**Proceedings of the 19th International Symposium on the
Packaging and Transportation of Radioactive Materials
PATRAM 2019
August 4-9, 2019, New-Orlean, LA, USA**

NUMERICAL SIMULATION OF HELICOFLEX® METALLIC GASKET AGEING MECHANISM FOR SPENT FUEL CASK

F. LEDRAPPIER ; J.F. JULIAA
TECHNETICS Group France
Laboratoire d'Etanchéité maestral, 2 rue James Watt, F-26700 Pierrelatte, France

A. BÉZIAT ; K. VULLIEZ ; L. MIRABEL
CEA/DEN/SDTC/Laboratoire d'Etanchéité maestral
F-30207 Bagnols Sur Cèze, France

ABSTRACT

In the framework of CEA, TECHNETICS GROUP, GNS and CRIEPI collaboration an experimental program has been carried out to assess the long-term use of HELICOFLEX® metallic seals in nuclear spent fuel storage casks. Accelerated ageing tests performed with the use of 120 mock-ups has provided more than 440 points measured over 12 years at different temperatures, which is relevant to address behavior scattering from a statistical point of view.

Beside this 100,000 hours experimental ageing program and the related consistent database, extensive work has been dedicated to the development of a numerical model using finite element analysis to be able to study seal ageing mechanisms and allow extrapolation of seals behaviors, like residual linear load or spring-back, to various ageing conditions and seal designs. Thus, following fundamental material characterization, a specific 3D digital model of HELICOFLEX® seals has been developed to describe its relaxation mechanisms and its relevance has been validated by comparison with the available experimental database.

Beyond the analysis of a nominal seal design, the presentation shows the latest developments on analyses techniques, which aim to address seals behavior reliability with numerical analysis. This work is built on numerical models developed a few years ago which are now completed by design of experiments and model reduction sampling techniques to consider uncertainty propagation regarding the seal and its environment. The analysis aims to assess the influence of geometrical tolerances related to seals and grooves as well as specifications related to mechanical behavior range in material supply on seals properties. The results are then a range of expected behaviors, which are compared with the available experimental database scatterplot. This approach completes the experimental database by an informed evaluation of the influence of uncertainties on product reliability.

INTRODUCTION

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, 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]. In these conditions, metallic seals are subjected to relaxation, which leads to a progressive decrease of its reaction force at a constant compression. This aspect is one of the key feature regarding sealing performances over decades [5].

The metallic seals ageing question has been addressed through a long-term ageing experimental program with mockups that consists in two symmetric bolted flanges holding a tightened HELICOFLEX® seal. These ageing tests provide a large database of more than 450 points, for different ageing temperatures (Room Temperature, 100 °C and 200 °C) and for ageing time up to 100,000 hours. The harvested results have been interpreted using the Larson & Miller Parameter (LMP) for time-temperature equivalence [6][7][8]. This work has been completed by creep tests and a numerical model using Finite Element Analysis (FEA), which describes well the reaction force decrease, as well as the evolution of seals residual spring-back after ageing [9]. This model, whose consistence has been validated with experimental database, is relevant to address seals behavior in different ageing scenario and to describe more precisely seals ageing mechanisms.

Beyond the possibility to describe tests results by simulation, the comparison of experimental database scatterplot and calculated behavior highlights that measurement scattering, used to address reliability with a statistical approach [6], was not addressed by simulation, performed with nominal geometries and materials behavior.

Therefore, the seals ageing digital model is considered to address influence of the most important parameters on seals mechanical behavior, through a design of experiment including manufacturing geometrical tolerances and materials behavior scattering. These uncertainties are then propagated first in the analysis of seals compression, and then in ageing simulation.

EXPERIMENTAL DATABASE

HELICOFLEX® seals characteristics

The HELICOFLEX® metallic seal consists in a helicoidal spring covered by linings. With a proper combination of materials for spring and linings, this structure provides high sealing performances with leakage-rate below 10^{-10} $Pa.m^3.s^{-1}$, tolerant to flanges surfaces imperfections (roughness, waviness), with a significant spring back able to keep the leak-tightness with severe thermal transient, pressure effect or external loads resulting for example from drop tests.

In case of significant ageing, the outer lining, which is pinched between the spring and the flange, becomes thinner and thinner, which unload the spring. That mechanism leads to a progressive decrease of the reaction force with time as shown in Figure 1 hereafter, which is accelerated with a higher temperature. This trend works with a useful spring back decrease, which can be critical if unloading is expected after ageing.

The analysis detailed in this paper focus on behavior of seals with a 8.4 mm cross section subjected to long terms (i.e. up to 100,000 hours) ageing tests. They consist in a spring made of Nimonic 90 alloy, an inner lining made of 304L stainless steel, and a silver outer lining. The nominal compression (e_2) is 0.9 mm, and the corresponding initial maximum linear loads (Y_2) is 545 N/mm.

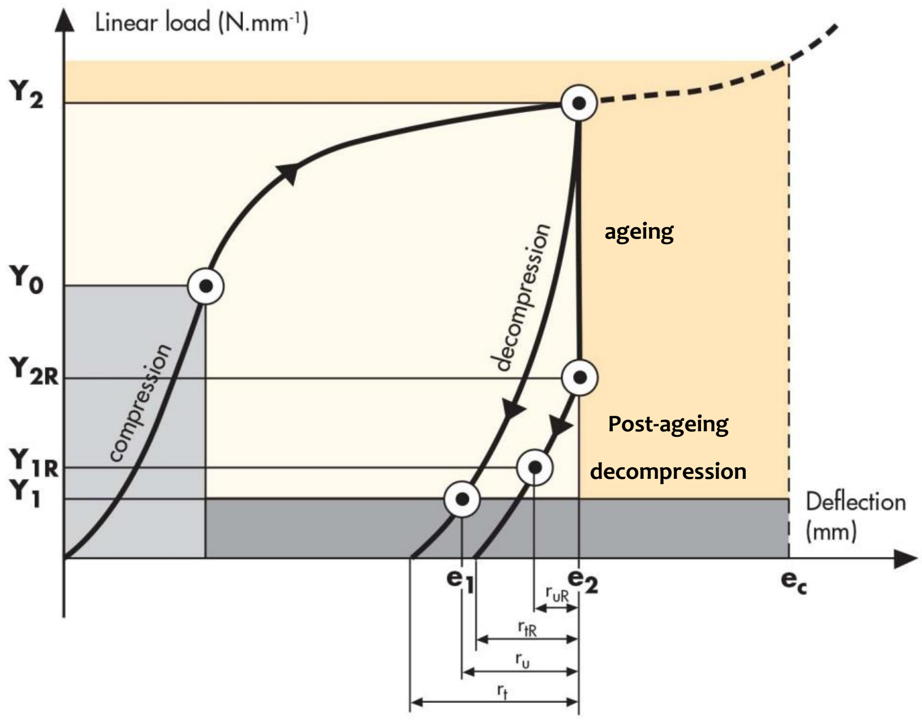


Figure 1: HELICOFLEX® seals characteristic curve

Ageing tests procedure

As ageing tests are carried out for over 12 years, test procedure has been described in other publications [6][7][9]. The seal is installed in a groove between two rigid blinded flanges. The initial tightening is obtained with a hydraulic instrumented press device to achieve the metal-to-metal contact. 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 15 mockups are used for each of the three selected temperatures: Room Temperature, 100°C and 200°C.

After a given ageing period, the mockups are removed from the oven and once at RT placed back under the instrumented press. Then, they are loaded before removing bolts. The load applied by the press is then decreased down progressively to an opening of the flanges of 50 µm, while the load and the distance between the flanges are measured to obtain the unloading curve. The analysis of these post-ageing unloading curves provides information about seals ageing, essentially through the analysis of the residual reaction force (Y2R) evolution.

NUMERICAL MODEL PRESENTATION

Geometry and materials behavior

A 3D numerical model has been developed to analyze tests results [9]. The analysis has been carried out with ABAQUS® v2018 software. For seals compression and ageing simulation, a specific elastic-plastic behavior is considered for each component of the seal (spring, inner lining and outer lining) with the help of tabulated data, including temperature dependence. In addition, visco-plastic behavior is considered for Silver outer lining for ageing simulation. It has been implemented as a strain-hardening creep model which describes the strain-rate as a function of the stress and strain, identified from creep tests performed on silver strips. More details of the model and the methodology are described in [9].

Uncertainty propagation analysis

Seals design and inspections consider tolerances to ensure that targeted behavior is reached, to meet customer specifications. The purpose of the analysis presented in this paper is to propagate all the tolerances, within the manufacturing specifications, and evaluate the corresponding deviation on seals global behavior. The parameters considered in this paper falls into two categories:

- Geometrical parameters:
  - Wire diameter, typically a -0.01 / +0.02 mm tolerance is considered
  - Spring outer diameter
  - Inner lining thickness
  - Outer lining thickness, depending on raw material and affected by the forming process
  - Groove depth, depending on user tolerances on groove design (±0.05 mm tolerance is considered in that work).
  - Gap between inner lining and spring, resulting from spring-back after forming process
- Materials parameters:
  - Wire ultimate tensile strength, which results from the cold-work process
  - Hardening related to the forming process
  - Friction coefficient

The influence of the last two parameters on seals behavior is often discussed, but can be complex to investigate. For example, the tribological parameter can varies with surface roughness, temperature, surfaces oxidation, flange material, ageing… It is not a specified tolerance, but an uncertainty. In this analysis, a friction coefficient from 0.1 to 0.3 is considered.

A total of 9 significant parameters are considered. Then, the corresponding design space is meshed with a design of experiment which consists in 100 evaluations, distributed with the help of an Optimized Latin Hypercube (OLH) algorithm. Due to the small variations of parameters, the evolution of the response is expected to be smooth. For each evaluation:

- An analysis of compression and unloading is performed at Room Temperature.
- Ageing simulations are performed at 100°C and 200°C.
- Unloading simulations are performed after 7 durations (100, 1000, 5000, 10 000, 25 000, 50 000 and 100 000 hours) at both temperatures, using restart files generated by ageing simulation itself.

The results of all these simulations are synthetized in a simulation database which consists in:

- For compression simulation, the total compression is divided in ten equidistant slots. The linear load at each interval is exported, thus the compression curve can be described by ten points.
- For ageing simulations, at each temperature, the residual linear load and total spring back are exported at intervals mentioned above.
- For unloading curves, the decreasing reaction force is divided in ten equidistant slots and the corresponding unloading is exported.

These data compression is considered to write results files, containing values for all parameters and the corresponding results for compression, unloading and ageing as defined above.

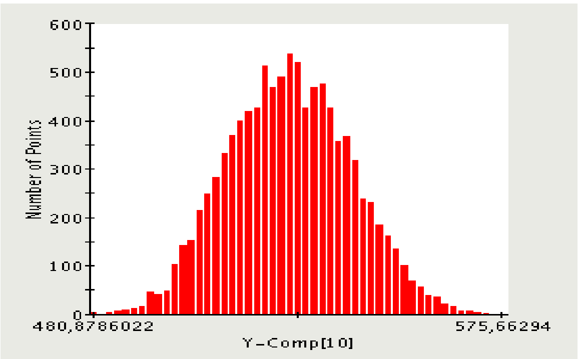
These files are then used to build a surrogate model of seals behavior. A response surface is defined with this database with the help of Radial Basis Functions (RBF). This model allows interpolations within the design space with a very fast response compared to FEA. It enables the run of thousands of evaluations through a Monte-Carlo analysis to address expected behavior scattering. The response surface building and the Monte-Carlo analysis has been performed with the help of ISIGHT 2018 software.

For the Monte-Carlo analysis, different distributions are considered to cover the design space. Most of them are described with a normal law, centered on nominal value, with a standard deviation defined to fit the total deviation expected. The friction coefficient, spring hardening and gap between parts are not controlled after manufacturing. As a result they are considered as unknown parameters and are described with a uniform distribution through their interval.

RESULTS

Initial characteristic curves

The analysis results consist not only in a bounding box of expected behavior related to the tolerances specified, but also provide information about distribution density of behavior, according to distribution of parameters assumptions. Therefore, the following figure presents the distribution density histogram of maximum linear load at metal/metal contact (Y_2). It reveals that maximum linear load, with theoretical value of 545 N/mm, can varies from 481 to 575 N/mm.



Parameter	Values (N/mm)	Relative Gap vs. Theoretial value
Theoretical Y2	545	N/A
Computed Mean Y2	529	-3.0%
Min. Y2 (0.2%)	493	-9.6%
Max. Y2 (99.8%)	567	4.1%

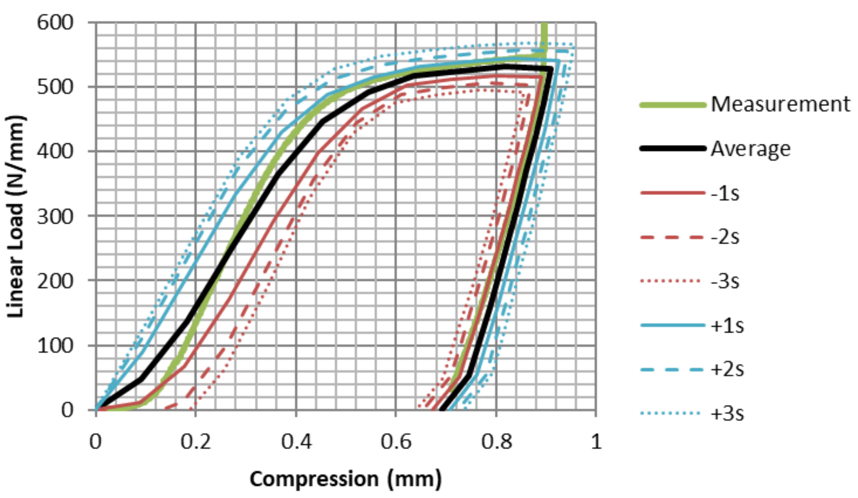
Figure 2: Distribution of maximum linear load at Metal/Metal Contact

This analysis reveals that:

- Calculated mean value is consistent with theoretical behavior (gap is around 3%).
- Extreme values at are consistent with ±10% specification usually mentioned for seals reception.

As this behavior follows a normal distribution, it therefore seems relevant to describe its scattering as a function of a multiple of its standard deviation "s". Thus, the following figure presents a batch of characteristics curves, which includes the probability to get a linear load greater than a value, as a function of the compression. In this figure, the average behavior is described by the black continuous line while green line corresponds to an experimental characteristic curve. Blue and red lines describe respectively upper and lower boundaries of decreasing probability.

This figure reveals a significant scattering at the beginning of the compression curve, due to the combination of jackets thicknesses variation (strip thickness tolerance and thinning related to forming) and groove depth tolerance. The standard deviation decreases significantly at nominal compression. The apparent scattering of unloading curve is mainly related to the groove depth ±0.05 mm tolerance.



Criterion	Probability to get a greater Y2
-3s	99.8%
-2s	97.7%
-1s	84.1%
Average	50%
+1s	15.9%
+2s	2.3%
+3s	0.2%

Figure 3: Description of characteristic curve distribution

Ageing analysis

This uncertainty analysis methodology has been then considered with the seals ageing model developed previously [9]. This 3D Finite Element Analysis include compression phase, followed by temperature transients (heating phases), ageing itself at 100°C and 200°C to meet ageing tests conditions. The evolution of the residual linear load as a function of the ageing time, for both ageing temperature, is processed with the same methodology (DoE using OLH algorithms, surrogate model with RBF, and then Monte-Carlo runs to address behavior scattering).

Both residual reaction force (Y_{2R}) and total spring back (R_{tR}) after ageing are considered for this analysis. For R_{tR}, restart files are generated at the 7 durations processed in this analysis, as specified above, and then an additional model is considered including a cooling-down thermal transient phase, to fit with the seals tests conditions (spring-back is measured at room temperature), and then unloading itself until 1 N/mm residual linear load. It is then convenient to present the evolution of the residual linear load as a function of the Larson-Miller Parameter (LMP) [8] defined as follow:

$$\mathrm{LMP(T;t)} = \mathrm{T} \cdot [\mathrm{C} + \log_{10}(\mathrm{t})] \qquad \text{(Eq. 1)}$$

Where T is the ageing temperature (K) and t is the ageing time (hours)
C is a constant which depends on materials and seal design. C = 11 to fit with [6][7] and [9].

The following figure presents the evolution of the residual linear load as a function of LMP. It compares the calculated density probability curves, determined with the methodology detailed above (lines), with the experimental results (yellow scatter plot). Ageing simulation performed at 100°C are presented in dark colors (black for the average, blue and red for upper and lower stream respectively), whereas simulations at 200°C are presented in clear colors (grey for the average, clear blue and orange for upper and lower boundaries).

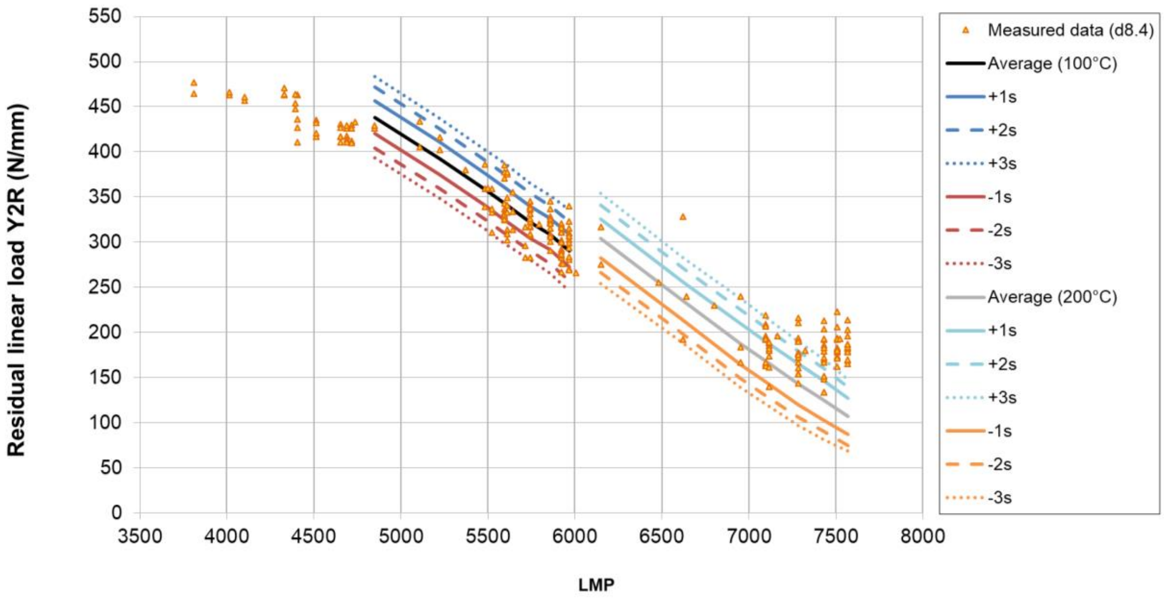


Figure 4: Evolution Y_{2R} with ageing – Comparison of analysis and tests results

This figure reveals that uncertainties propagation analysis provide a distribution consistent with experimental database: The mean trend go through the experimental database, and most of measurements remains within the ± 3 times the expected standard deviation range.

For the most severe ageing conditions (i.e. ≥ 50,000 hours @ 200°C), simulations overestimate ageing effects. This gap probably results from silver recrystallization effects identified in [10] which slow-down its strain rate.

An analysis of the responses effects on residual reaction force after ageing highlights, among the most influent parameters contribution of wire yield strength (full range variation leads to +18% of maximum response variation), seals compression (+10%), and also a significant influence of friction coefficient (-20%) and of sealing liner thickness (-17%).

This analysis also reveals that upper and lower streams remain parallel to each-other. The Y_{2R} distribution is characterized by its average with a ± 45 N/mm deviation, with a 99.7% reliability, whatever the mean value or the ageing scenario considered. This point reveals that ageing mechanism is a stable one and that a slight variation of initial conditions leads to a slight variation of behavior, which can be addressed just by an offset of the reference curve. To illustrate this significant point, the following curve compares the evolution of Y_{2R} of three sets of parameters, which lead to the highest and the lowest reaction force, and a point which lies on the mean trend curve (respectively in red, green and blue), at 100 and 200°C (respectively continuous and dotted lines). According to this analysis, if a seal presents a reaction force greater than another one, it will remains greater whatever the ageing scenario considered, without any intersection. From a mathematical point of view, it means that ageing is an increasing monotonic function of the initial linear load, and decreasing with ageing time and temperature. This result can be explained by creep mechanism itself, which slow-down when stress decrease.

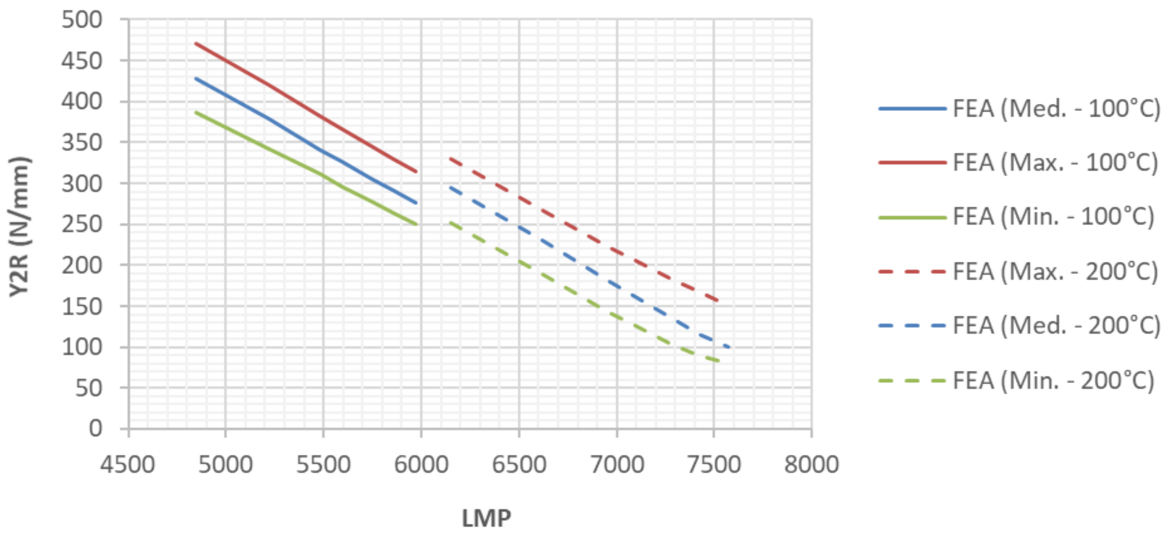


Figure 5: Evolution of residual linear load with ageing for 3 samples

Besides its ability to predict evolution of residual linear load due to ageing, numerical simulation is also relevant to assess residual spring back evolution. The Figure 6 hereafter presents the results from uncertainty analysis on seals total spring-back, which is on the prime interest for transportation purposes. This Figure presents the evolution of the R_{tR} density distribution as a function of LMP, for both ageing temperatures, and compares this theoretical result with experimental extrapolated values. It reveals mean values and deviations consistent with tests data. Few points remain out of trend, especially at low LMP, mainly due to uncertainty of the extrapolation method considered to address experimental R_{tR}. Indeed, test procedure and mock-up design, defined in early 2000's, focused on Y_{2R} measurement and has not been optimized for spring-back measurement. As a result, spring-back related to this database is dispersed due to extrapolation of a short segment far from the target.

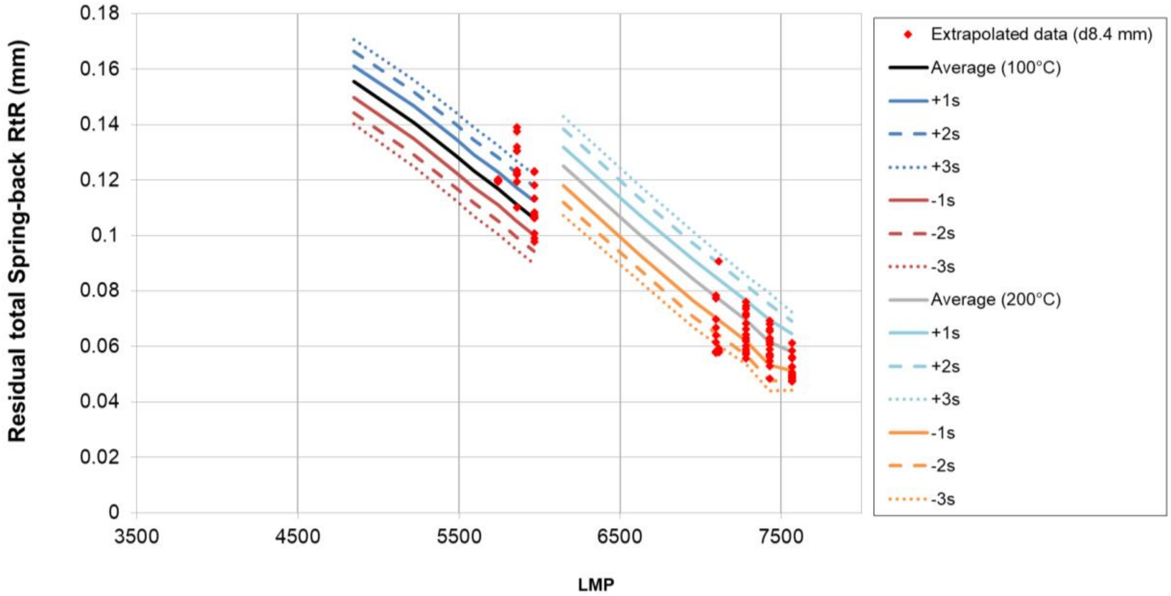


Figure 6: Evolution of R_{tR} with ageing – Comparison of analysis and tests results

As for residual reaction force, iso-probability lines are parallel to each other, which mean that a point below the average will remain always below the average whatever the ageing scenario considered. The residual total spring back can be characterized by its mean value and a maximum deviation of ±16 µm with a 99.7% reliability, whatever the ageing scenario considered.

CONCLUSIONS

A 3D numerical model developed to study HELICOFLEX® seals behavior is considered to address influence of standard manufacturing tolerances and uncertainties not only on seals compression curve, but also on seals ageing behavior. For that purpose, simulations, usually performed with nominal parameters are completed by an analysis based on sampling techniques, model reduction and then statistical processing to presents results in terms of reliability interval. The comparison of these results with an ageing tests database reveals that experimental deviations are consistent with boundaries identified with the theoretical approach.

The data mining performed on the thousands Monte-Carlo evaluations performed with the reduced model highlight different significant features:

- The usual ±10% tolerances considered on seals nominal reaction force is consistent with the usual tolerances considered for manufacturing and controls.
- Initial deviations observed on loads, within the design space considered, are kept after ageing. No intersection is observed between ageing curves when initial load is different.

These results and the methodology developed to address influence of tolerances and uncertainties on seals compression and ageing behavior can be very useful to support reception tests, for example by setting justified lower limits for acceptance.

ACKNOWLEDGMENTS

This analysis has been performed in the CEA Marcoule - TECHNETICS GROUP joint lab.
It refers to test database which result from a GNS, CRIEPI and CEA joint research program.

REFERENCES

[1] Yamamoto, T., 2001. *Dual-purpose metal cask integrity after long-term interim storage (activities for the verification test of a dual-purpose metal cask)*. In: Proceedings of the PATRAM 2001, Chicago, IL, USA, September 7–9.

[2] Droste, B., 1988. *Safety evaluation of dry spent fuel storage casks*. In: Soviet-West German Seminar, USSR, Leningrad, June 27–July 1.

[3] Rouaud, C., Lefrancois, M., Caplain, P., 1999. *Static sealing: technologies of the future*. In: Proceedings of the First International Conference on Sealing Technology and Plant Leakage Reduction, Charlotte, NC, USA, November 15–19.

[4] Birembaut, Y., Ledauphin, T., Vignaud, J.C., 2001. *Mechanical and sealing performances of gaskets specifically manufactured for use in metal to metal conditions*. In: PVP Conference 2001.

[5] Benda, B.J., Langland, R.T., 1980. *Methods for Evaluating the Leak Tightness of Spent Fuel Container Closures*. Lawrence Livermore Lab.

[6] H. Sassoulas , L. Morice , P. Caplain, C. Rouaud, L. Mirabel , F. Beal, *Ageing of metallic gaskets for spent fuel casks: Century-long life forecast from 25,000-h-long experiments*. In Nuclear Engineering and Design 236 (2006), p 2411.

[7] A.Béziat, F.Ledrappier, K.Vulliez, B.Deschamps, J.F.Juliaa, L.Mirabel, M.Wataru, K.Shirai, H-P.Winkler *Ageing of HELICOFLEX® metallic gasket for spent fuel cask: results and analysis of sealing performances of a 75,000h campaign* Proceedings of the 17th International Symposium on the PATRAM 2013 - San Francisco, CA, USA

[8] Larson F.R., Miller J., 1954. *A time–temperature relationship for rupture and creep stresses*. Trans. ASME 174, p. 765.

[9] F. Ledrappier, J.F. Juliaa, A. Béziat, K. Vulliez, L. Mirabel, M. Wataru, K. Shirai, R. Hueggenberg, H-P. Winkler *Numerical simulation of HELICOFLEX® metallic gasket ageing mechanism for spent fuel cask* - Proceedings of the 18th International Symposium on the PATRAM 2016 – Kobe, JAPAN (Paper #5009)

[10] M. Wataru, K. Shirai, A. Béziat, F. Ledrappier, K. Vulliez, B. Deschamps, J.F. Juliaa, L. Mirabel, H-P. Winkler, R. Hueggenberg, *Ageing of HELICOFLEX® metallic gasket for spent fuel cask: results of sealing performances of a 100,000h campaign* - Proceedings of the 18th International Symposium on the PATRAM 2016 – Kobe, JAPAN (Paper #5026).