R&D Program on sealing issues for in-service inspection and repair tools on ASTRID sodium prototype

K.Vulliez\textsuperscript{a}, L.Bruguière\textsuperscript{a}, L.Mirabel\textsuperscript{a}, A.Béziat\textsuperscript{a}, F.Baqué\textsuperscript{c}, M.Berger\textsuperscript{d}, B.Deschamps\textsuperscript{b}, J.F. Julias\textsuperscript{b}, F.Ledrappier\textsuperscript{b}, G.Rodriguez\textsuperscript{c}, B.Rouchouze\textsuperscript{d}

\textsuperscript{a}CEA, DEN, SDTC, Laboratoire d’Etanchéité Maestral, 30207, Bagnols Sur Cèze France.

\textsuperscript{b}TECHNETICS Group France, Laboratoire d’Etanchéité maestral, 2 rue James Watt 26700 Pierrelatte.

\textsuperscript{c}CEA, DEN, DTN, CEA Cadarache, 13108, Saint-Paul-lez-Durance France.

\textsuperscript{d}TECHNETICS Group France, 90 rue de la roche du geai, 42029 Saint-Etienne

\textit{Presented by K.Vulliez}

\textbf{Abstract.} The development of in-service inspection and repair tools for sodium cooled nuclear reactors is a challenging task. In present design, the tools regardless of their design and function are foreseen to be embedded inside a bell mounted on a remote handling device. Apart from the constraints inherent to the remote actuation and the docking of the system on the vessel structures, the high temperature sodium-tightness of the bell is a tedious issue to solve. This paper presents the R&D program conducted at CEA-Technetics sealing laboratory to address this matter. This program is divided along two axes, a characterization phase with radiation and sodium aging of several elastomer compounds, and the development of a full scale mock-up of a docking flange to qualify the sealing efficiency of different profiles. Advanced concepts of sealing systems and mechanical obturator for the inspection bell developed in the frame of this program are presented.

1. Introduction

In the framework of the ASTRID (Advanced Sodium Technological Reactor for Industrial Demonstration) project, innovative systems for In-Service Inspection and Repair (ISI&R) are under development \cite{1, 2}. The nuclear vessels environment with radiation and high temperature sodium where the ISI&R equipment will be deployed imply stringent technical constraints. The simplest and most straightforward way to limit the constraints on these systems is to keep them away from sodium (Na) exposure. The reference design option for most of the ISI&R tools foreseen is to embed them inside a sodium-tight diving bell. By the mean of a remote handling (RH) device, the bell will be moved in the nuclear vessel up to the structures requiring inspection or repair. Once docked and tightened on the chosen surface, a sealing system will be required to create of volume free of sodium where the ISI&R systems can operate. The development of the sealing system and the mechanism allowing the bell aperture and closure while immersed in sodium are therefore mandatory. The CEA-Technetics MAESTRAL sealing laboratory has been involved to provide its expertise to develop an integrated system to be interfaced on a Remotely Handled Inspection Bell (RHIB).

A dedicated R&D program was initiated hinged on two axes: a program to select and characterize proper sealing materials that include mechanical tests of samples exposed to sodium and radiation and the development of a test stand to qualify full scale mock-ups of sealing concepts. The description of these activities, their main results, and advanced concepts are presented here after.
2. Materials selection and characterization

The choice of a seal with a given technology and material among the large panel available is always the result of a compilation of requests specific to the foreseen application. In the case of ISIR systems, with a sealing system immersed inside sodium, the constrains of the environment both thermally with temperature up to 220°C (the retained temperature during reactor shut-down), radiation, and chemical, strongly reduce the technical options. If the low pressure involved (below 3 bars) and the short duration of immersion (below 30 days) partly release the constraints, the uneven geometries of the vessel surfaces to inspect, together with the RH tooling specification are other matters to address. Two type of sealing technologies emerge from a first analysis: metallic seals, and seals made with silicone compounds.

![Diagram](image)

**FIG. 1.** Tests samples for mechanical characterization and sealing performance test

The metallic seals presents several advantages in terms of working temperature (featuring large margins for temperature below 250°C), and for most alloys a good sodium compatibility. In regards of the quasi-isothermal conditions, the purity of the sodium and the short-term immersion, the corrosion on steel and nickel base alloys will not be a concern [3]. However, the limited forces the RH systems (Fig.1) can transmit to the RHIB sealing-system during docking (estimated below 10kN) strongly limited the technical options. Indeed, a sealing-system is at some point constrained and designed in regards of the minimal force required to ensure the seals compression, and most of metallic seals require rather high compression forces. With a proper choice and shape of the seal together with a well-designed assembly this matter can be overcome. At first in the program, with a design of the RH component of the ISIR still evolving, the metallic seals option was set aside. Solutions with this type of seals were only worked out on more advanced concepts.

Solution based on elastomer seals was the second option considered, thanks to the far lower compression forces they require to ensure sealing. But if the mechanical issues are lowered, the material compatibility with high temperature and sodium become a tricky concern. First, the range of 200°C offers little operating margins for elastomer, for the few materials compatible with high temperature the maximal allowable working temperature seldom exceed 250°C. Secondly, most
elastomer materials are disqualified for sodium use due to the presence of Fluor or Halogen elements, two elements commonly present in most of the high temperature compatible materials. Thanks to their chemical composition and thermo mechanical properties, some silicone based material can be considered for the RHIB.

FIG. 2. Tests samples for mechanical characterization and sealing performance test

Many studies on sodium chemical compatibility with this type of elastomers have been conducted since the early sixties [5][6][7], and further tests were also performed later on during the PHENIX project[8]. All these experiments made on various types of silicone compounds, under a large span of constraints (temperature, geometries) demonstrate the compatibility of this type of materials for sodium use, with however some reservations regarding material aging. In the choice of a specific silicone, the quality and chemical composition (in particular the incorporated oxide rate) also appear to be important regarding the manner the material will behave in sodium.

FIG. 3. Test stand for sealing performance characterization by vacuum leak detection.
**Table 1. Mechanical characteristics of silicone C85MC6/60 under several test conditions.**

<table>
<thead>
<tr>
<th>Test conditions</th>
<th>Duration or CD(^a)</th>
<th>Hardness(^b)</th>
<th>Ultimate strength (MPa)</th>
<th>Tear strength (kN/mm)</th>
<th>RCD(^c)</th>
<th>Leak rate(^d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°C Air</td>
<td>30 days</td>
<td>59.1</td>
<td>9</td>
<td>43.3</td>
<td>1.7 \times 10^-5</td>
<td>3.5 \times 10^-5</td>
</tr>
<tr>
<td>200°C Air</td>
<td>30 days</td>
<td>60.3</td>
<td>7.9</td>
<td>37.1</td>
<td>12.5%</td>
<td>2.2 \times 10^-5</td>
</tr>
<tr>
<td>200°C Na</td>
<td>30 days</td>
<td>67</td>
<td>3.9</td>
<td>26.8</td>
<td>12.7%</td>
<td>9 \times 10^-4</td>
</tr>
<tr>
<td>11Gy/h</td>
<td>666Gy</td>
<td>60.6</td>
<td>7.4</td>
<td>38</td>
<td>10%</td>
<td>1.2 \times 10^-6</td>
</tr>
<tr>
<td>+ Na 200°C</td>
<td>15 days</td>
<td>65.6</td>
<td>4.8</td>
<td>25.3</td>
<td>9%</td>
<td>9.5 \times 10^-2</td>
</tr>
<tr>
<td>71Gy/h</td>
<td>6117Gy</td>
<td>64.5</td>
<td>8</td>
<td>35</td>
<td>12%</td>
<td>7.6 \times 10^-7</td>
</tr>
<tr>
<td>+ Na 200°C</td>
<td>15 days</td>
<td>64.8</td>
<td>4.9</td>
<td>27.4</td>
<td>10%</td>
<td>1 \times 10^-1</td>
</tr>
<tr>
<td>397Gy/h</td>
<td>662Gy</td>
<td>61.5</td>
<td>8.5</td>
<td>43.3</td>
<td>9%</td>
<td>9.8 \times 10^-8</td>
</tr>
</tbody>
</table>

\(^a\) Cumulative Dose in Gray.
\(^b\) Shore A Hardness scale.
\(^c\) Residual Compressive Deformation in percentage.
\(^d\) Mean leak rate express in (mbar.liter.s\(^{-1}\)) for a ΔP=0.1MPa at T=20°C (after 15 minutes) and 200°C (after 30 minutes).

Two different silicone based materials compatible with high temperature and with proper mechanical characteristics for sealing applications were selected. Test samples of different geometries (Fig.2) were produced to perform classical uniaxial traction tests, tearing strength and Residual Compressive Deformation (RCD) measurements. O-rings shaped samples were also made to validate by means of dedicated leak-tests (Fig.3) the sealing performances of the materials after aging.

Batches of samples were exposed to irradiation, with ambient gamma dose rate up to 400Gy/h and Cumulative Dose (CD) up to 10kGy. The samples were then immersed for 15 days in a sodium crucible maintained at 200°C. The other samples were exposed to radiation only, or aged in air at 200°C or in sodium at 200°C for duration ranging from 15 to 30 days. These different batches exposed to different conditions aim to verify the respective effects of environmental solicitations on the materials. Table I presents for all the different tests the results of the mechanical characterization and sealing performance tests performed on the most promising of the two silicone compounds tested.

The first observation that can be made from these tests is the relatively low influence of irradiation on the material (Table I); this point is to be confirmed with complementary tests at higher dose rate and CD. The effect of the sodium is however more significant and highly dependent on the silicone composition and test duration. The first compound featuring stronger degradation of its mechanical behavior (up to 30% higher than the one presented in Table I) had to be rejected. On the selected silicone, the degradation of the mechanical properties remains significant, but the losses (above 40%) do not jeopardize the use of material for sealing application. The hardening of the material and the surface degradation observed on the samples (Fig.4) are more bothersome as sealing is concerned.
FIG. 4. Samples of O-ring made of C85MC6/60 silicone (table I): (a) After 30 days at 20°C in air (b) after 30 days immersed in 200°C Na

After the aging and the mechanical characterization, the sealing performance was tested on the leak-test stand. A significant increase of the forces required to compress the seals was observed, in coherence with the previously observed hardening (link to bulk densification) and mass losses of the seals. And as expected, the degradation of the outer surface of the seal exposed to sodium, strongly affect the sealing performance (Table I). The surface cracks offering potential leak-paths all over the seal circumference.

The on-going program is now testing a new silicone compound developed for high temperature. Samples exposed to higher dose rate and CD will be tested, and some of the O-ring seals will be aged in sodium mounted between flanges. Indeed, it should be pointed out that the plain immersion of the sample in sodium strongly increase the surface exposed to chemical attack compared to a compression seal mounted in a groove in real assembly. The sealing-tracks created the seal compression between the two surfaces are kept sodium-free; therefore the formation of the leaking paths induced by the chemical attack will take longer in this configuration. Chemical analysis of the sodium and silicone after aging will also be performed to better understand the chemical reaction responsible of the silicone surface damages. The data collected from these analyses will be helpful to optimize the silicone composition or develop specific coatings for the seal outer surface.

3. Sealing system development and qualification

FIG. 5. Seal profiles: (a) double lip (b) simple lip with delta.

In parallel of the material selection and characterization, the mechanical design of the RHIB sealing system, a key component part of the ISI&R equipment, was studied. With rather low definition of the future systems to be embedded inside the RHIB, that can go from camera for inspection to complex repair tools, some hypothesis were taken to set around the design. A cylindrical geometry was chosen
with outer diameter not exceeding 350mm, with a minimal operating window (once docked on the vessel) for the ISL&R systems of Ø120mm. The maximal outer pressure was fixed at 3 bars, offering some margins in regards of the future operating conditions. Considering a seal of Ø350mm, the maximal planar default the seals shall accommodate is below 15mm, corresponding to a docking of the bell on a cylindrical surface of one meter radius. The design focused on the shape of the seal, trying to limit the required compressive forces needed to achieve a proper sealing. In collaboration with the CEA industrial partner Technetics Group France (a word leader in scaling technologies), several profiles of silicone seal were considered. A lip-shape concept (Fig.5) emerged among a large panel of designs. This type of shape allows a large contact surface and tolerates important geometrical defaults with only limited applied forces, thanks to the high flexibility of the lip.

![Diagram of MARIUS test facility](image)

**Fig. 6. MARIUS test facility. [A] Docking of the bell on the surface followed by a pressurization of the water tank [B] Draining of the bell leak test and visual survey.**

To qualify the sealing efficiencies of seal-profiles and measure the corresponding applied forces, a dedicated test-device (Fig.6) was built. Named MARIUS (acronym for Modular Assembly for Repair and Inspection Under Sodium), this test facility consists of an Electromechanical force driven press connected to a cylindrical bell immersed inside a pressurized water tank. The bottom of the bell is equipped with modular flanges on which seals can be mounted in a groove. In front of the seal, docking surfaces of various shapes (plane, concave or convex) can be installed. The principle of the test is to immerse the bell inside the water, and then the tank is pressurized to a given pressure. The water can be used to mimic sodium thanks to its rather similar hydraulics properties of concern regarding sealing, such as viscosity, density or silicone-wettability. Once the seal is docked on the surface, a pressure is applied on the bell with the press then the bell is drained of its water. Leak-test and visual survey of the inner part of the bell are made, while in the meantime, the force applied on the bell is decreased until a leak appears. Several prototypes of seal were made and tested on MARIUS. With the lip-seal profile (b) shown on Figure 5, the sealing was achieved with only 200N applied (seal Ø350nm). Thanks to the seal shape, the water pressure on the outer surface of the lip provides almost enough pressure to stick the seal on the surface. At 350N, the seal compression was sufficient to a watertight contact for the delta tip of the seal located behind the lip. With this double contact the sealing is improved and a better stability of the bell is ensured, especially on a surface with strong local defects. These results, demonstrating the efficiency of a silicone lip-seal to seal the front RHIIB face with less than 500N of applied force, are encouraging and promote solutions based on a silicone seal. Indeed, this 500N have to be compared with the estimated compression force of 10kN than can be transferred to the RHIIB by a robotic arm.
FIG. 7. Principle of the triple seals docking flange: [A] Flange approach [B] Docking of the silicone lip-seal, 1st compression [C] Flushing of Na from the middle of the RHIB followed by a draining by depressurization, 2nd compression of lip-seal and inner seal [D] The resulting suction effect lead to the compression of the metallic seal, the RIHB is maintained in depression with three sodium-thigh barriers.

In order to solve the issues raised by the aging tests and to cope with the degradation of the silicone immersed in sodium, an advanced concept is under consideration (Fig.7). The idea is to combine two silicone seals to form a closed volume which will be depressurized to generate a suction effect, providing extra-force to compress a metallic seal. Protected behind a metallic barrier, the silicone seals will be only exposed to un-drained sodium residues and therefore will be less exposed to chemical degradation. The metallic seal shall be carefully chosen to feature a low compressive stress, even though the suction effect can generate high forces proportional to the surface of the enclosed volume. The metallic and silicone seal-shapes also need to be designed to help the flushing of the sodium during the second compression phase. If the lip of the outer seal, despite a higher compression, is leaking, the sealed enclosed volume and therefore the suction effect will be maintained (and even increased) by the inner silicone seal and outer metallic seal. The extra-force generated by the suction will also be of some interest to release constraints on the RH system to counteract the torque and forces of repair tools (such as mechanical washing brush).

The next challenge of the RHIB is the design of the bell shutter required to seal the bell before its docking. The sealing system of the obturator must allow the bell opening flushing the residual sodium in front of the working window, and once the operation completed the bell closure and sealing before the undocking. If the sealing between the shutter and the RHIB flanges is not an issue, the flushing and draining of the sodium, trapped in front of the bell after the docking, remains a tricky problem to solve. Indeed, most ISIR tools will not accommodate a thick sodium film after docking, and sticking residues on the shutter or bell flanges may strongly impact the sealing efficiency.

FIG. 8. Conceptual RHIB shutter system
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Added to these functional constraints and the very restricted volume of the RHIB, the design of this system was conducted with the idea to conceive of a simple system with as few interfaces as possible. Indeed, the impact on the design of the future ISI&R systems (still to be defined) mounted on top of the RHIB have to be strictly limited. With the assumption of O120 circular working aperture and a bell outer diameter below 350mm, a conceptual design of an obturator with its subsystem was conceived. The chosen design consists of a robust mechanical system (Fig.7) based on simple mechanical cams transferring the movement of linear actuators (located on the side) to a rotatable shutter lid pressed against the bell closure flange. Pneumatic actuators were preferred to others mechanical or electrical systems. In this solution, inlet and outlet gas pipes are the only mechanical interfaces required, and they are used both for the actuation and the sodium flushing and draining. A flushing pipe with a non-return valve is connected to the center of the shutter flange, to allow an argon blow after docking. On the shutter flange a thick and smooth silicone sole (possibly hollow or inflatable) is mounted to limit the volume of sodium trapped between the seals. Another pipe located near the external lip-seal is used to drain the remains of sodium after flushing, and ensure the suction effect described above once the two elastomers are compressed. Further analysis and mechanical calculations are on-going to improve the system to the mature stage. The next step will be the development of a full scale prototype to be tested in the MARIUS facility.

4. Conclusions

Ensuring the dynamic and static sealing of a remotely handled system inside a nuclear vessel filled with sodium at 220°C is a real challenge. The choice of a proper sealing material is probably the hardest issue. Confident in the possibility that silicone base compound can be used providing a limited exposure of the seal to sodium (time and exposed surface), new compositions of silicone are under study. More severe aging under radiation and surface coatings are foreseen.

In this R&D program the study of preliminary concepts has been an opportunity to address several technical options and to compile a list of pertinent features for very specific mechanical system such as the RHIB. On the sealing system operating during the docking phase, an efficient seal profile has been designed and successfully tested. The concept of concentric seals used to drain the residual sodium, and attach the bell by suction to the surface is a promising and innovative idea. The proposed obturator associated with this sealing system form an integrated system fulfilling the requirement. The detailed definition of the system to be followed by its test in MARIUS is the next step of the program.

The integration of the obturator and sealing system with the embedded ISI&R tools will be another task on its own. The development of specific systems allowing for the inspection and repair of complex geometries will be from the sealing point of view a very challenging task. The RHIB concept presented in this paper is a rather universal concept that might be adapted depending on the reactor zone to inspect or repair.

ACKNOWLEDGEMENTS

The authors would like to thanks all the colleagues at CEA, Technetics group and EDF who provided us with fruitful information, guidance and technical insight. We would like to quote the work of the CEA Cadarache team of DTN/STPA/LIET which operates the sodium crucible facility PENEOPE for their availability.

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(2012).


