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Ageing of HELICOFLEX® metallic gasket for spent fuel cask: results of sealing performances of a 100,000h campaign

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Abstract

In the framework of CEA, the TECHNETICS GROUP France, GNS and CRIEPI are collaborating on an experimental program to assess the long-term use of HELICOFLEX® metallic seals in spent nuclear fuel storage casks. The harvested data on more than 60 mockups after 100,000h of ageing provide a consistent database to extrapolate the long-term sealing performances. After a description of the HELICOFLEX® gasket and of the test program, the results of the entire measurement campaign are discussed to interpret them from a statistical point of view. This paper then focuses on two methods based on a time-temperature equivalence Larson & Miller Parameter and a time extrapolation.

Introduction

The long-term dry storage of spent fuels in metal casks is a very commonly used solution. This technical choice requires the use of leak-tight casks and therefore seals to ensure a containment criterion [1]. Among a large panel of existing sealing systems, the expected lifetime of the casks, that can exceed a few hundred years, combined with thermal constraints favor the use of metallic-seal-based technologies [2]. The optimal seal arrangement to efficiently ensure the long-term tightness between the cask closure flanges relies on a Metal To Metal (MTM) contact between them [3][4], which is a mechanical junction where the gasket load relaxation is one of the key parameters regarding sealing performances over time [5].

To investigate the detrimental loss of tightness linked to the time-evolution of the seal materials, a long-term ageing experimental campaign is conducted on a large panel of mockups that consist of two symmetric flanges holding a tightened HELICOFLEX® gasket. This study aims to evaluate the minimum residual linear load that can be guaranteed for a seal after a given time of relaxation. Taking advantage of the influence of temperature on creep kinetics and thus on seal relaxation, the ageing of the mockups in a furnace is made at different constant temperatures: Room Temperature

(RT), 100 and 200°C. The residual load and 'useful' spring-back have been measured after the holds under an instrumented press. The measurements were made after 10,000, 25,000 [6], 50,000, 75,000 [7] and 100,000 hours. The harvested results provide a large database that can be interpreted according to two methods based on a time-temperature equivalence Larson & Miller Parameter (LMP) [8] and a time extrapolation. Both methods rely on assessed linear relationships through statistical analyses (calculation of scatter applied to the large database) and are also used to estimate the minimum guaranteed residual load for a given period of time.

The HELICOFLEX® Gasket

The HELICOFLEX® is a metallic seal (Fig. 1) patented and manufactured by the TECHNETICS Group and consists of a helicoidal spring covered by several linings. With a proper combination of materials for spring and linings, this mechanical structure can provide a very interesting sealing system tolerant to the flanges' surfaces imperfections (roughness, waviness), delivering a significant spring back able to withstand important deformations. The HELICOFLEX® is therefore well suited for long-term use in nuclear spent fuel casks.

The spring of the gaskets tested in this study are made of Nimonic 90, and the 0.3-mm-thick outer lining is pure silver. Two different cross-sectional diameters are studied: 6.2mm and 8.4 mm with 304L Stainless Steel (SS) inner lining respectively of 0.3 mm and 0.4 mm. The choices of suitable material for the outer lining is driven by considerations about hardness, creep resistance and corrosion properties. Thus, preliminary 10,000-hour ageing tests reveal that silver is suitable for long-term use. For the study, the seal mean-diameter is 250 mm, to be compared with the real application diameters ranging from 1 to 2 meters.

The gasket mechanical behavior can be described by the set of parameters summarized in Table 1 and Fig. 2. Among them, the most important is Y_2, which represents the recommended linear load in Newtons per millimeter required to tighten the seal, and e_2, the corresponding compression of the seal (height difference between an untightened and tightened seal).

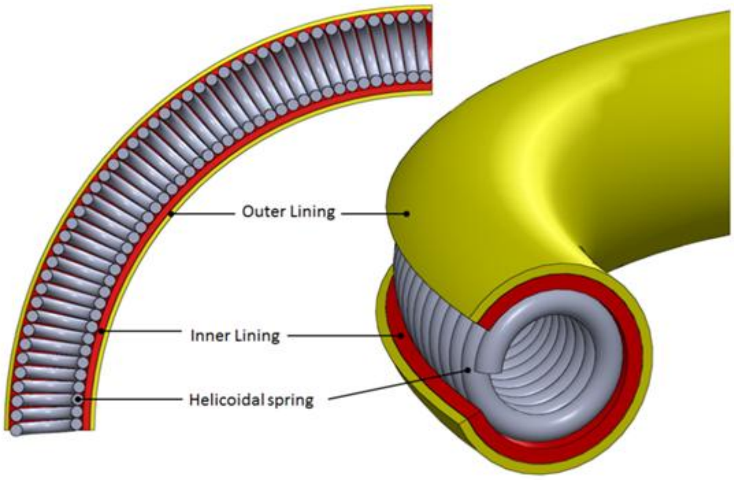


Figure 1 HELICOFLEX® metallic gasket

Table 1 Nomenclature

Y	Linear load of a seal (reaction of the seal on its flanges, divided by the seal perimeter).
Y_0	Linear load of seal required to obtain the seal during the first seal tightening.
Y_1	Linear load below which the leak rate exceeds a target value, upon untightening of a seal after relaxation.
Y_2	Linear load of a seal (just after tightening at room temperature) when the metal-to-metal contact is achieved. The compression of the seal is then the initial height of the seal minus the height of the groove. This compression is named e_2.
Y_{2R}	Residual linear load (after relaxation due to a temperature hold).
Y_{2Rlim}	Minimal residual linear load required to avoid leak during and after an incident.
r_t	Total recovery.

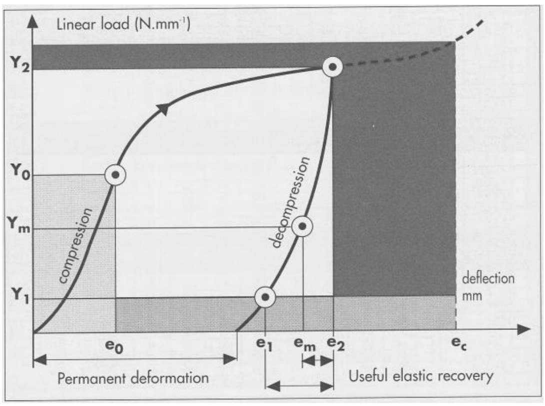
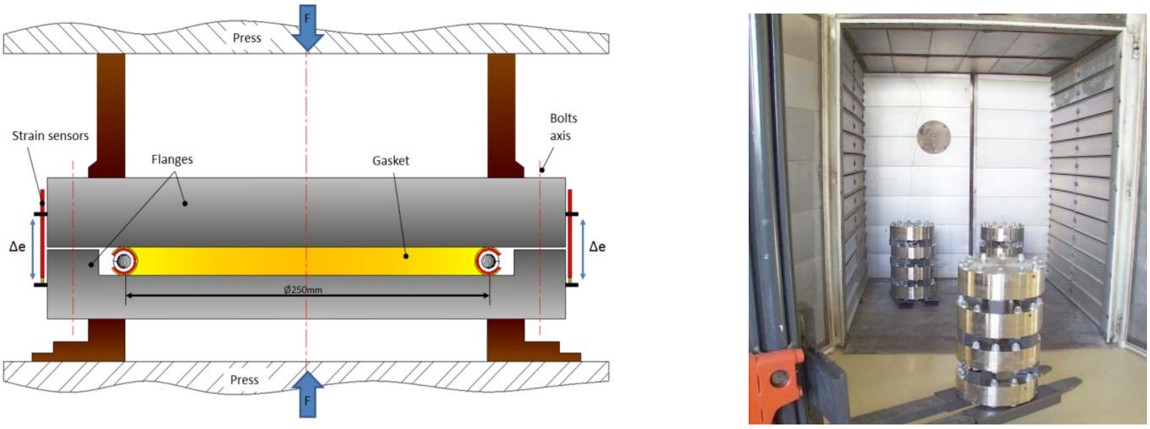


Figure 2 Loading-unloading curve of a seal

Experimental Procedure

The seal is mounted in a groove between two rigid blinded flanges. The experimental protocol begins with the first compression of the seal between the flanges with a hydraulic instrumented press to achieve the MTM contact. During the process, the load F and the seal compression Δe are measured (Fig. 3). The Y_2 and the corresponding seal compression e_2 are determined when the MTM is obtained. The bolts of the mockup, kept under the press, are then screwed up to a given torque. Once released from the press, mockups are piled up inside an oven maintained at a constant temperature. In this program, about 40 mockups are used for each of the three selected temperatures: RT, 100°C and 200°C. As a reminder, in a real-life cask the maximal expected temperature at the seal location will be in the range of 150°C and will decay with time down to 50°C.



(a) Mockup under the press **(b) Mockups piled up inside a furnace**

Figure 3 Test principle

After a given ageing period, the mockups are removed one by one from the oven and once at RT are placed back under the instrumented press. Then, they are loaded up to the Y_2 load before removing bolts. The load applied by the press is then decreased until the recovery reaches 50µm, while the load and the distance between the flanges are measured to obtain the unloading curve. From this data the seal recovery range can be derived, the flanges distance obtained when the applied load is equal to zero gives the parameter r_t (total spring back). It is estimated that when the recovery reaches 25 µm all the direct contact between flanges is lost, due to their bending. The measured data for recovery values ranging from 25 to 50 µm are used to evaluate a best fitting second order polynomial curve. This range is chosen because the first part of the decompression curve (from 0 to 10 µm) can be affected by the mockup stiffness and is not representative of the gasket properties. The upper limit of 50 µm is fixed by the experimental protocol, to avoid any influence of contact lost between seals and flanges on its sealing performances. The Y_{2R} is then derived by an extrapolation as shown on Fig.4. During the decompression, the leak rate is monitored with a helium spectrometer to evaluate the Y_{1R} corresponding to the linear load under which the leak rate exceeds an accepted limit (10^{-8} atm.cm^3.s^{-1}). For ageing time exceeding few thousands of hours even at RT, the Y_{1R} can be equal to zero, meaning that the mockups remain vacuum-tight with leak rate below the limit. That point is linked to a very close contact between seals and flanges roughness related to the outer lining creep.

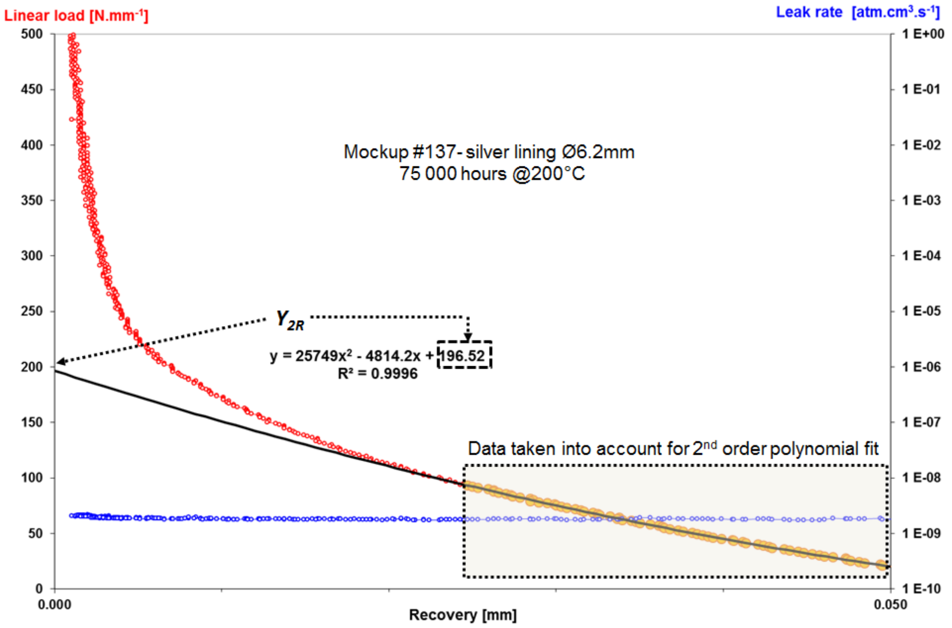


Figure 4 Example of Y_{2R} determination: mockup #137, Ø6.2 mm section silver lining seal held at 100°C for 75,000 h. Blue curve: leak rate measurement. Red curve: residual seal loading

Data Analysis

Fig. 5 and 6 plotting the Y_{2R} parameter as a function of the ageing time show a strong influence of the temperature that can only be explained by a creep regime of the seal material, assumed to be a dislocation climb of the silver outer lining. In these figures, two points connected by a dotted line correspond to values measured on the same seal. In case of 200°C condition, irregular data tendencies were observed between 50,000 and 75,000 hours. Up to 50,000 hours, Y_{2R} decreases with time. But, Y_{2R} of 75,000 hours increases. Metallurgy observations of aged seals show one reason. Fig.

8 shows the photos of the silver outer lining by microscope. Recrystallization occurred after 50,000 hours at 200°C, while nothing happens for the data at 20°C and 100°C. The silver recrystallization is usually associated with a hardness decrease and an increase of the grain size.

On the basis of this assumption, the data collected throughout this very long-term experimental program are analyzed using two different methods.

A time extrapolation method, based on the assumption that the mean value $y^*(T,t)$ of Y_{2R} at a given time and temperature behaves as:

$$y^*(T,t)=\mathrm{K}(T) - \mathrm{C}(T) \log_{10}(t) \quad \{\text{Eq.1}\}$$

K and C are two parameters interpolated using experimental data that depend on the ageing temperature. Thanks to the large database, statistical data processing can then be made to estimate long-term evolution of the Y_{2R} parameter. This analysis assumed that the scatter of Y_{2R} is a Gaussian normal stochastic variable with a variance independent of hold time. By mean of a probabilistic approach based on Student law, the probability of failure can then be estimated. It can be established that a seal can be safely used provided its Y_{2R} remain superior to a limit value Y_{2Rlim} that will depend on the most severe accidental cases the cask has to withstand, such as drops or shocks. Therefore, with proper definition of this limiting value, based on this study, the seal lifetime can be estimated associated with a failure probability. The same statistical analysis can be performed on the total spring-back parameter r_t to evaluate its long-term evolution.

The second method implemented considers a Larson Miller Parameter (LMP) as a time-temperature equivalence improving the statistical consistence for long-term extrapolation. Indeed, this method allows us to increase significantly the number of available results used to define the long-term seal reliability. In this method the LMP is given by:

$$\mathrm{LMP}(T,t)=\mathrm{T}(\mathrm{C}+\log_{10}(t)) \quad \{\text{Eq.2}\}$$

C independent of the temperature is characteristic of the metal and seals designs and is defined such as Eq.3 and Eq.4 match at best the experimental data:

$$Y_{2R}(T,t) = \mathrm{A}_1 - \mathrm{B}_1\, \mathrm{LMP}(T,t) \quad \{\text{Eq.3}\}$$

$$r_t(T,t) = \mathrm{A}_2 - \mathrm{B}_2\, \mathrm{LMP}(T,t) \quad \{\text{Eq.4}\}$$

Fig. 7 shows the results using this method. We suppose that C=11 for silver seal. In Fig. 7, several pieces of data at 130, 150 and 250 °C are included. In the beginning, experiments at these temperatures were performed but finished within about 1,500 hours.

The same kind of probabilistic prevision can be implemented with this method. This method also presents the great advantage of enabling the prediction for temperatures at which no relaxation data are available. By reversing the LMP expression formula, the maximum guaranteed temperature for a given time and limiting value of r_t can be derived.

The statistical analyses are described and discussed with much more detail in [6]. Using data in this paper, more predictive results based on the analyses made on 25,000-hour measurements are obtained, with such maximum seal temperature ensuring a given Y_{2Rlim} after hold time of 100 years with a probability greater than 0.99999.

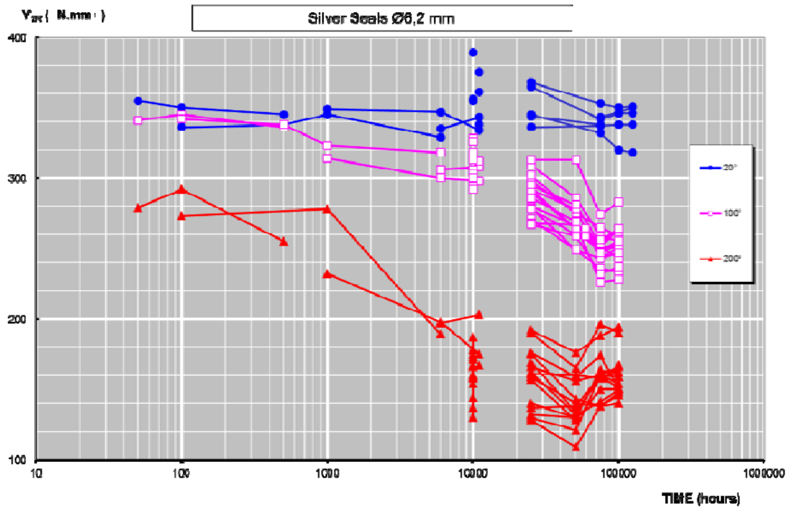


Figure 5 Relation between Time and Y_{2R} values (Seal with Ø6.2 mm)

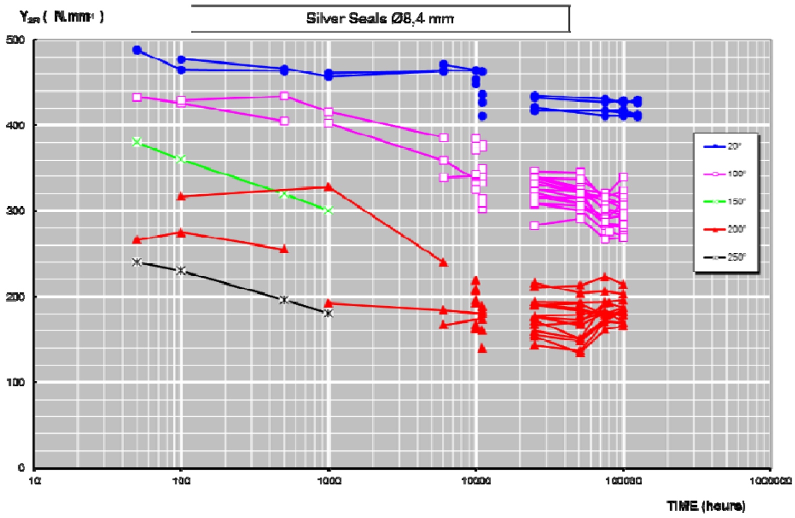


Figure 6 Relation between Time and Y_{2R} values (Seal with Ø8.4 mm)

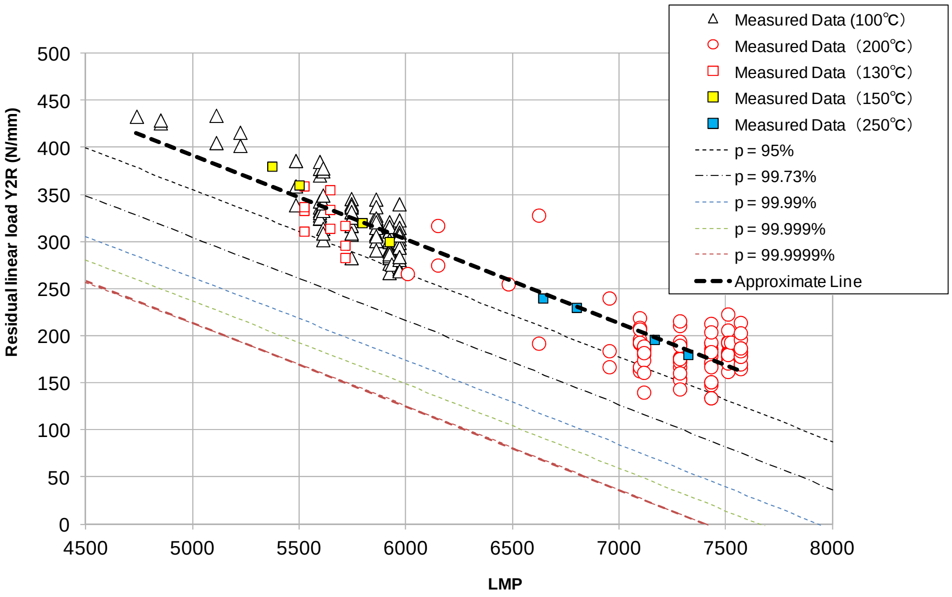
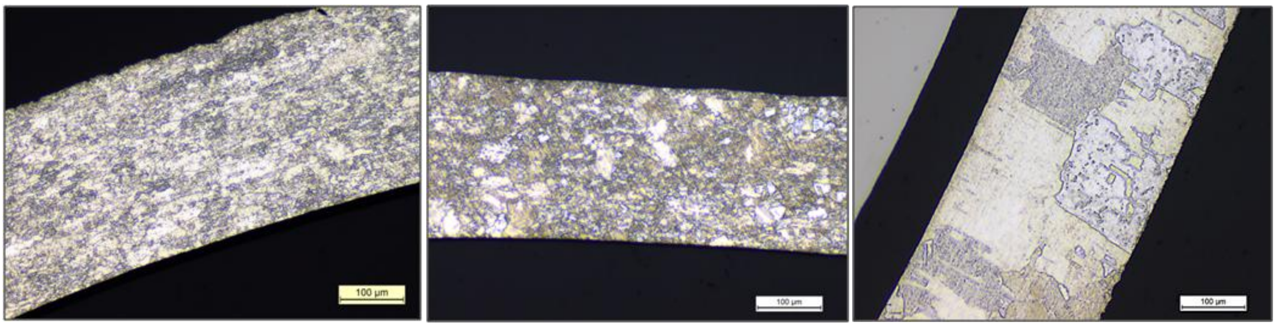


Figure 7 Relation between LMP and Y_{2R} values (Seal with Ø8.4 mm)



(a) 500 hours at 20°**C** (b) 80,000 hours at 100°C (c) 80,000 hours at 200°C

Figure 8 Metallurgy observation of silver outer lining (Seal with Ø8.4 mm)

Discussion

The statistical analyses based on the 100,000-hour experimental program confirm the ability of HELICOFLEX® seals to preserve a significant residual maximum linear load over a century and the increased database size used for the statistical analysis improves significantly the forecast reliability. The evaluation of seals spring back for a given residual load, which allows the prediction of the maximum temperature imposed to preserve a given spring back, has, however, to be considered with caution. Indeed, the suggested method is rather too pessimistic as it considers a constant linear load for sealing performances losses, when experiences demonstrate a significant decrease of this key parameter.

Regarding the numerical simulations, the results of the FEA provided very useful information to support the statistical analyses [9]. The understanding of the mockup bending deformation mechanisms and the estimates of the large deflections provide valuable inputs for the creep simulations. The comparison of FEA results with experimental data demonstrates an acceptable concordance of initial silver creep law from the Y_{2R} estimation point of view, bolstering the FEA model reliability.

Conclusions

The experimental campaign was performed up to 100,000 hours (125,000 hours for RT mockups), with additional data that increase the forecast reliability.

As suggested by some abnormal results observed in the analysis of the 75,000h/200°C mockups, the time-temperature method should be adapted to describe more precisely the creep deformation mechanisms. Indeed, as observed during the ageing tests, seal stress is decreasing due to creep-relaxation as their own deformation affects their residual linear load. A promising solution might be to modify the LMP analysis in order to take into account the RT ageing results and to predict horizontal asymptote of residual maximum linear load.

The improvement of the silver creep law is also a key point for the precision of the ageing numerical simulations. A specific effort is made based on further creep test results to improve our understanding of this mechanism. Metallurgy analyses of aged seals, machined in the equatorial and poloidal plane are also planned on RT/120,000h and 200°C/100,000h mockups. The measurement of the outer/inner lining thickness and hardness evolution of the material, added to a characterization of the aged metallic structures compared to the one of unused seals, will provide very interesting inputs to better understand the creep regime. The measurement of the penetration of the spring wires inside the inner lining will also give elements to benchmark and enhance the numerical model.

In these tests, reliable data were obtained for the extrapolation methods and validation of numerical simulation.

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