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APPLICATION OF LEAKAGE RATES MEASURED ON SCALED CASK OR COMPONENT MODELS TO THE PACKAGE CONTAINMENT SAFETY ASSESSMENT

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ABSTRACT

The containment systems of transport and storage casks for spent fuel and high level radioactive waste usually include bolted lids with metallic or elastomeric seals. The mechanical and thermal loadings associated with the routine, normal and accident conditions of transport can have a significant effect on the leak tightness of such containment system.

Scaled cask models are often used for providing the required mechanical and thermal tests series. Leak tests have been conducted on those models.

It is also common practice to use scaled component tests to investigate the influence of deformations or displacements of the lids and the seals on the standard leakage rate as well as to study the temperature and time depending alteration of the seals.

In this paper questions of the transferability of scaled test results to the full size design of the containment system will be discussed.

INTRODUCTION

Type B(U) casks for transport of radioactive materials have to meet the International Atomic Energy Agency requirements for routine, normal and accident conditions of transport (RCT, NCT and ACT). In regard to containment capability a transport cask has to be designed to restrict the release of radioactive content to the required limits of 10^{-6} A_2 per hour under NCT and A_2 per week under ACT ([1] and [2]).

The mechanical and thermal loadings under corresponding conditions of transport could lead to deformations or displacements of cask components involving an unloading or a lateral or axial movement of the lids or the seals, which could have a significant effect on the leak tightness of the cask containment. These effects have to be properly considered in the safety analysis.

Drop and thermal tests required by the regulations to assess the deformation behavior of the components of cask containment can be performed with full size or reduced scale cask models. Leakage rates measured in such test campaigns are used for the containment evaluation as well. However, for statistical justification of covering design leakage rates as the basis for activity release calculation, multiple test series are preferable. Scaled cask components are mostly used for these experiments.

Based on the experience of Bundesanstalt für Materialforschung und –prüfung (BAM), this paper presents approaches for configuration of reduced scale cask tsts and component tests. Questions of transferability of leakage rates measured on scaled lid flange systems to full size cask are discussed as well.

NOMENCLATURE

A_2 – activity value of radioactive material
D – capillary diameter [m]
M – relative molecular mass [kg mol^{-1}]
Q – leakage rate [Pa m³ s^{-1}]
Q_{SHeLR} – standard helium leakage rate [Pa m³ s^{-1}]
R – universal gas constant [R = 8,31 J mol^{-1} K^{-1}]
T – temperature (fluid) [K]
a – capillary length [m]
p_d – downstream pressure [Pa]
p_u – upstream pressure [Pa]
r_u – useful elastic recovery of a metallic seal [mm]
μ – dynamic viscosity of the fluid [Pa s]

CASK CLOSURE SYSTEM AND SPECIFICATION OF DESIGN LEAKAGE RATES

Type B(U) casks for transport of spent nuclear fuel (SNF) and high level waste (HLW) mostly consist of thick-walled cylindrical shells with plane bottoms. The containment of Type B(U) casks used in Germany for transport and interim storage is closed by two bolted lid systems (primary and secondary lid). A lid system includes the lid, covers for openings in the lid, bolts, the corresponding cask area (flange) and metallic or elastomeric seals put in special grooves on any lid and cover.

The double jacket metallic seals of the HELICOFLEX type used for the German dual purpose cask designs consist of a circular spiral spring encased in two jackets; the inner layer is made of stainless steel, the outer layer is made of aluminium or silver. Fig. 1 shows an example of this seal type and Fig. 2 illustrates the closure system and the assembly situation. A standard helium leakage rate $Q_{SHeLR} \leq 10^{-8}$ Pa m^3 s^{-1} is specified for an optimal tightening function of such type of seal (manufacturer information, www.techneticsgroup.com, the typical characteristic of metallic seal is showed in Fig. 3). An additional elastomeric seal is required to create the necessary volume for leak tests via test ports.

Radioactive material in form of gas, liquid, solid or combinations of these can be released through leaks or in case of elastomeric seals additionally by permeation. The common method for the specification of leak-tightness is to relate the permissible limits of activity release to equivalent standardized leakage rates. Various physical-mathematical models are available for different leak designs and types of fluid. For Type B (U) cask design testing the "one capillary leak model" has become accepted [3], which means, that the maximum permissible activity release rate can be expressed in terms of a maximum permissible capillary leak diameter.

The modified Knudsen equation gives the correlation between the equivalent capillary diameter and flow rate. This equation is valid for the whole range of molecular, transitional and viscous laminar gas flow through a capillary.

$$Q = \frac{\pi}{128} \cdot \frac{D^4}{\mu \cdot a} \cdot \frac{(p_u^2 - p_d^2)}{2} + \frac{\sqrt{2\pi}}{6} \cdot \sqrt{\frac{R \cdot T}{M}} \cdot \frac{D^3}{a}(p_u - p_d)$$

The efficiency of the cask containment under transport loading is generally characterized by design leakage rates. For the activity release assessment shall demonstrate, that the design leakage rates specified for the regulatory conditions of transport (RCT, NCT, ACT) do not exceed the maximum permissible standardized leakage rates calculated for the radioactive content to be transported in the package. The International Standard ISO 12807 [4] gives the basis for the mode of calculation.

During the lid assembly, the seal is compressed until contact of the flange surfaces is achieved. The groove geometry ensures that the optimal compression of the metallic seal (necessary for $Q_{SHeLR} \leq 10^{-8}$ Pa m^3 s^{-1}) is achieved in this state. Further tightening leads to additional preload (pretension) in the bolts, which is balanced by the clamp load on the lid flange. Increasing the preload after the contact in the flange is achieved does not change the seal compression practically.

Depending on the load situation under regulatory conditions of transport (RCT, NCT, and ACT), the forces acting on the lid are balanced by additional bolt loads in combination with a change of the clamp load or friction force on the lid flange. The seal can be impaired if either contact on the flange is reduced significantly by the axial outside force and/or if the friction grip is overcome by the transverse one. An impairment of containment due to outside forces can be caused by the following effects:

- Significant change of the seal position in the flange (sliding displacements of the seal) due to transverse (lateral) outside forces on the lid or transformation of the cask cross section near the lid flange into an elliptical shape.
- Seal decompression (lid lifting) beyond its useful elastic recovery $r_u=e_2-e_1$ (Fig. 3) due to axial outside forces on the lid.
- Significant change of the seal position due to its axial rotation during short term decompression
- Loss of pretension in the lid bolts as a result of their plastic deformation or complete failure due to outside forces.

These effects or their combinations can lead to an increasing of the leakage rate of the closure system compared to the assembly state. Therefore, justified or reasonably conservative design leakage rates shall be defined for every transport condition as basis for the evaluation of the containment capability of the package. In the following, different issues concerning the derivation of the design leakage rates from results of reduced scale cask drop testing or scaled component tests are discussed.

REGULATORY ADVICES AND EXAMPLES FOR APPROACHES IN REGARDS TO SCALING OF LEAKAGE RATES

A summarizing key message in a paper by T. C. Chivers and R. P. Hunt [5] states: *"In most cases it is not possible to formulate accurate rules for scaling [of leakage] and hence the objective has been to develop reasonably pessimistic assessments."*

There seems to be still a common understanding about the difficulties in scaling a sealing system which is reflected in the IAEA Advisory Material SSG–26 [2]:

§ 701.25 *It might be difficult to extrapolate the results of scale model testing involving seals and sealing surfaces to the responses expected in a full sized package. Although it is possible to acquire valuable information on the deformation and displacement of sealing surfaces with scale models, extrapolation of seal performance and leakage should be approached with caution (see para. 716.7). When scale models are used to test seals, the possible effect of such factors as surface roughness, seal behaviour as a function of material* *thickness and type, and the problems associated with predicting leakage rates on the basis of scale model results should be considered.*

§716.11 *If specimens less than full size have been used for test purposes, direct measurement of leakage past seals may not be advisable as not all parameters associated with leakage past seals are readily scaled. In this instance, because loss of sealing is often associated with loss of seal compression resulting from, for example, permanent extension of the closure cover bolts, it is recommended that a detailed metrology survey be made to establish the extent to which bolt extension and distortion of the sealing faces has occurred on the test specimen following the mechanical test. The data based on detailed metrology survey may be scaled and the equivalent distortion and bolt extension at full size determined. From tests with full sized seals using the scaled metrology data the performance of the full size package may be determined.*

The Oak Ridge National Laboratory gives in ”The Radioactive Packaging Handbook” [6] the statement (sec. 4.10): *“…Tests must perform with full size seals, preferably with the model which is expected to be used in the package.”*

The Lawrence Livermore National Laboratory published in 1995 “Guidelines for Conducting Impact tests on Shipping Packages for Radioactive material” [7] with a remark (sec. B.2): *“No attempt appears to have been made to use scale models to directly demonstrate the compliance of a package with the regulatory safety-performance requirements. Leak tests on scale models with bolted closures have been conducted following a drop test on those modes. However, there exists no indication that the results have been used and accepted as the complete evidence of the compliance of the packages with the regulatory requirement for containment.”*

An example of a quantitative approach is discussed in [8] and [9]. In [8] a series of leakage tests using 1:10 model of a cask lid structure was conducted to investigate the relationship between the amount of lateral sliding of the lid and the leakage rate. The obtained relationship was compared with the results of the impact test of a 1:2,5 reduced cask crashed by simulated aircraft engine. From this comparison the authors conclude the applicability of similarity law for leakage rate translation. That means that the leakage rate measured in the scale model could be transferred to the full size cask by multiplication with the square of the scale factor. The same transfer approach was used in [9] by comparison between the 1:11 model of cask lid structure and full size cask tests of a simulated drop accident during handling in a storage facility.

But is the compliance observed in these papers generally valid and the formal application of similarity law to the leakage rate measured by reduced scale models physically correct? The phenomenology of leak formation is not yet fully understood and the influence parameters are too manifold to answer affirmatively to these questions. Nevertheless, the scaled model tests have some advantages compared to the full size cask tests, especially in statistical terms. In this respect, it is important to discuss the methodological aspects and practical experiences in the interpretation and treatment of the leakage rates measured in reduced scale experiments.

CONDITIONS FOR REDUCED SCALE MODEL DROP TESTING

An exact scaling of all structural components of a cask and their mechanical characteristics is practically not possible in drop tests with reduced scale models. This has to be especially considered for bolted closure systems. On the one hand, the sizes of the bolts cannot be scaled with the same geometrical scale factor. On the other hand, the possibilities of an accurate scaling of seal characteristics are very limited. Due to nonlinearity of the force-compression relationship of a seal it is, for instance, impossible to simulate the maximum compression force and permissible elastic decompression of a metallic seal simultaneously on the same scale model. Additional problems can also result from a variability of friction conditions in the bolted joints (at threads and under bolt heads). This variability, as well as an imprecise bolt tightening technique, leads to more or less considerable scatter of the bolt pretension. The minimum pretension creates more severe conditions in a drop test with regard to the seal function (higher probability of the lid opening and sliding). The maximum pretension is usually conservative for the total bolt stress (the sum of the initial tension and additional load due to the drop test).

When using scale cask models, a “functional” similarity between the sealing functions of the test model and the full size cask shall be ensured [10]. Potential failure modes of the sealing function in the original closure system should be identified first to achieve this “functional” similarity. Calibration of the closure system of the scale model before the drop test shall exclude the model having higher resistance against these failure modes than the full size cask. Some aspects of modelling of closure systems in reduced scale cask drop testing are discussed in [10].

First of all due to unavoidable variability in the assembly state, the pretension of model lid bolts shall be adjusted to allow conservative loading the closure systems components in the tests. An impairment of the sealing function is always expected if decompression of the seal beyond its useful elastic recovery r_u takes place under axial loads acting on the lid. Therefore, it makes sense to choose a seal with approximately scaled useful elastic recovery and a corresponding torus diameter. The optimal compression load of the model seal is obviously not similar to the full size seal in this case. This deviation can be compensated by the correction of the bolt pretensions to provide the similarity of clamp load on the lid flange. The condition is that the complete opening of the lid flange, if possible, must occur in the model at least under the outside force which is in a similarity relation to the appropriate external force in the original cask. A conservative adaptation of radial gap sizes between lid and cask wall can be also important for the scale mode test, if lateral displacement in the lid systems cannot be excluded.

Such calibration measures are crucial to the proper interpretation of reduced scale test results regarding the sealing function of the cask. During the drop test strains in the lids and bolts shall be measured. Changes in the lid positions and model deformation in the lid region shall be registered after the test. This information combined with the closure system leakage rate before and after the drop test is the basis for estimating whether it is acceptable to transfer the test results for the sealing function to the full size design or not.

It shall be demonstrated by additional calculations that no other problems will also occur in the closure system (e.g. failure of the bolts under the maximum preload) under different assembly conditions from those as simulated in the test. In general, tests with scale models always shall be supported by additional calculations.

In any case adequate safety factors shall be included in transfer procedure for a design leakage rate of the full size cask. However such factors cannot be determined universally. It also depends on the global (displacements) and local (deformations, stresses) loading conditions of closure system components in drop tests.

CONDITIONS FOR COMPONENT TESTS

Regarding the reasons for an impairment of cask containment discussed above, there is a need for systematic analysis of behaviour of the seal due to lid/seal movements. Test series with test flanges prepared to simulate the corresponding loading conditions of the seal are often used for this purpose. Their results can be an appropriate basis for determination of conservative statistically safeguarded design leakage rates if certain conditions are fulfilled.

The primary objective of these component tests is examination of the seal behaviour. Therefore it is important to modify the seal design used as little as possible. In the tests discussed below (s. [11] and [12]) the HELICOFLEX type metal seals have the same torus diameter (9.9 mm for Al-seals, 9.7 mm for Ag-seals), wire dimension of the helical spring and thickness of inner and outer layer as the original seals used in the full size cask designs. The seal diameter is the only reduced seal dimension. The circumference chosen for test seals is 1 m. Full size seal circumference can vary depending on cask design between 4 m and 6 m. Also the surface finishing (roughness and tooling marks) of seal and flange surfaces is identical. The tolerance limits for waviness of the flanges is met.

An axial lid/seal movement induced by the vertical drop test (e.g. drop on the lid or bottom side of the cask) can cause short-term elastic deformations of the bolts involving a short time relaxation of the clamp force on the lid flange. The component tests simulated this process have shown that after five compression/decompression cycles, provided that no seal dislocation (rotation) occurs, a leakage rate of $Q_{SHeLR} \leq 10^{-8}$ Pa m^3 s^{-1} is achieved again. Leakage rates measured after a repeated compression including an intentional seal displacement (rotation) are considerably higher [11].

The lateral lid movement as a reason for a shifting of the seal is a typical effect associated with the horizontal cask orientation in a drop test. The maximum displacement of a lid is limited by cask design and can be calculated from geometrical configuration of cask components in the flange area considering permitted manufacturing tolerances.

Component tests at flange systems with metallic seals of the HELICOFLEX type simulating a quasi-static lateral seal displacement did not indicate a significant increase of standard leakage rates after lateral sliding [11]. For specification of conservative design leakage rates for NCT and ACT, BAM requires tests to investigate the sealing behavior after a dynamic lateral lid displacement in a range of maximum possible displacement distances [13].

A component test program with bolted flanges for investigation of the influence of dynamic loading on the closure lid system with metallic seals, planned and prepared by Gesellschaft für Nuklear-Service (GNS) and assessed by BAM, has been started in 2011. This program comprehends several test series for testing metallic seals of the HELICOFLEX type at ambient and lower temperature (-40°C) as well as with aged and non- aged seals. More details were presented in [12].

A significant influence of the dynamic lateral lid displacements on the standard helium leakage rate can be observed in the tests already done. The increase of leakage rate with realized sliding distances relevant for typical cask designs is significant. A clear dependency of the standard leakage rate on the sliding distance can be observed as well.

The aspects listed below should be considered by transferring of these component test results to cask designs with full size seals.

- According to the manufacturers specification the optimal tightness of the sealing system of $Q_{SHeLR} \leq 1x10^{-8}$ Pa m^3 s^{-1} is achievable with appropriate compression and flange surface characteristics practically independent of the seal diameter. The physical fluidic process resulting in the measured leakage rate is not well understood, especially for very low leakage rates in the range of transitional and molecular gas flow.
- A gas movement through unfilled surface roughness is assumed as main contributor for the leakage past this metallic seal. In case of repeated compression without seal displacement it is assumed that roughness interlinking remains unchanged in the whole contact area. So, it seems to be acceptable to postulate that the seal ability for regaining the optimal tightness after repeated compression, provided without seal rotation, is also independent from the seal circumference.
- In case of repeated compression including seal rotation it can be assumed that the optimal roughness interlinking is impaired in the whole contact area. Therefore, the increasing leakage rate is supposed to depend on the seal diameter respectively the circumference.
- To explain the consistently low leakage rate after the very slow quasi-static lateral seal sliding one could imagine that contact areas of the interlinked surface roughness do not rip down but rather smear up. However, this movement does not comply with realistic impact load conditions under NCT or ACT.
- In contrast to the slow lateral sliding, it could be assumed that a dynamic shifting results in a break-off of roughness peaks and contact areas. A characteristic deformation of the seal due to dynamic shifting shows an additional effect. In the 0° and 270° area the deformation is like a rolling, whereas in the 90° and 360° area a

strong axial compression and buckling can be observed (Fig. 4). Both effects could be a reason for the higher leakage rates measured in tests of this investigation program. For transferring such increased leakage rates to the full size cask design also a dependence of the seal diameter should be considered.

Component tests are also used to investigate the temperature and time depending behaviour of the useful elastic recovery of the metallic HELICOFLEX type seal.

When assessing containment safety, it is important to correlate widening between the lid and body flange surfaces in the seal area under mechanical and thermal loading to the useful elastic recovery of the seal (r_u, Fig. 3). Above this range the efficiency of the seal is exhausted and the standard helium leakage rate Q_{SHeLR} exceeds the optimal tightening value of 10^{-8} Pa m^3 s^{-1}. Maintaining the efficiency of the seal regarding the limiting value of r_u in principle is a precondition for the applicability of any specified design leakage rate.

Results of a test program with scaled down flange systems at the Technetics/CEA Test Laboratory for testing temperatures and time dependent behavior of the metallic HELICOFLEX type seals (reported in [12]) show a significant reduction of r_u with temperature and time.

There are no reservations about transferring these test results to full size casks. Seal design used for the tests corresponds to the original design except for the seal diameter. The possible modifications of the distances between each spring coil of the circular spiral spring depending of the seal diameter is marginal in the relevant range of 1 m to 5 m seal circumference. The influence in seal behaviour is expected to be negligible.

CURRENT BAM APPROACH IN ASSESSMENT OF CASK TIGHTNESS

Whenever deformations of the bolted lid connection induced under transport conditions cannot be compensated by the seal, the leak tightness of the cask containment is no longer guaranteed. The compliance of the maximum seal decompression (widening in seal area) with the allowable limit is a crucial condition for the specification of any tightness. The leakage rate of a cask with metallic seals can also increase after a rotation or a lateral sliding of the seal due to movements of the lid.

Therefore, the specification of a standard helium leakage rate of $Q_{SHeLR} \leq 1x10^{-8}$ Pa m^3 s^{-1} as the design leakage rate for release calculation is acceptable only under the following limiting conditions:

- only short term elastic deformation in bolted connection with a maximum widening of flange
- surfaces < r_u
- no lateral sliding of the lid.

The compliance with these requirements has to be verified by tests, calculations or by combinations of both proof approaches.

For RCT this compliance is binding. Transport and handling accelerations (e.g. 2 g vertical and horizontal) as well as operational temperature and pressure must not induce any reaction in the closure system resulting in a reduction of leak tightness.

If an axial seal rotation due to lid lifting or a seal sliding due to a lateral lid movement under NCT and ACT drop test loads (e.g. 0.3 m or 9 m horizontal drops) cannot be excluded, reasonable conservative values of design leakage rates have to be specified for release calculation.

In case of the test with reduced scale casks, it is important to ensure a ‘functional similarity’ between the sealing functions of the test model and the original cask. As discussed above, calibration of the closure system of the scale model before the drop test has to exclude the model having higher resistance against potential failure modes than the original cask. The safety factor for the transfer of the measured leakage rate to the full size cask should be defined considering the global (displacements) and local (deformations, stresses) loading conditions of closure system components.

If full size or reduced scale cask drop test results need a statistical validation concerning the possible seal movement, then component test series to investigate an intentional lateral or axial seal movement or a seal rotation in circumferential direction are needed. Leakage rates measured in component tests with test seals being identical in construction with those of original cask designs except for seal diameter can be applied in cask containment assessment without consideration of any scaling factor, if no seal movements occur. Whenever leakage rate measurement results from component tests simulating a seal decompression including seal rotation or a seal shifting should be transferred for specification of a design leakage rate of a full size cask designs, the influence of the higher seal diameter has to be considered.

CONCLUSIONS

In this paper the question of transferability of leakage rates measured on scaled lid flange systems to full size cask was discussed. Based on experience in the approval assessment of transport casks for radioactive materials, some recommendations for configuration of sealing system in such experiments were presented.

Obviously there is a need to inquire the conditions for transferability the measured leakage test results. Even if there is a common understanding about the difficulties to formulate accurate rules for scaling of leakage an effort should be made to develop reasonable conservative assessments.

In the drop tests with reduced scale casks the “functional similarity” of the closure system shall be ensured. Choosing test seals with almost the same seal design except of the scaled down seal diameter seems to be an appropriate solution for component tests. In any case adequate safety factors shall be included in transfer procedure for a design leakage rate of the full size cask.

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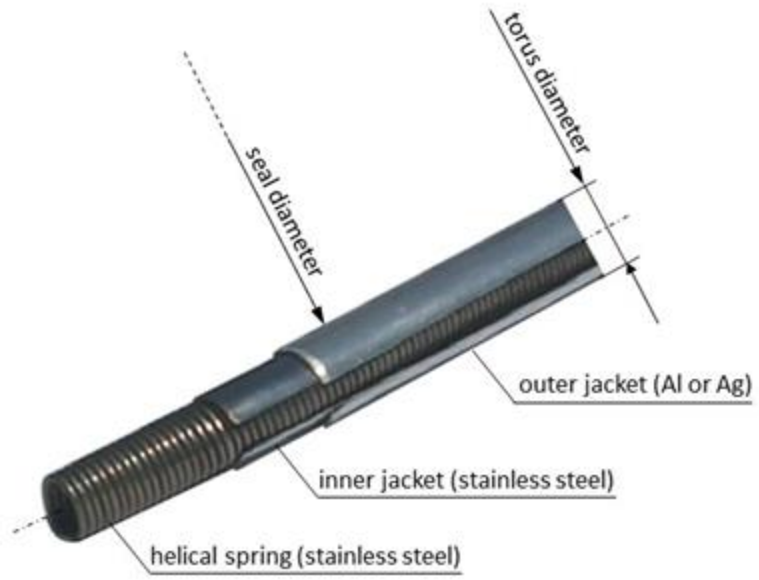

Fig. 1: Design of a HELICOFLEX type seal

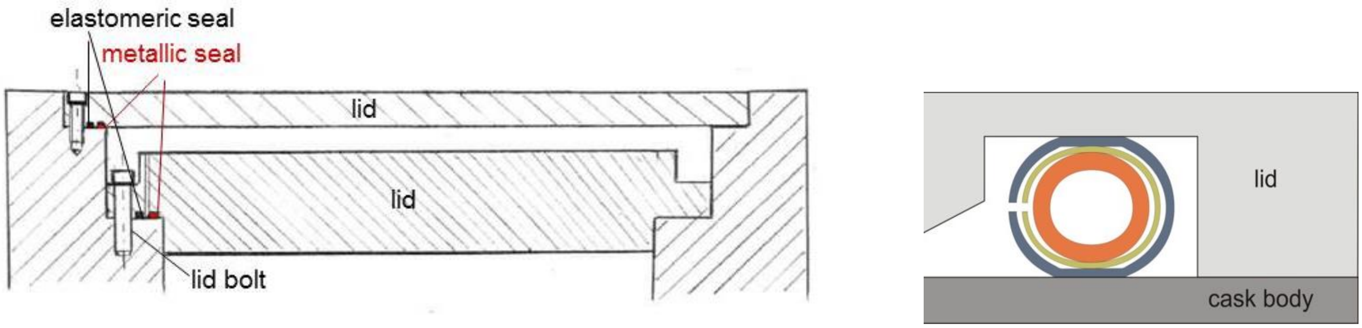

Fig. 2: Cask closure system and HELICOFLEX type seal assembly situation

Definition of Terms

Y_0 = load on the compression curve above which leak rate is at required level

Y_2 = load required to reach optimum compression e2

Y_1 = load on the decompression curve below which leak rate exceeds required level

e_2 = optimum compression

e_c = compression limit beyond which there is risk of damaging the spring

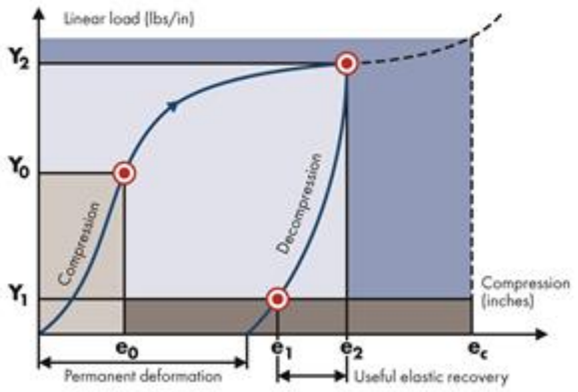

Fig. 3: Characteristic curve of a HELICOFLEX type seal for illustration of useful elastic recovery (according to www.techneticsgroup.com)

Fig. 4: HELICOFLEX type seal with typical deformation after an excessive dynamic lateral sliding