Performance Testing of Elastic Metal Seals Under Static and Dynamic Load

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INTRODUCTION

Due to several advantages such as insensitivity against ionizing radiation, elevated temperatures and a favourable ageing behaviour elastic metal seals are sometimes preferred to elastomeric seals especially for long term storage of radioactive materials. In normal transport or intermediate storage the sealing system is subjected only to pure or nearly pure static mechanical load. But under severe accident conditions the sealing system of a cask could be considerably deformed which results in large variations in stresses acting on the contact surfaces of the seal. In order to assess the suitability of elastic metal O-rings with a spring core the following data were evaluated experimentally:

- The static sealing characteristic, that is the compression of the seal as a function of the applied force.
- The values of the compression force necessary for achieving helium tightness and the minimum value to maintain tightness during decreasing force.
- The region of residual elasticity of the seal.
- The behaviour under rapid transient changes of the compressing force.
- The effect of long term periodic load alternations.

EXPERIMENTAL SETUP

The central part of the experimental setup is shown in Fig. 1. The seal under investigation is mounted between two flat stainless steel flanges with known surface roughness. The load on the contact surfaces of the seal is applied using a 100 ton servohydraulic press which in addition to static load, allows a rapid variation of the force. A ball - and - socket joint between the upper piston of the press and the upper flange ensures a uniform distribution of the compressing force along the circumference of the seal even if the faces of the two pis-

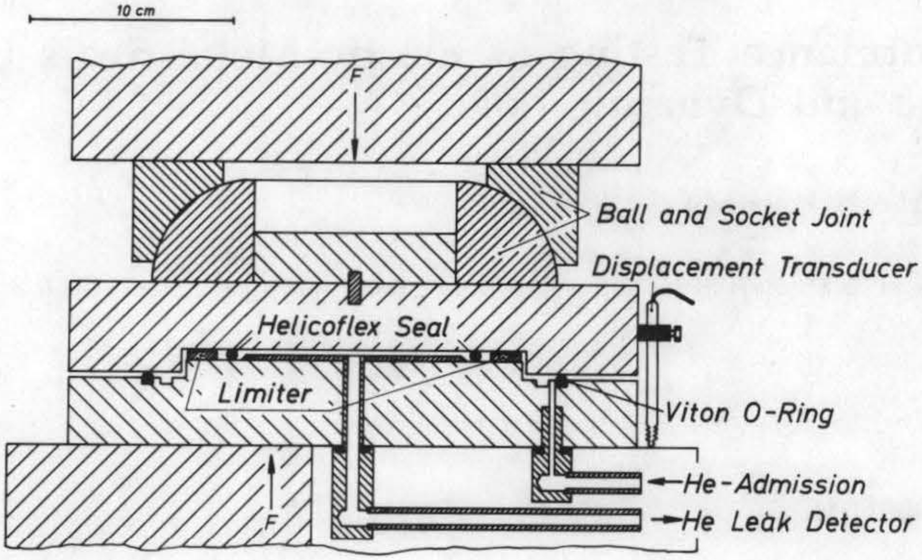

Fig. 1. Experimental setup for testing metal gaskets

tons are not exactly parallel. The deviation from parallelism of the two piston faces con amount up to a few tenth of a millimeter (piston diameter: ≃ 300 mm). The distance between the sealing surfaces or the deformation of the seal respectively are measured by means of electric displacement transducers and the force is controlled using an electric force transducer. The volume between the sealing surfaces inside the seal is connected to a helium leak detector or to a high vacuum pumping unit respectively. An annular volume adjacent to the outside of the seal can be filled with helium or air. The gas leakage rate of the seal is recorded as a function of the compression force by measuring the standard helium leakage rate with the leak detector or by determining the rate of pressure rise in the test volume while the high vacuum pump is closed. A third criterion for the leakage rate of the seal is the minimum pressure achievable while the high vacuum pump is connected to the test volume. The leakage measuring method is selected depending on the sensitivity and on the time constant required.

HELICOFLEX* SEAL

The elastic metal seals investigated are of type HELICOFLEX* which are made up of one or two metal linings around the toroid of a helically wound spring. The sealing principle is based on the plastic deformation of the lining of greater ductility than the material of the sealing faces of the flanges (CEFILAC, France). A permanent compressive force on the lining material is provided by the elasticity of the spring core (Fig. 2). Fig. 3 gives a schematic representation of the characteristic curves describing the relationship between the load force F and the deformation S. The curve starting from the origin characterizes the behaviour of a new gasket which is compressed for the first time (zero preload).

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*Trade mark CEFILAC, France

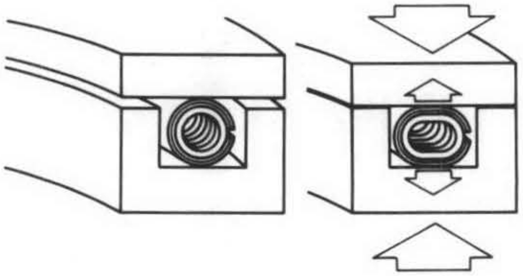

Fig. 2. Sealing principle of HELICOFLEX gaskets

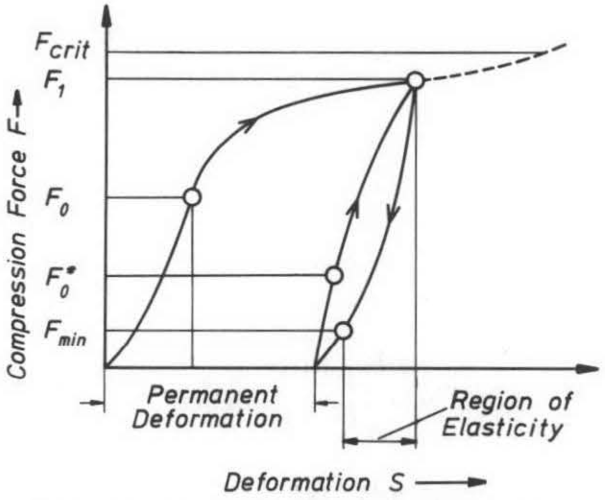

Fig. 3. Characteristic deformation curves of metal gaskets (schematic)

With increasing force the plastic deformation increases up to the point F_0 where the seal becomes helium tight. The normal operating point F_1 is chosen considerably above F_0 in order to ensure sufficient matching of the lining to the surface structure of the sealing faces. If the compressing force is reduced (starting from the operating point F_1) the mechanical contact between the sealing surfaces is maintained due to the residual elasticity of the gasket down to the point F_{min} where the gas leakage rate rapidly increases. If the gasket is compressed again after previous complete force release helium sealing is now achieved at F_0^*. This branch of the curve rising from zero force does not coincide with the falling branch starting at the operating point F_1. The difference between these branches is due to mechanical hysteresis. Fig. 4 shows a typical load cycle from which the characteristic forces F_{min} and F_0^* were determined using the system pressure as a criterion for the gas tightness of the sealing.

CHARACTERISTIC DATA OF HELICOFLEX SEALS FOR STATIC LOAD

As typical examples the characteristic data of HELICOFLEX seals with Al - or Cu - outside lining were measured. The mechanical dimensions are given in Tab. 1. The spring core was made of Nimonic 90 and the inside lining of stainless steel. In addition to the absolute values of the measured characteristic forces Tab. 1 contains these values normalized to the operating point F_1 recommended by the producer of the gaskets.

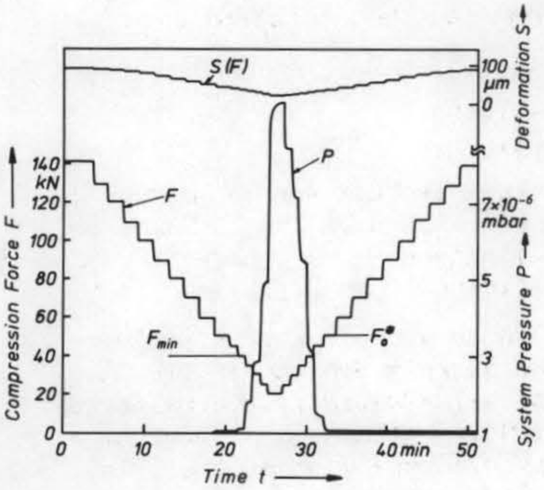

Fig. 4. Determination of characteristic forces for a HELICOFLEX gasket (lining: Cu; preload: 140 kN)

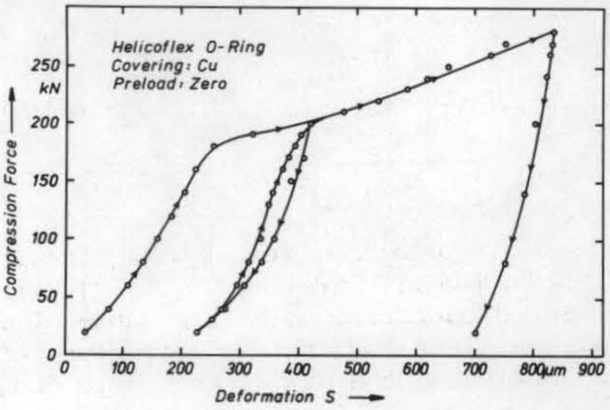

Fig. 5. Characteristic deformation curves for a HELICOFLEX gasket (lining: Cu; preload: zero)

Tab. 1. Characteristic data for HELICOFLEX gaskets (lining: Al and Cu)

			Al	Cu
Section diameter Outside diameter Mean sealing length	d D_a L	mm mm cm	4.8 120 36	4.8 120 36
Operating point	F_1/L	$kN \cdot cm^{-1}$	2.1	4.7
Deformation at operating point	S	μm	900	800
Helium sealing for zero preload	F_o/L F_o/F_1	$kN \cdot cm^{-1}$ -	0.83 0.40	1.4 0.30
Sealing failure at decreasing force	F_{min}/L F_{min}/F_1	$kN \cdot cm^{-1}$ -	$\leqslant 0.14$ $\leqslant 0.066$	$\leqslant 1.2$ $\leqslant 0.26$
Helium sealing at increasing force	F_o^*/L F_o^*/F_1	$kN \cdot cm^{-1}$ -	$\leqslant 0.28$ $\leqslant 0.13$	$\leqslant 1.4$ $\leqslant 0.30$
Helium sealing range depending on preload	ΔS	μm	50...170	50...140

- He-sealing for new gaskets (zero preload) is obtained for

$$F_o \simeq \begin{cases} 0{,}4 \cdot F_1 \text{ for Al-lining} \\ 0{,}3 \cdot F_1 \text{ for Cu-lining.} \end{cases}$$

- Releasing the compressing force starting from the operating point leads to failure of the seal at

$$F_{min} < \begin{cases} 0{,}1 \cdot F_1 \text{ for Al-lining} \\ 0{,}26 \cdot F_1 \text{ for Cu-lining} \end{cases}$$

- Reloading after complete force release restores the gas tightness at

$$F_o^* < \begin{cases} 0{,}13 \cdot F_1 \text{ for Al-lining} \\ 0{,}30 \cdot F_1 \text{ for Cu-lining} \end{cases}$$

All the data were measured using sealing faces with 3 µm to 6 µm surface roughness (Sakai et al. 1982). If the gaskets are run at the recommended operating point the range of residual elasticity during force release is of the order of magnitude of 100 µm. Within this range of decompression the gas tightness is conserved independent of the relative movement of the sealing faces. This is demonstrated in Fig. 6 showing measurements for slow sinusoidal variation of the compressing force. The peak value of the load roughly corresponds to the recommended operating point. In the left hand part the minima of the force slightly exceed the critical value F_{min}. Consequently the system pressure remains constant and the gas tightness in preserved irrespective of the movement of the flanges. In the right hand part of Fig. 6 however the minima of the compressing force fall below F_{min} resulting in short term losses of the sealing contact between the gasket and the flange faces. The short pulse shaped rises of the system pressure clearly indicate the periodic failure and recovery of the sealing function.

LONG TERM PERIODIC LOAD

During transport and handling of shipping casks the sealing system may be subjected to vibrational forces which act on the seal in addition to the static load at the operating point. Vibrational load was simulated with the servohydraulic facility of the press. The frequency could be varied between 0,1 Hz and 10 Hz. The compressing force sinusoidally oscillated between the operating point of the seal (F_1) and virtually zero. In comparison with realistic vibrational load during normal handling and transport this test is extremely hard with respect to the amplitude of the force variation. After $2 \cdot 10^4$ load cycles the seals did not show any severe deterioration with respect to their sealing properties. However the deformation curves exhibit a reduction of the residual elasticity (Fig. 7). After $4 \cdot 10^4$ load cycles the seal was still He-tight though the Al-lining showed significant deterioration. The X-ray radiograph of the O-Ring (Fig. 8) clearly indicates a flaw in the lining. With increasing number of load cycles the properties of the spring core are negatively affected. After $2{,}5 \cdot 10^5$ load cycles the spring core was completely destroyed (Fig. 8). When highly ductile lining materials are used the lining is more sensitive to long term alternating stress than the spring core on account of progressing plastic deformation. Slight deterioration of the lining does not necessarily result in a dramatic increase of the gas leakage rate. Therefore in general the gas leakage rate is not an unambiguous criterion for the perfect condition of the seal.

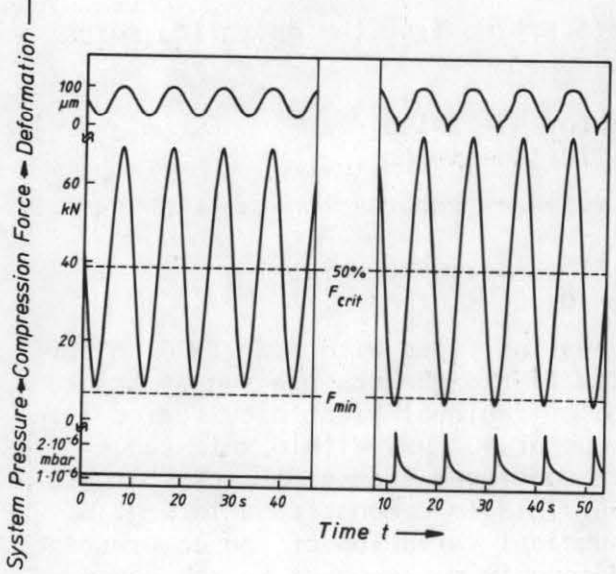

Fig. 6. Low frequency sinusoidal load of a HELICOFLEX gasket (lining: Al)

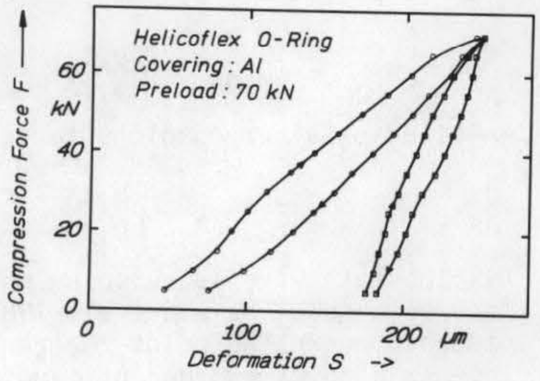

Fig. 7. Deformation curves after a few and after 20.000 load cycles (Al-lining; 5 kN F 70 kN)

SHOCK TEST

If a shipping cask or a storage container is involved in a severe accident a high transient mechanical load could result in a considerable deformation of the sealing systems. Due to acceleration forces for example the bolts supplying the compressing force of the seal will be stretched so that for a short time interval the normal load of the O-ring is greatly reduced. This situation was simulated with the servohydraulic press by rapidly releasing the compressing force starting from the operating point down to nearly zero load and by restoring the force instantaneously. The same behaviour as for sinusoidal load variation was observed. If the minimum of the sealing force remains above F_{min} the leakage rate is not affected but if the load falls below F_{min} a short term rise of the gas leakage rate results. Fig. 9 shows the pulse shaped rise of the leakage rate every time when F falls below F_{min}. Between the pulses however the seal is He tight again. Therefore we may conclude that even for the shortest transient times we were able to realize with the experimental setup, the HELICOFLEX seals could respond to the force variation elastically without detectable time delay. Even after more than 10^2 pulses no deterioration of the sealing properties was observed. These simulation measurements show that after a severe mechanical shock acting on the sealing system the sealing function of the HELICOFLEX O-ring is reestablished. A long term failure of the sealing system as a consequence of the shock can therefore be excluded. It very much depends on the construction of the whole container (especially the lid and the bolts) whether a short term transient failure of the sealing system during the impact will occur.

Fig. 8. Top: X-ray radiograph of a HELICOFLEX gasket with Al-lining after 40.000 load cycles (10 kN $\lesssim F \lesssim$ 75 kN) Bottom: Destruction of the spring core

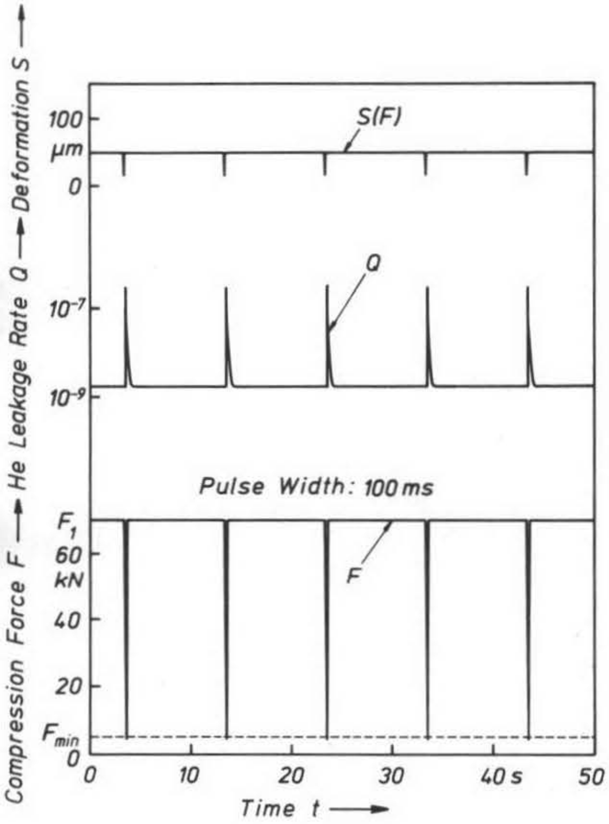

Fig. 9. Pulsed compression force release starting from the operating point of the HELICOFLEX gasket (Al-lining)

CONCLUSIONS

The investigation of the mechanical properties and of the sealing behaviour of HELICOFLEX-gaskets yielded the following results:

- Helium sealing is maintained at compressing forces well below the recommended operating point.
- In spite of the significant plastic deformation of the seal at the operating point the residual elasticity ensures leakage tightness during force release over a deformation range of at least 100 µm.
- The favourable sealing properties are not affected by periodic load alternations between the operating point and nearly complete force release up to about 10^4 load cycles. At several 10^4 load cycles an increasing deterioration of the lining and finally complete destruction of the spring core is observed.
- HELICOFLEX gaskets can follow a sudden decompression without significant delay. During rapid force release and subsequent compression the seal remains helium tight if the minimum force does not fall below F_{min}. Therefore if the container is subjected to a severe mechanical shock, the sealing system will remain intact unless the sealing faces are irreversibly deformed. Only during the accelera-

tion pulse the sealing could fail for a very short time interval if the load becomes less than F_{min} on account of elastic elongation of the bolts which supply the compressing force of the seal under static conditions.

- Reusability is however limited because each dismounting and reassembling of the seal results in a new matching of the lining to the surface structure of the sealing faces of the flanges by plastic deformation. If the ductility of the lining materials is significantly higher than that of the flange material the seal may be reused a few times. If the ductilities of the two materials are comparable, helium tightness of a reused HELICOFLEX gasket can not be guaranteed. If the deformation is not limited - for example by the depth of a groove or by spacers - helium sealing may be reachieved by increasing the operating force. This method however is limited because exceeding a certain value of the compressing force will definitely destroy the seal.

Compared to elastomeric seals HELICOFLEX seals have several important advantages (Ishimaru 1978, Kohlhaas et al. 1984, Miyahara et al. 1979):

- Long term stability of the mechanical properties.
- Higher resistance to elevated temperature.
- Virtually no sensitivity to ionizing radiation.
- Virtually no gas permeation.

In contrast to elastomeric O-Rings the use of HELICOFLEX seals requires very careful machining and maintenance of the sealing surfaces. Only a limited range of the surface roughness guarantees helium tightness. Handling of the gaskets and assembling of the sealing system of the cask is more sophisticated. Scratching of sealing surfaces must be carefully avoided.

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