness: 0.3 mm (Al) / 0.5 (Ag)

2. FLANGE SYSTEM

A special flange system which enables leakage rate measurements during a running test allowing almost 100% helium concentration (standard conditions) was designed and manufactured by BAM.

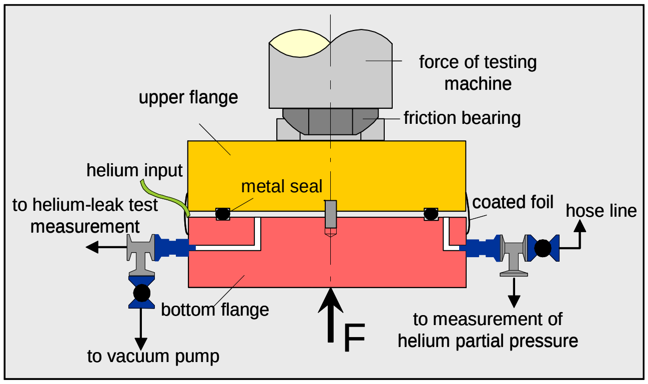


Figure 2: Flange system in principle

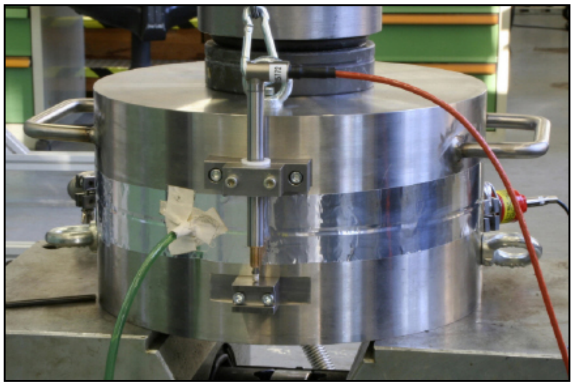
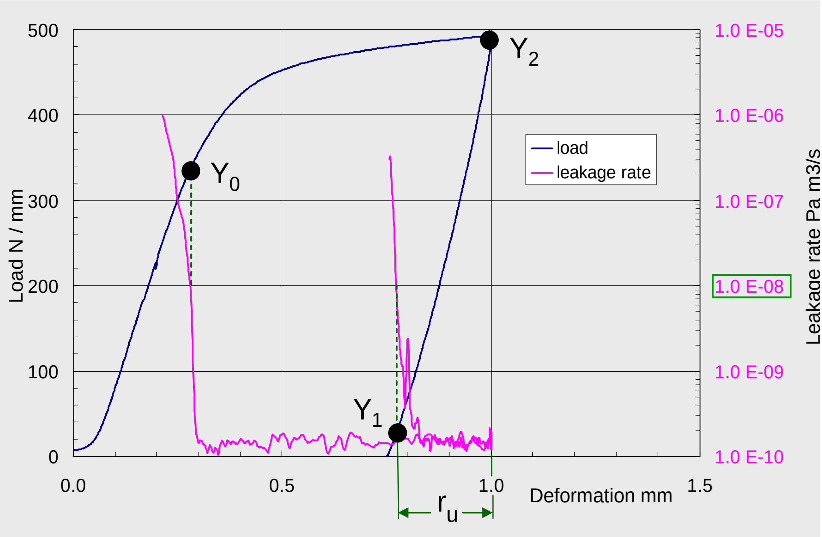


Figure 3: Flange system – installed in testing machine

3. STANDARD CHARACTERISTIC CURVE

As a verification of the test procedure on the one hand, and to get first seal data under standard conditions on the other hand, tests aimed at gaining characteristic curves were performed. Figure 4 shows a test result as an example for a seal with a silver outer jacket.



- As the quality criterion, a specified helium standard leakage rate for the use in casks for interim storage is $Q_{He/St} \leq 10^{-8}$ Pa m^3/s
- Y_0 = Achievement of $Q_{He/St}$ during pressing process
- Y_1 = Exceeding $Q_{He/St}$ during load relieving
- Y_2 = Optimal operation point according to manufacturers specification
- r_u = useable resilience

Figure 4: Standard characteristic curve as an example of a seal with a silver jacket

Three tests were performed of each outer jacket aluminium and silver. The following table shows the approached leakage rates and the measured values for r_u.

Table 1: Standard characteristic curve and test results for seals with Al-jacket

	r_u [mm]	Q_{Y2} [Pa m^3/s]		r_u [mm]	Q_{Y2} [Pa m^3/s]
Al 1 $_{SC}$	0.23	2 x 10^{-10}	**Ag 1** $_{SC}$	0.21	8 x 10^{-10}
Al 2 $_{SC}$	0.18	3 x 10^{-9}	**Ag 2** $_{SC}$	0.23	1 x 10^{-10}
Al 3 $_{SC}$	0.21	9 x 10^{-11}	**Ag 3** $_{SC}$	0.23	1 x 10^{-11}

Al 2_{SC} in Table 1 shows a noticeable effect, as was also determined by internal preliminary tests. It can be said that, if the leakage rate in Y_2 (optimal operating point) barely approaches $Q_{He/St}$ (in case of Al 2_{SC} 3 x 10^{-9} Pa m^3/s), the value for r_u after load relieving is comparatively low. In the case of Al 2_{SC} it means that there is only a useable resilience r_u of 0.18 mm in the vertical seal dimension between the seal's assembling status Y_2 and Y_1, where the leakage rate exceeds the specified value of 10^{-8} Pa·m^3/s.

4. PRESSING OPERATION BEYOND THE OPTIMAL OPERATING POINT Y_2

In cask lid systems, maximum (and optimal) load and deformation of seals are usually determined by the depth of the groove, wherein a seal is installed. After surface contact between lid and cask, further pressing is normally impossible. Additional mechanical stresses caused by accident scenarios could lead to elastic and plastic deformation of the groove geometry. In this case, reduced groove geometry would cause higher seal compression. Knowing this, seals were pressed beyond Y_2 to supply technical information of relevant seal behaviour in principle. Figure 5 shows the test results. The tested seals were pressed up to Y_2, $Y_{2+0.2mm}$ and $Y_{2+0.4mm}$ including load relieving and determination of Y_1 and resulting r_u at each step. In this test series three tests of each outer jacket material were done.

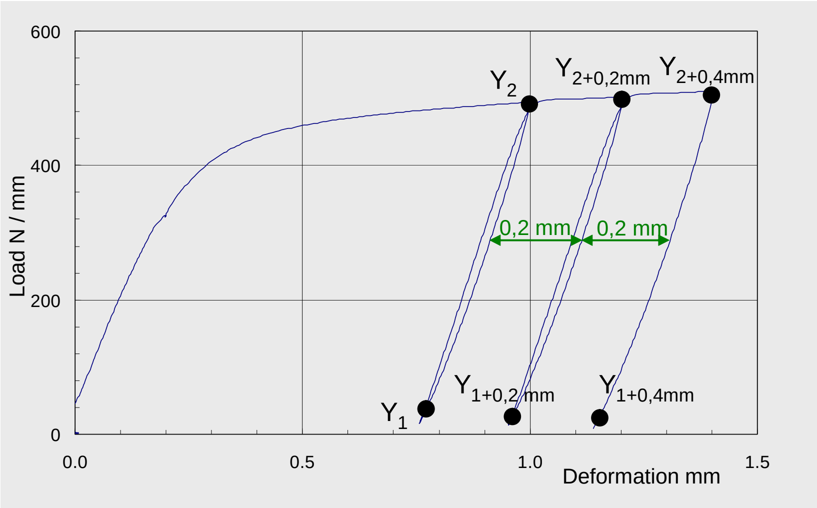


Figure 5: Compression beyond Y_2 as an example of a seal with an Ag-jacket

Besides other test results, in this diagram the distances of the relieving curves are marked. It can be noticed that the distance between the relieving curves from one compression step to the next corresponds exactly with the measure of each compression relating to the deformation beyond $Y_{2.}$

Table 2: Compression beyond Y_2 and test results

	Al 1 $_{OP}$	**Al 2 $_{OP}$**	**Al 3 $_{OP}$**		**Ag 1 $_{OP}$**	**Ag 2 $_{OP}$**	**Ag 3 $_{OP}$**
Q $_{(1.2)}$ [Pa m^3/s]	1 x 10^{-9}	2 x 10^{-11}	6 x 10^{-9}	**Q** $_{(1.0)}$ [Pa m^3/s]	6 x10^{-11}	9 x10^{-11}	2 x10^{-11}
Q $_{(1.4)}$ [Pa m^3/s]	1 x 10^{-9}	2 x 10^{-11}	2 x 10^{-8}	**Q** $_{(1.2)}$ [Pa m^3/s]	7 x10^{-11}	9 x10^{-11}	2 x10^{-11}
Q $_{(1.6)}$ [Pa m^3/s]	1 x 10^{-9}	3 x 10^{-11}	2 x 10^{-8}	**Q** $_{(1.4)}$ [Pa m^3/s]	7 x10^{-11}	9 x10^{-11}	2 x10^{-11}
$r_{u(1.2)}$ [mm]	0.27	0.24	0.16	$r_{u(1.0)}$ [mm]	0.23	0.23	0.20
$r_{u(1.4)}$ [mm]	0.29	0.28	-	$r_{u(1.2)}$ [mm]	0.24	0.25	0.22
$r_{u\ 1.6)}$ [mm]	0.30	0.29	-	$r_{u(1.4)}$ [mm]	0.25	0.25	0.23

The leakage rate of seal No. Al 3_{OP} at point Y_2 was 6 x 10^{-9} Pa m^3/s and hence close to $Q_{He/St} = 10^{-6}$ Pa m^3/s. The following associated value for r_u was 0.16 mm, which is quite low. The apparent relation between a relatively high leakage rate and low r_u is already mentioned above (see standard characteristic curve). For the following compression steps of seal Al 3, $Q_{He/St}$ could not be achieved. Therefore, associated values of r_u could not be evaluated.
Moreover, it was detected in every single test that r_u increased and hence improved with each step of higher compression due to higher plastic deformation and enhanced material contact.

5. CYCLIC TESTS

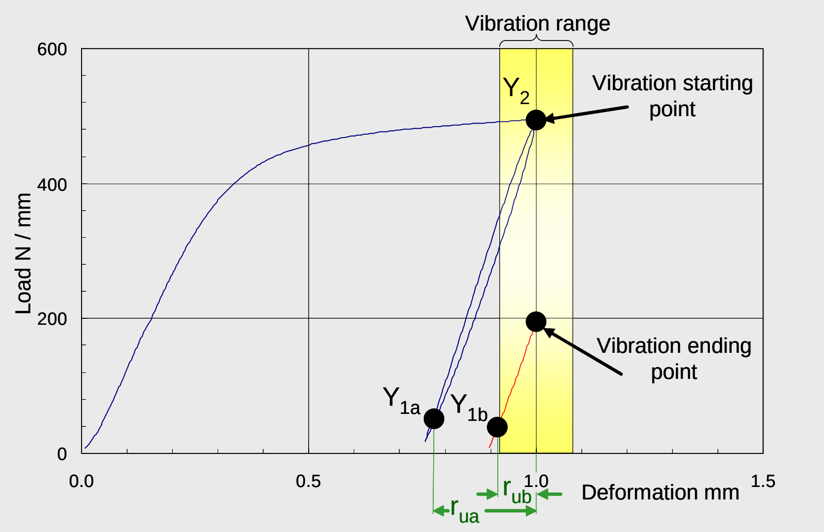
For an examination of accident effects on casks for the transport and storage of spent fuel, beside others stress conditions which put the lid system in vibration have to be discussed in view of leak tightness behaviour. Lid system vibration could be caused, for example by a cask-drop from a crane, or by an airplane crash onto a cask (a case which has to be considered in Germany as a so-called residual risk). The basic assumption is that the lid system vibrates with specific frequencies and amplitudes, which also causes vibration in the seal groove area. By using the finite element method, an internal estimation, assuming an impact of an aircraft engine arbor onto a cask lid system, has been carried out with a result of a dynamic load of about 150 Hz, an amplitude of several 1/10 mm, and about 100 load alternations before fading away. Elastic deformation of the lid in question and plastic deformation of the groove geometry have been assumed. As a result of this, the groove geometry is situated in its home position after vibration and the respective seal has received load amplitude both above and below its optimal operating point Y_2. It was investigated with appropriate test configuration, which basic effects on the sealing behaviour of concerning seals have to be expected. As the presented here test series was performed in the framework of a basic research project and the relevant impact effects could only be simulated in general, the test results can be understood as basic information on seal behaviour according to cyclic load.

For the time being the available machinery allows frequencies of 35 Hz. Internal preliminary tests showed that 0.08 mm is the suitable amplitude to gain basic information concerning seal behaviour under cyclic loads. Therefore, the following test conditions were chosen:

frequency = 35 Hz, amplitude = 0.08 mm, number of load alternations = 1000.

To obtain information of frequency influence and for comparison, test series with a frequency of 1.5 Hz were also carried out. Three tests with frequencies of 1.5 and 35 Hz were performed for each aluminium and silver outer jacket.

The following figure 6 gives information about the test principle:

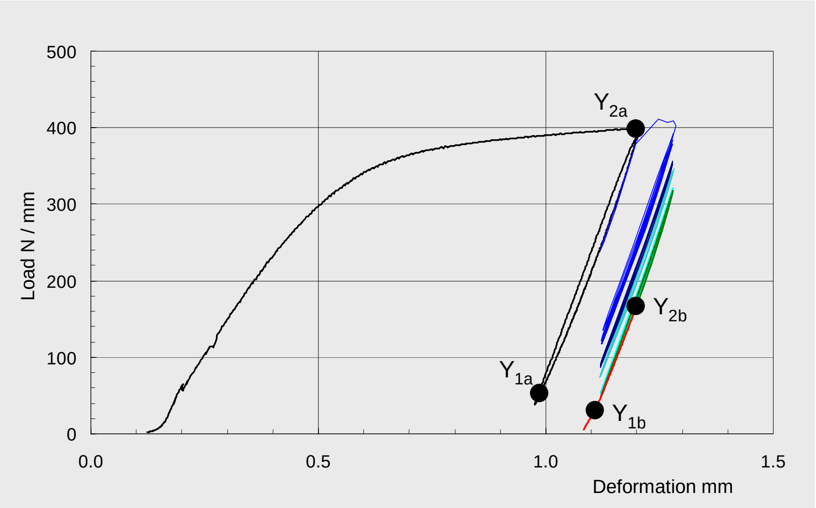


Test steps:

- Pressing to Y_2
- Load relieving to Y_{1a}, determination of r_{ua}
- Restart compression to Y_2, vibration starting point
- Vibration, incidental vibration ending point
- Load relieving to Y_{1b}, determination of r_{ub}
- Determination of distance of relieving curves

Figure 6: Tests with cyclic load in principle

Two diagrams as examples of different cyclic test series are Figure 7 and 8 below. For a comparison of the influence of different outer jacket materials, tests with a frequency parameter of 1.5 Hz are listed together with a result table (Table 3). There is also the result table for the test series with a frequency of 35 Hz (Table 4). The related diagrams are not presented in this paper.



The cycling curves are coloured and divided into five series of 10 each for a clearer depiction.

▬ Cycles 1 to 10

▬ Cycles 45 to 55

▬ Cycles 95 to 105

▬ Cycles 495 to 505

▬ Cycles 990 to 1000

▬ Load relieving after load

Figure 7: Cyclic test with outer aluminium jacket. Frequency of 1.5 Hz

In every case (with outer jacket materials aluminium and silver and with different frequencies of 1.5 and 35 Hz), the first load cycle generated plastic seal deformation in the rate of the applied amplitude of 0.08 mm. The following different cycling series in Figure 7 show, that the maximum load diminished depending on the number of cycles. This effect is typical for seals with aluminium outer jackets and is due to cumulative plastic deformation during the load alternations.

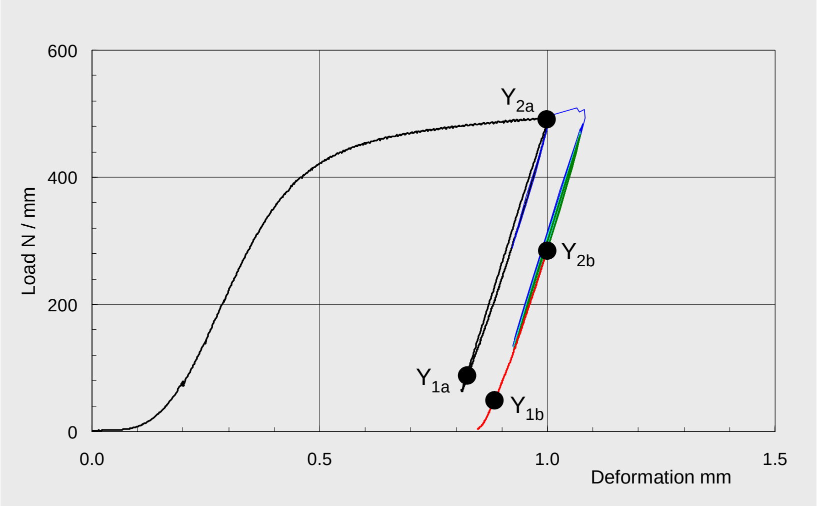


Figure 8: Cyclic test with outer silver jacket. Frequency of 1.5 Hz

Though the cycling curves in Figure 8 are in different colours as well as in Figure 7, the separate cycling series are not recognizable because they are located in a much closer range.
The red curve shows the relieving after load.

The narrow range of all load cycling alternations following the first one in Figure 8 shows that seals with a silver outer jacket behave differently to those with an aluminium one. This fact can be explained with the occurrence of very low or no plastic deformation of seals with a silver outer jacket.
In the following Tables 3 and 4 r_{ua} stands for before cyclic load, r_{ub} after cyclic load.

Table 3: Cyclic test results with aluminium and silver outer jackets. Frequency of 1.5 Hz

	Al 1 $_{CL1.5}$	**Al 2** $_{CL1.5}$	**Al 3** $_{CL1.5}$	**Ag 1** $_{CL1.5}$	**Ag 2** $_{CL1.5}$	**Ag 3** $_{CL1.5}$
Q_{Y2} [Pa m^3/s]	6×10^{-11}	9×10^{-10}	4×10^{-9}	6×10^{-10}	1×10^{-11}	2×10^{-10}
r_{ua} [mm]	0.21	0.21	0.18	0.17	0.18	0.19
r_{ub} [mm]	0.09	0.09	-	0.09	0.11	0.10

The leakage rate after cyclic load of seal Al 3 $_{CL1.5}$ in Table 3 could not be measured under the terms of $Q_{He/St} \leq 10^{-8}$ Pa m^3/s after cyclic load. Therefore, r_{ub} is not given.

Table 4: Cyclic test results with aluminium and silver outer jackets. Frequency of 35 Hz

	Al 1 $_{CL35}$	**Al 2** $_{CL35}$	**Al 3** $_{CL35}$	**Ag 1** $_{CL35}$	**Ag 2** $_{CL35}$	**Ag 3** $_{CL35}$
Q_{Y2} [Pa m^3/s]	4×10^{-11}	6×10^{-11}	4×10^{-8}	2×10^{-11}	1×10^{-11}	2×10^{-11}
r_{ua} [mm]	0.24	0.24	-	0.21	0.21	0.21
r_{ub} [mm]	0.14	0.11	-	0.13	0.12	0.12

In the case of Al 3_{CL35} in Table 4, $Q_{He/St} \leq 10^{-8}$ Pa m^3/s could not even be achieved in the initial stage (before cyclic load), which means neither r_{ua} nor r_{ub} are given. However, the test results of both seals (Al 3 $_{CL1.5}$ and Al 3 $_{CL35}$) are mentioned because of their interpretation for consideration of the distance “e” of the relieving curves, which is discussed below.

Distance of relieving curves **“e”**

Besides the results for r_{ua} and $r_{ub,}$ the plastic deformation is of interest. Usually a lower load is required for r_{ub} than for r_{ua}. Hence, the plastic deformation of the tested seals cannot be derived directly from the difference $\Delta r_u = r_{ua} - r_{ub}$. Therefore, the distance of the relieving curves “e” at an equal load level has to be considered. The schematic description in Figure 9 explains these facts.

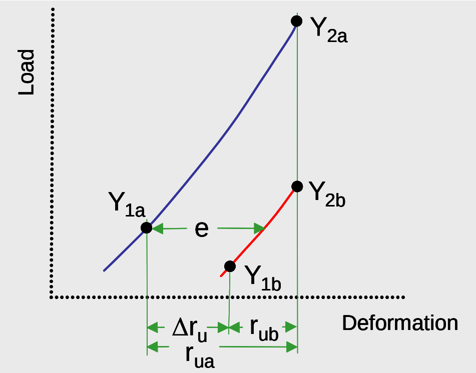


Figure 9: Distance of the relieving curves e; schematic description

The following Table 5 shows the average value of e in all cyclic tests. Each value $e_{\text{average value}}$ is calculated from three single pieces of data.

Table 5: Distance of the relieving curves

	Al 1.5 Hz	**Ag 1.5 Hz**	**Al 35 Hz**	**Ag 35 Hz**
e average value [mm]	0.13	0.08	0.11	0.08

The tests showed that one mere load cycle with a velocity correlating to 1.5 and 35 Hz caused plastic deformation of the same magnitude as the rate of the amplitude. This means that the resulting distance of the related relieving curve corresponds with the rate of the amplitude. Therefore, a higher value of e than the chosen amplitude of 0.08 mm has to be attributed to the influence of the following cyclic load alternations.
Table 5 shows, that in the case of seals with a **silver outer jacket** $e_{\text{average value}}$ is 0.08 mm. This means that there is no additional plastic deformation after the first cycle. There is no difference between the results in tests with both frequencies 1.5 and 35 Hz.
In the case of seals with an **aluminium outer jacket** and a frequency of 1.5 Hz, $e_{\text{average value}}$ = 0.13 mm; with a frequency of 35 Hz, $e_{\text{average value}}$ = 0.11 mm was determined. Hence, additional plastic deformation of:
63% for tests with 1.5 Hz and **38%** for tests with 35Hz were detected.
Since the number of the load alternations was equal in all cases, the difference in the plastic deformation rate has to be attributed to the different duration (667 sec in the case of 1.5 Hz; 29 sec in the case of 35 Hz) and, therefore, more time for yielding processes.

6. CONCLUSIONS

The **first tests** (characteristic curve and step-wise pressing operation) were done, on the one hand, as a trial of the flange system and the test procedure including the proper performance of the helium leakage rate measurement and, on the other hand, to get first basic data for a finite element calculation. The trial was successful and, hence, the equipment and the procedural method could be used for the following test series.
Pressing operation beyond the optimal operation point Y_2 led to the result that the distance between the relieving curves from one compression step to the next corresponds with the measure of each compression relating to the deformation beyond Y_2. Furthermore, it can be noticed that $r_{u,}$ due to the higher compression level and thus higher plastic deformation, increased

with each compression step. However, there was an exception with Al 3 $_{OP}$, whose leakage rate at the first compression step up to Y_2 relatively barely approached Q $_{He/St}$ in the range of 10^{-9} Pa m^3/s, and the related r_u was relatively low (0.16 mm). For the leakage rate during the following compression steps a value > Q $_{He/St}$ was measured; therefore no value for the related r_u is specified. According to test results from preliminary test series, the following statement can be made: if the achievable leakage rate of a seal at the optimal operating point Y_2 is relatively close to Q $_{He/St}$, a value of r_u lower than usual has to be expected.

Tests with a cyclic load were done to point out the principle behaviour of seals under cyclic load conditions. Preliminary test results showed that an amplitude of 0.08 mm and a number of load alternations of 1000 are reasonable test parameters. In order to find information about frequency influence, two different frequencies of 1.5 and 35 Hz were chosen for comparison.

After all the tests the value for r_u was reduced. In the case of silver jacket seals r_u was reduced at approximately the rate of the amplitude. In the case of seals with an aluminium outer jacket the reduction was some 1/10 mm higher. This fact can be attributed to the higher plastic deformation and, thus, greater distances between the relieving curves of aluminium jacket seals due to the cyclic load. As the point Y_1 must be located in the relieving curve, the related value for r_u depends on the distance between the curves respectively on the plastic deformation. The plastic deformation of only one cycle is equivalent to the magnitude of the amplitude. Higher or additional plastic deformation after the test is due to repetition of the load alternations. Consideration of the distance between the relieving curves "**e**" led to the following results:

Average additional plastic deformation in the case of silver outer jacket seals: **0%**

Average additional plastic deformation in the case of aluminium outer jacket seals:

63% for tests with 1.5 Hz, and **38%** for tests with 35 Hz.

Due to the longer time period during tests with 1.5 Hz (667 sec instead of 29 sec) and, therefore, more time for the yielding process, plastic deformation is higher. We can conclude from these facts that in regard to preservation of mechanical properties under accordant test conditions, the behaviour of seals with a silver outer jacket are advantageous compared to those with an aluminium outer jacket.

As mentioned above, cyclic loads with an amplitude beyond Y_2 reduce r_u in at least the amplitude magnitude (in the case of seals with an aluminium outer jacket even more). Therefore, it can be concluded that a cyclic load with an amplitude in the range of the expected value of r_u or even higher leads at least to loss of $Q_{He/St} \leq 10^{-8}$ Pa m^3/s.

For the future, tests with cyclic loads and frequencies of up to 150 Hz at temperatures up to 150°C and static temperature dependent tests over a time period of three month are planned to investigate yielding processes.

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