Experimental qualification of rotatable plug seals for Sodium Fast Reactor on a large scale test stand

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Abstract. In the framework of the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project, the CEA Sealing Laboratory with its partner TECHNETICS (TGF) has been involved to propose a new concept of rotating plug seals to replace the commonly used liquid-metal seals. An innovative combination of static, dynamic and inflatable seals in silicone rubber ensuring double tightness-barriers for the cover gas has been developed. Following the design phase and materials studies, a dedicated test stand was built to qualify the technical performances of these seals. The large size of the test stand, made of a 2.5m diameter rotating plates, was chosen to provide a small profile height on seal diameter ratio, and a volume of enclosed gas large enough to allow representative qualification of leak-test methods. After a description of the test stand, the paper presents the mains outcomes of the technical qualifications (mechanical behavior, sealing performance, endurance test) led on several seals design.

Key Words: Rotatable plug seals, FBR sealing technologies, Large scale test stand, ASTRID

1. Introduction

Fast sodium Breeder Reactors (FBR) top shields are commonly equipped with one or two Rotatable Plugs (RP), that provide together with a shielding against thermal and gamma radiation, a practical system to ensure most of the in-vessel fuel handling operation. The RP are equipped with seals assembly that shall allow its lifting prior to the rotation of plug. On most existing FBR, the rotating seals ensuring the first leak-tightness barrier is made of fusible metal, melt to its liquid state during handling cycle and solidified during operation. This seal, commonly made of eutectic alloy is sensitive to air oxidation. In many designs an inflatable seal forms a second tightness-barrier between the reactor environment and the seal cover gas, to guarantee the conditioning of the argon atmosphere protecting the liquid-metal seal. Maintenance issues and technical hazards observed on several FBR [1-2-3], lead the designer to consider concepts without metallic seal. In the framework of ASTRID project, the CEA-TECHNETICS Sealing Laboratory has been involved to propose innovative concepts to cope with all the most generics RP design constraints. As part of these developments [4], a dedicated test stand was built to qualify these concepts (together with more classical solution) in RP relevant working conditions.

2. The Rotating plug Seals Test stand (RST)

2.1.Experimental objectives and context

The primary design choice was related to the size of the test stand, criteria with a strong impact on the choice and the cost of the equipment. The choice made to perform tests on full-size seals (cross-section of 30x30mm) leads to seal diameters in the range of 2m. This rather large dimension provides a small aspect ratio and bend radius that can be compared with the dimensions of the seal mounted on ASTRID RPs (diameter 5.5 and 7.5m). The second advantage provided by a large mock-up is to provide important volume helpful to qualify leak test measurement methods. The working conditions foreseen for ASTRID RP impose then most of the RST design criteria. For the rotation, an angular velocity $6°.s^{-1}$ was chosen to reach the linear speed criteria of $115mm.s^{-1}$ on the tip of the seal. The speed control system was also designed to mimic a realistic roundtrip rotation of the RP with acceleration/deceleration and pause phases. For ASTRID, the estimated vertical translation (up/down movement of the RP) height is 20mm, to ease the assembly the RST was design for a movement range of 30mm. The planarity of the seal flange and the plate facing the seal was specified at +/-0.1mm. This severe tolerance for such large parts (diameter of 2.5m) allows a precise compression of the seal, representing less than 2% of the full compression range. Since, on reactor such level can hardly be achieved, the RST was designed to allow an adjustable tilting between the top and bottom plates. The option of heating the RST to the working temperature (120°C) expected on ASTRID was not retained because of the difficulty to achieve the planarity. Dedicated studies on small scale mock-up were conducted in parallel to assess the influence of the temperature, together with the impact of surface roughness and surface treatment, on the wear and tribology of the seal. Regarding the working conditions the objective of a 100km covered distance corresponding to 60 years of fuel handling operation imposed an operator-free operation during period up to 12h. This type of heavy duty cycle, 360° back and forth with short pause, is conservative compared to the reactor operation cycle where longer pause are foreseen between smaller angular rotations.

Two other objectives were identified as part of the experimental program: the development of adequate leak-test measurement that can be implemented on a reactor, and the demonstration of the feasibility assembly of extruded strip-shaped seal with endings vulcanized on-site. A specific skid was build (see §2.2) to ensure these measurements. Compact heated tools were also developed to achieve the seals splicing directly on the RST.

2.2.RST description

The RST is a mechanical structure composed of a machine-welded frame on top of which two sub-assemblies are mounted. The first one is a rotatable cover composed of two parallel plates (upper/lower plates) separated by a spacer connected to a ring gear. The second one, that can be translated up/down is composed of mid-plane plate with seals flanges, connected to casing that can be filled with water or silicon oil. The movements of these sub-assemblies are ensured by: three motors connected to the ring gear by drive sprocket allowing the rotation of the cover, while three linear actuators located at the periphery ensure the up/down translation of the seal holder.

The test stand is instrumented by several sensors and gauges to allow the operation and the collection of experimental data. Added to the encoders of the motors and actuators providing angular displacement and position, six laser sensors located evenly spaced around the upper plate allow a fine measurement of the spacing between the plates. Torque-meters on drive sprockets and cell-forces in line with the linear actuators provide information on force and torque applied on the rotatable seals during operation. Temperature is monitored on five different points of the setup.

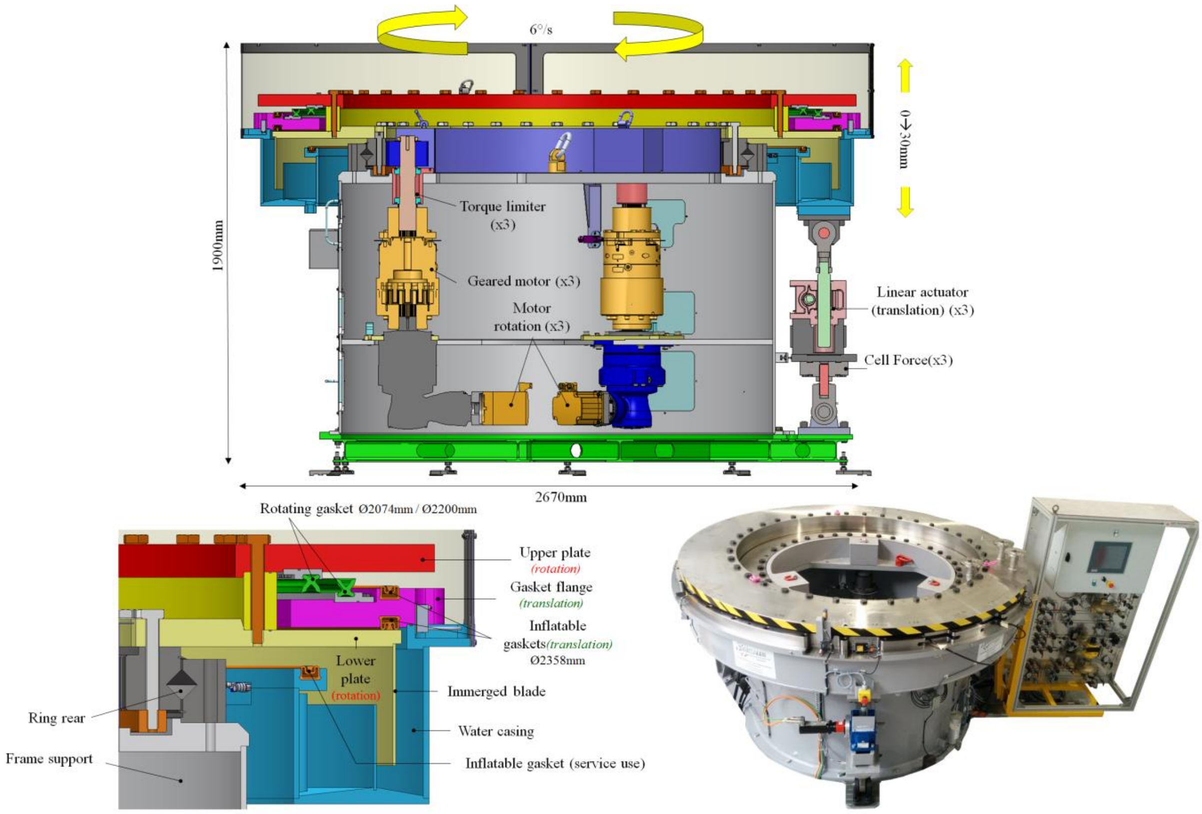


FIG. 1. Top: RST schematic cut-view of the mechanical structure; Bottom left: detailed cut-view; Bottom right: picture of the RST

A skid is connected to the RST to provide the gas supply for the inflatable seals and to monitor the pressures of the enclosed volumes delimited by the seals. The eight pressure transducers are combined with 4 flow sensors based on different technologies covering a large range of flow-rate (0.01 to 20Nl.h^{-1}). More than forty five independent data measurements are collected by the instrumentation and control systems of the RST.

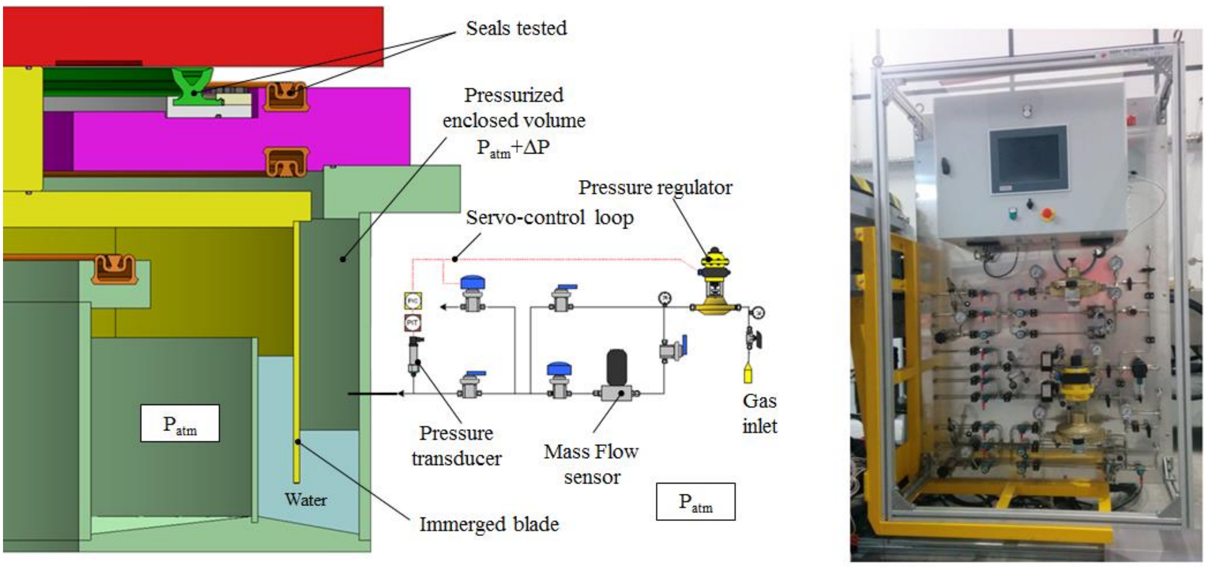


FIG. 2. RST skid for gas supply and leak-test measurement

2.3.Reference rotatable seals layout and RST operational principles

The innovative layout of seals proposed by the CEA-TECHNETICS Sealing Laboratory to replace the liquid-metal seals is based on a combination of an inflatable and a massive dynamic elastomer seals (Fig. 3). Both seals, mounted side-by-side, are working in the axial direction providing independent functions. In this design the dynamic sealing of the reactor vessel cover gas during the up/down vertical movements of the RP is ensure by the inflatable seal, while the massive double lips-seals (inverted-π shape) once compressed at the end of the translation ensure the sealing during the RP rotation. The RST reproduces the RP cinematic, starting with pressurization of the inflatable seal followed by a vertical movement of the seals holder plate up to a position where the rotatable seals is compressed by the upper plate. After deflation of the seal the upper plate can be set in rotation. The enclosed volume (Fig. 2) delimited by the inflatable and rotatable seals and the free-surface of the liquid in the casing can be pressurized at a value corresponding to the standard pressure of the vessel gas cover.

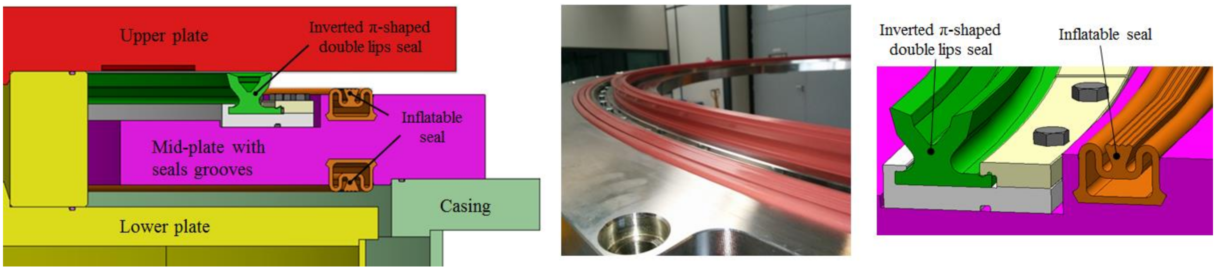


FIG. 3. Assembly of the inflatable and inverted-π shaped seals on the RST

The leak-rate measurement during static and dynamic phases is based on the flow-rate measurement on the gas supply line monitored by a control loop. A given pressure is set as a target value for the servo-system mounted upstream of the line, in order to maintain the enclosed volume at this reference pressure when a leak occurs, the system must fill the enclosed cavity. The flow-rate measured on the gas supply line provides then a direct measurement of the leak-rate. For pressures ranging from 5 to 200 mBarg, leak-rates down to $0.01 Nl.h^{-1}$ can be measured; leak below this Sensitivity Threshold (ST) cannot be estimated.

3. Mains results and outcomes on the RP seals reference design

All these measurements were combined for the qualifications of the seals mechanical behaviours in RP relevant configurations, which include: assembly, inflating pressure, force and torque, sealing performance, thermal behaviour, wear and fatigue.

3.1 Inflatable seals

The profile of the inflatable seals was designed to allow vertical displacement over 25mm (the RP stroke on ASTRID is 20mm). Mechanical and seal performance characterizations were performed on the seal for various inflating pressure and operating conditions (cover gas pressure, distance between plates …). These measurements were compared to the Finite Element Analysis (FEA) studies conducted throughout the seal design. The comparison between FEA and experimental measurements (see Fig. 4) provides a meaningful way to benchmark the numerical model. In the case of the free expansion of inflatable seal, comparing the measured and numerical deformations prior and after the seal is deployed is an interesting way to assess the validity of the numerical model. Featuring a good mechanical behavior, the others outcomes of these measurements concern its sealing performances. Its sealing behavior operates on a ‘all-or-nothing’ basis: once the tip of seal is compressed on the upper plate for a given pressure (450mBarg) the leak-rate drop below the ST. Once the leaking paths close at the seal-plate interface, a pressure rise is observed because of the permeability of the pressurized seal. Indeed, the silicone high performance grade selected for the seal [5] is a rather permeable material. Compared to most of the polymer, silicone based elastomer features rather high permeation coefficients [6]. The pressure rise of the inflatable seal was studied for different operating conditions (plate opening, seal pressure). In the foreseen application, this phenomenon will have little consequence since the RP translation is a short operation, and the volume of gas injected is negligible over such short period compared to the reactor cover gas volume. Complementary studies on ad-hoc mock-ups are on-going to evaluate the effects of temperature and gases, and different types of coating are foreseen to be tested to reduce the permeation coefficient.

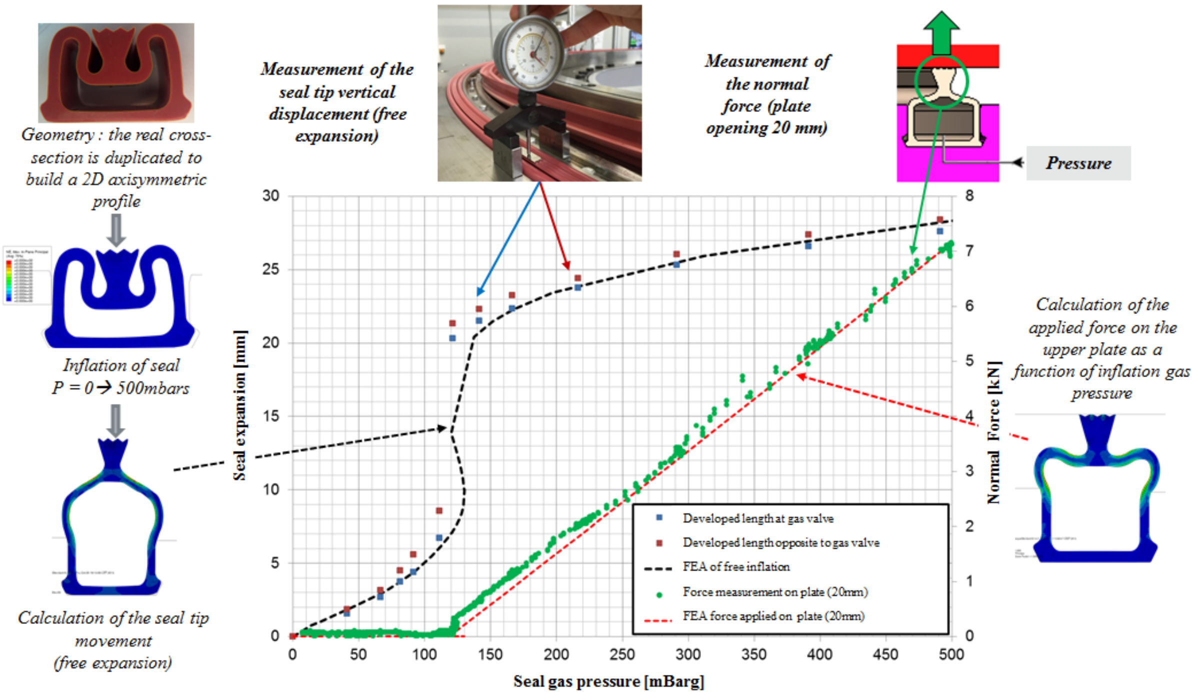


FIG. 4. Inflatable seal comparison between experimental measurements and FEA: FEA results - dashed lines, experimental measurements - dots

3.2 Rotatable inverted-π shape seal

The rotatable seal profile design is an inverted-π shaped massive gasket mounted axially. The profile was selected among several other option for its robustness and capability to accommodate large radial movements. The double lips ensure a double sealing track and provide a good mechanical stability of the profile. The final profile geometry is the result of numerical topological optimisation based on mechanical criteria of stability and linear response over the compression range. Likewise the inflatable seal, prior to the endurance tests the rotatable seal went through a large series of static and dynamic mechanical tests. The compression curves were consistent with the one estimated by FEA analysis. The classical behaviour of this type of hyper-elastic material is observed with stabilization after several cycles (see Fig. 5). Once stabilized after cycling, the compression of the seal was correlated to the leak-rate. As for the inflatable seal, the 'all-or-nothing' behaviour was observed. Once a linear compressive force of about 0.5N.mm^{-1} is applied on the lips, the leak-rate goes below the ST. The seal tightness is then maintained during rotation, even with the drop of the normal force down to 0.2 N.mm^{-1}.

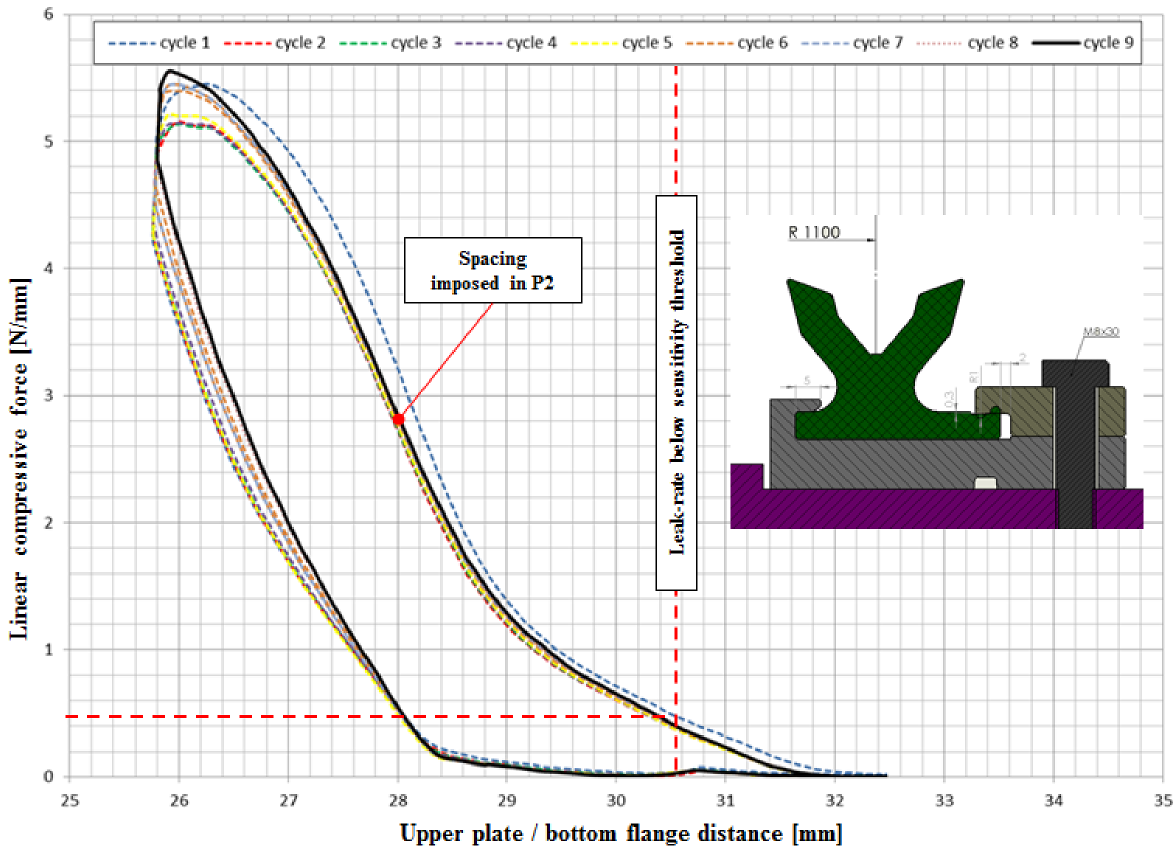


FIG. 5. Compression curves of the Rotatable inverted-π shape seal: linear compressive force as a function of plates spacing (the last cycle is in bolded line).

In order to qualify the endurance of this seal over 100km, the first experimental phase was based on the following first Protocol (P1) : the seal was compressed to achieved a leak-rate below ST, then cycles of 360° back and forth rotation with pause of 10s are launched for duration of 6 to 8 hours. If at the end of the test, a leak-rate is measured, the upper plate is lifted and the seal compressed again in order to obtain again a leak-rate below ST. A new cycle is launched, and the test continued to cover a distance of 100km. Aware that proceeding this way will complicate the reactor operation, a second Protocol (P2) was used. This time the spacing between the plates (seal groove/upper plate) is fixed (4mm) and the cycles are launched for 100km with regular loading and unloading of the seal.

During the first fifty kilometers (P1 protocol), we observed a rather steady behavior with a limited wear of the seal and tightness achieved with a normal force below 0.2 $N.mm^{-1}$. After fifty kilometers, the wear increases together with the seal reaction force since thicker section of the lips get involved. This evolution can be correlated to the compression curve (see Fig. 5). During P2 protocol, we observed a decrease of the reaction force generated by the wear, and a first leak intermittent measured after 87km. After 97km, the leak-rate measured reaches a steady level over $2Nl.h^{-1}$. It is interesting to note that the first leak occurs at a level comparable to the one measured prior to the endurance test, illustrating the contact pressure dependency of the leak. The small steps observed on the spacing values (mean values of the 6 laser sensors see Fig. 6) during cycles are linked to temperature variations of the plate generated by the friction of the seals. At the end of the two endurance tests, the compression curves over the same height range were repeated (see Fig.7). The seals were dismounted, and the wears were estimated by mean of comparative weighting and profilometry measurements. The results and observations are consistent with the mechanical measurements. The lips heights abrasions are about 1 and 1.5mm respectively for P1 and P2 protocols. It can be observed with a shift of on the compression curve (see Fig.7). The wear and weight loss are also in good agreement with the results obtained on small mock-up used for tribology studies.

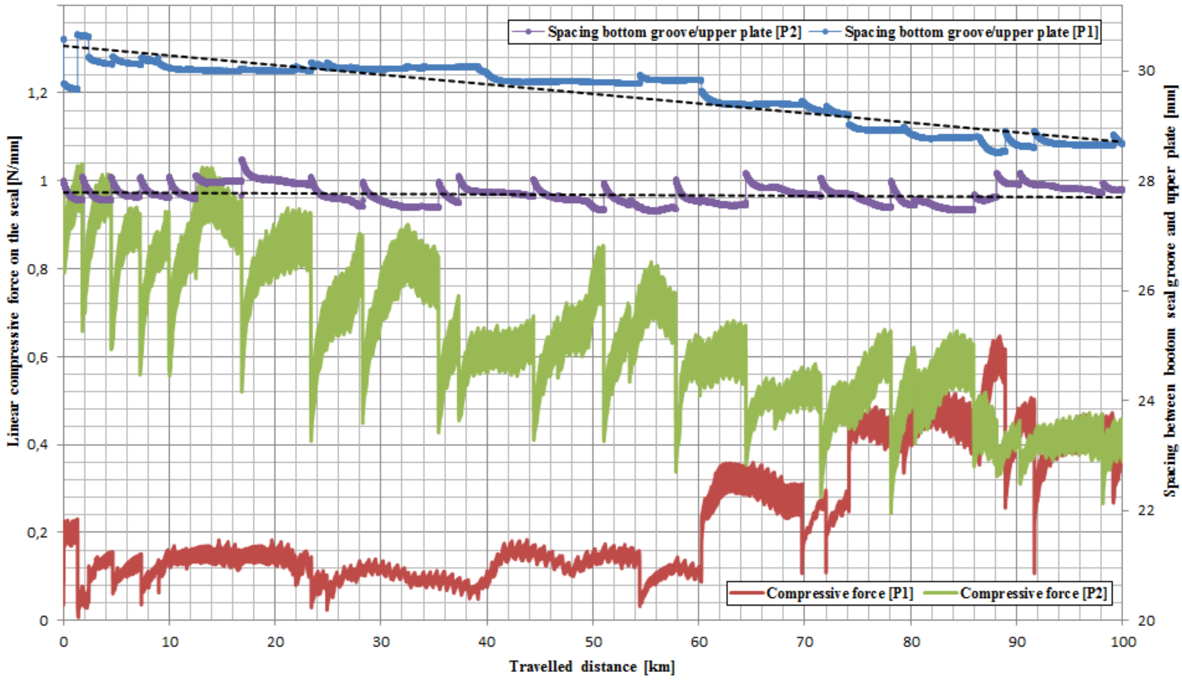
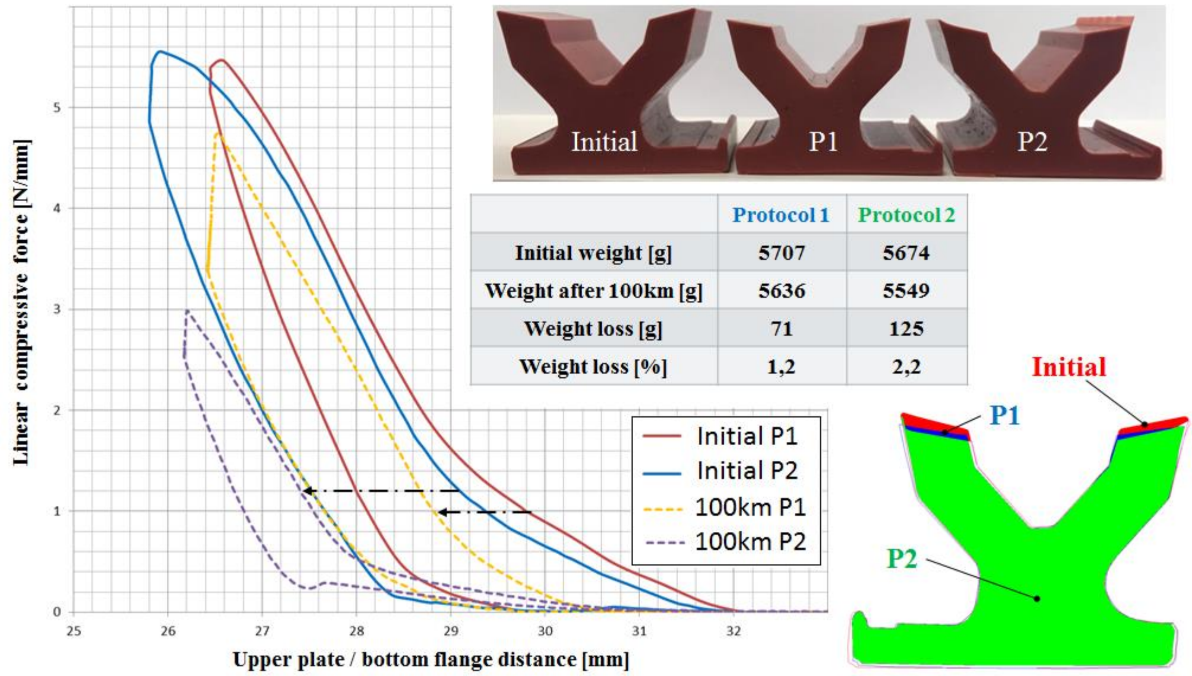


FIG. 6. Reaction forces and spacing between bottom groove and upper plate for the 100km endurance tests P1&P2

The overall behavior of the seal, in term of mechanical, wear and sealing performances are very satisfactory for both protocol. The robustness of the profile was demonstrated for traveling distance up to 100km. It shall be underlined that, at the end of the performance test a large margin on the seal compression remains, while the friction conditions were rather severe: no surface treatment was used on the seal or on RP (raw silicone on stainless steel without lubrication) and the tests were made at ambient temperature. Indeed, the satellite on-going R&D programs on tribology shows that temperature in the range of 120°C, has a favorable impact on friction coefficient and wear. Moreover, coating of the seal and use of Molybdenum based lubrication applied on the rotatable plate are also under consideration in these studies to minimize the seal's wearing and to further improve the seal lifetime.

Together with a detailed material characterization of the silicone initiated at the beginning of the project (compression set, uniaxial, bi-axial, shear, compression, hydro-compression standard test), temperature ageing laws of the material were studied. Seals are presently aged inside a heat chamber at 150°C. Once ready, the studies will be continued with tests on the aged seals. Mechanical, tightness measurement and endurance tests are also planned with tilted plates to assess the impact of RP misalignment on the seal performances. To complete the qualification, vulcanized seal junctions, similar to the ones used to close up the seal, went successfully through fatigue test, with mechanical constrains applied similar to P2 protocol conditions.



	Protocol 1	Protocol 2
Initial weight [g]	5707	5674
Weight after 100km [g]	5636	5549
Weight loss [g]	71	125
Weight loss [%]	1,2	2,2

FIG. 7. Compression curves of the inverted-π shaped seal (initial bold, 100km dashed) for P1&P2. Comparison of seals profiles: initial and after 100km.

4. Other designs tested

With minor mechanical adjustments, the tests stand was adapted to perform tests on other seal profiles and configurations. A campaign was dedicated to the qualification of inflatable seals for the PHENIX reactor (PHX), and an alternative design for ASTRID based inflatable seals mounted radially is under qualification.

4.1 Inflatable PHX seals

In order to qualify new references of seals designs for PHX RP, the groove of inflatable seal on the mid-plane plate of the test-stand were modified (reduction of the width). On PHX, the RP is sealed by a liquid metal fusible seal, protected from air oxidation by inflatable seals that form a second tightness barrier ensuring the cover gas pressurization [7]. This configuration features two inflatables seals mounted side-by-side; providing with their axial expansion once pressurized the sealing during the up/down translation and rotation phases. Three different types of seals (see Fig. 8), based on different technologies and materials, were tested with mechanical characterization, tightness and wear qualifications. Two seals made by TGF with the same shape but made one of Styrene Butadiene Rubber (SBR) and the other of silicone, and a seal made of Silicone with a Reinforced Textile structure (SRT) made by a French manufacturer.

Planned to replace the existing seals (mounted on the RP during the 1980 maintenance shut-off) in case of failure, the endurance test objective was fixed at 20km corresponding to two times the foreseen travelled distance expected on the RP for the PHX dismantling operations. The experimental protocol was rather similar than the one described above used for ASTRID seals (see §3.1), adapted to the PHX working conditions.

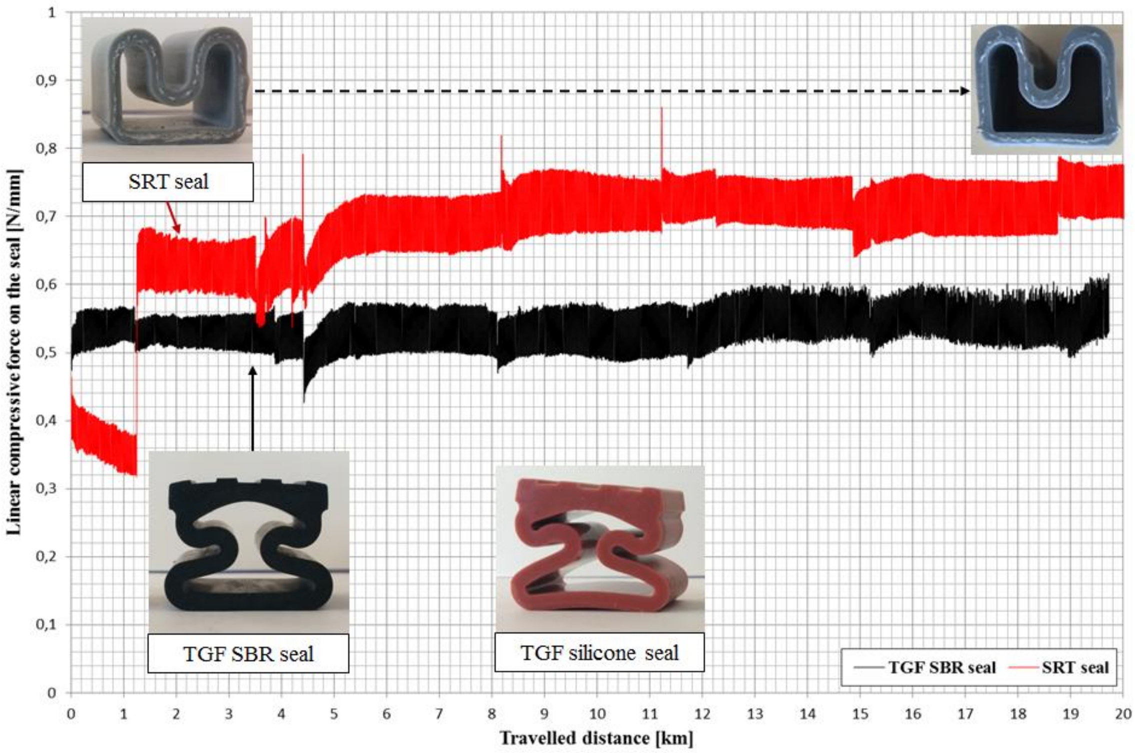


FIG. 8. Endurance tests on PHX axial inflatable seals. Two profiles tested: Silicone with a Reinforced Textile (top curve), TGF SBR seal (bottom curve).

Rather similar observations were made on the 'all-or-nothing' sealing steady behavior and on the effect of permeability, this phenomenon is enhanced for the SRT seal due to the textile inserted in the bulk material, and significantly reduced on the TGF SBR. These last two seals went through endurance tests, successfully for the SRT seal with a slight increase on the seal pressure after 1.2km made to improve the sealing. Despite the significant wear of the silicone (the reinforced textile is locally visible) the seal work well over the 20km travelled. On the opposite, the test on the TGF SBR seal failed after 19.7km, failure linked to a self-heating ageing phenomenon. The third seal by TGF made of silicone with a coating is about to be tested. Once achieved, this qualification tests will allow the selection of a technical solution based on a detailed experimental data.

4.2 Radial seals assembly

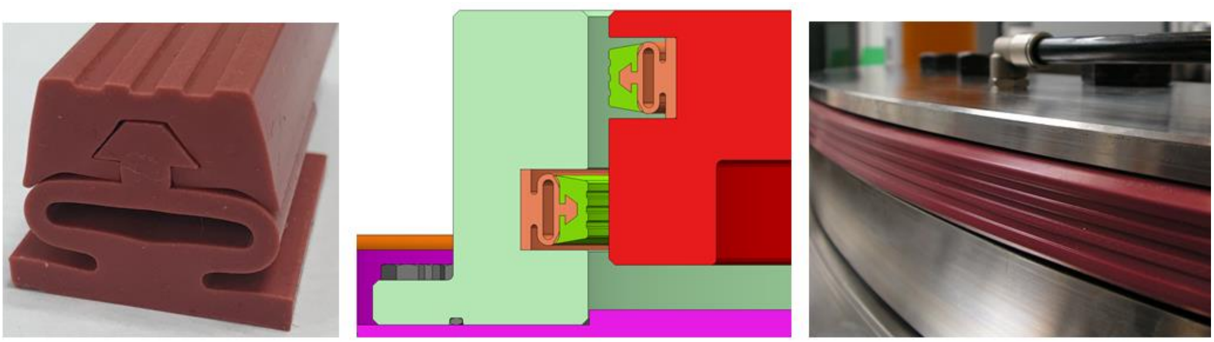


FIG. 9. From left to right: picture of the radial inflatable seal, seals assembly on the RST, inner radial seal inflated on the RST

An alternative design based on radial inflatable seals is under consideration for ASTRID. The test stand was modified (see Fig. 9), the top plate replaced by 2.2m diameter coaxial rings mounted on the mid-plate, machined with radial groove. Based on ASTRID primary design input, a radial spacing of 7mm was chosen as a reference for this new configuration. An inflatable TGF silicone seal was designed for the radial configuration. In order to mitigate the risk of failure and improve the seal robustness, the seal is composed of two individual parts: an inflatable chamber on top of which a massive head is clipped. Once the operating optimal working pressure measured, endurance tests (following a procedure similar to P1 protocol used for axial solution) will be launched to allow a comparison between the two technical options.

5. Conclusions and perspectives

The RST developed in the framework of the TECNA R&D program is a very useful tool to develop and qualify RP seals in support of ASTRID design [4]. The polyvalence of the RST made possible within a short time the test of five different types of seal, with five extra more to come, mixing two different tests programs (PHX/ASTRID) and two mechanical assembly layouts (radial/axial). Its large size and mechanical capacity, its instrumentation and controls system allow not only comprehensive measurements of the seal mechanical behavior for heavy duty uses, but also permit the development of seal tightness procedures adapted to the RP configuration and easy to implement on a reactor environment.

The seals configurations tested, starting with the axial combination of an inflatable and a double-lips seal was so far very successfully tested, providing a convincing technical demonstration. The experimental campaign continues on aged seal, and other seal tightness protocols are foreseen to be tested to improve the sensitivity threshold of the measure.

In parallel, tribology studies in temperature with a selection of surface treatments are on-going to optimize the lifetime of seals (reduction of friction coefficient and wear). The thermal sensibility of the permeability and gases types will also be assessed to complete the data on inflatable seals, and some seal coatings are also under study to reduce the permeability coefficient.

The vulcanized seal junction remaining a weak point in regard of wear and fatigue, samples that will go through mechanical characterization are ageing to finalized and comfort the existing data.

Appendix 1: References

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