Main R&D Objectives and Results for Under-sodium Inspection Robots – Example of the ASTRID Strongback Exceptional Inspection Robot

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Abstract. In Service Inspection (ISI) of sodium cooled fast reactor prototype ASTRID implies a large R&D effort for tool .A specific articulated robot is being designed to allow exceptional ultrasonic examinations of under-sodium core support structure (strongback) at about 200°C.

This robot has to reach deep in the main sodium vessel and adapt to the many different weld positions of the strongback, while being simple and robust. Its design thus includes a hollow rigid mast inside which a specific chain can deploy its ultrasonic transducers head in most directions.

First the specific components needed for this robot have to be developed and tested for these severe “sodium” environment conditions: small electrical motor (reducers, sensors), bearings, elastomers for leaktightness…

A qualification program is starting involving tests to be performed with specific samples and prototypes, in air at 200°C, in water, then in sodium.

Key Words: ASTRID, In-service inspection and repair, under sodium robot, 200°C temperature.

1. Introduction

In Service Inspection (ISI) of sodium cooled fast reactor prototype ASTRID implies a large R&D effort for tool .A specific articulated robot is being designed to allow exceptional ultrasonic controls of under-sodium core support structure (strongback) at about 200°C.

In order to develop such an under-sodium inspection robot, several issues have to be addressed: overall architecture of the robot, design of “classical” system use under sodium, development and qualification of “specific” parts, or “bricks”, for use under sodium.

The most important ones are: the “200°C under-sodium” motor and its accessories (magnetic coupling, reducer), bearings and the “200°C sodium leaktight” seals. Other parts such as the ultrasonic transducers, the sodium resistant plugs are needed but won’t be detailed in this paper.

2. Objectives and overall architecture of the robot for exceptional ultrasonic controls of the under-sodium ASTRID strongback

2.1 Objectives

While ASTRID has recently completed the preliminary design phase and now enters the basic design phase, the ability to perform exceptional ultrasonic examinations of strategic areas of the under-sodium core support structure (strongback.

It could be considered possible to inspect the strongback supporting shell from outside of the primary vessel (avoiding liquid sodium), as it was performed during PHENIX safety upgrading on its conical core supporting shell [6], the other parts of ASTRID strongback seem unreachable for ultrasonic guided waves initiated outside the main vessel.

This generated the need to study a specific under sodium inspection robot to access the strongback from its top periphery to the underside of the inferior baseplate.

Moreover the robot has to adapt to the many different weld positions of the strongback (see targeted extent in *FIG.* 1) and the limited access point through the primary circuit roofslab: only three access points (see green line in *FIG.* 1) to control straight horizontal welds of the inferior baseplate (see orange lines in *FIG.* 1) but also non-linear welds of the external stiffeners (see purple lines in *FIG.* 1).

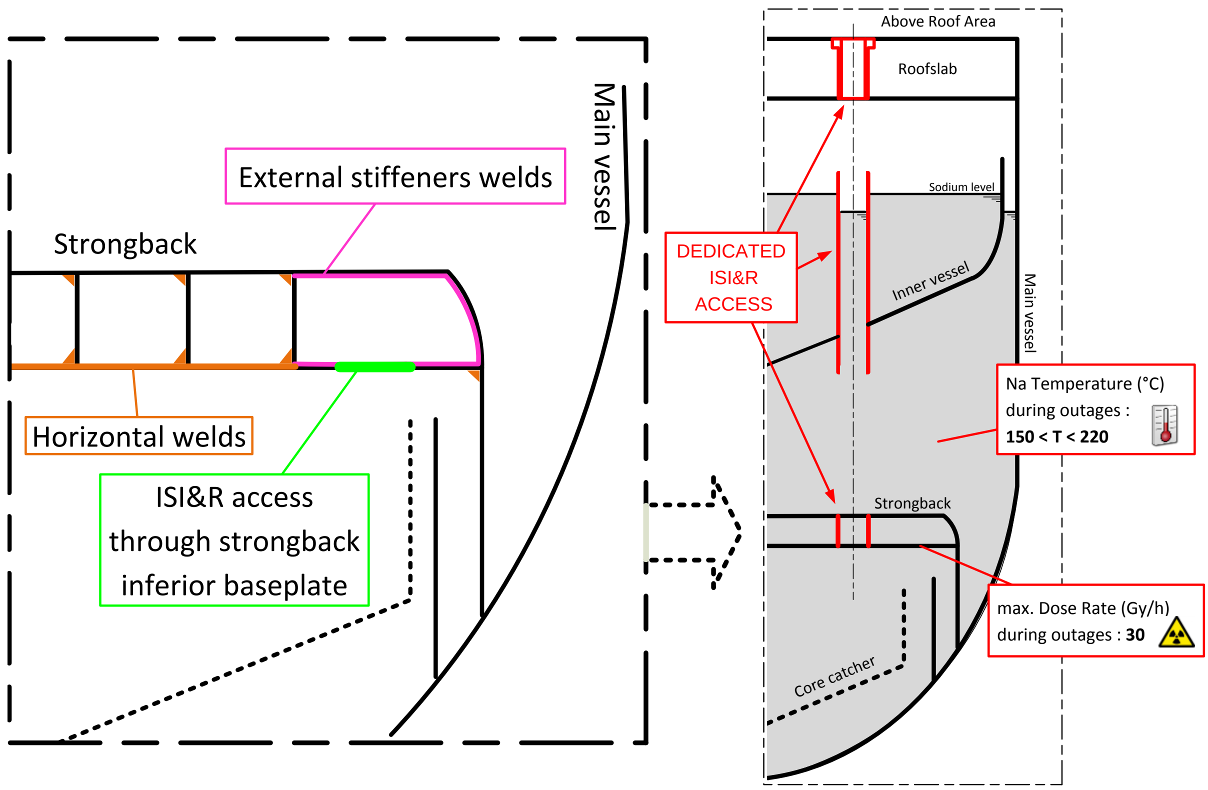

FIG. 1 : Strongback extent of inspectable areas (left), and access to strongback (right)

And the robot has to be simple and robust for manufacturing, operating and reliability reasons.

2.2 Overall architecture and its main challenges

Considering the requirements and constraints described previously, the robot overall architecture has been selected as follows:

- a slab adaptor integrated leaktightness and supporting solution,
- a main hollow mast can rotate around its central axis in the slab, of about 20 meters height,

- an internal box inside the main mast can translate vertically,
- an articulated elbow at the bottom of the internal box can orientate the unfurling of the chain,
- a chain in the box, that can deploy its multiaxis-ultrasonic-transducers-head up to 5 meters.

FIG. 2 and FIG. 3 illustrate the robot and its different articulations. FIG. 2 presents the deployment capacities of the robot to reach the target points mentioned in §2.1. FIG. 3 illustrates the entire preliminary design of the robot.

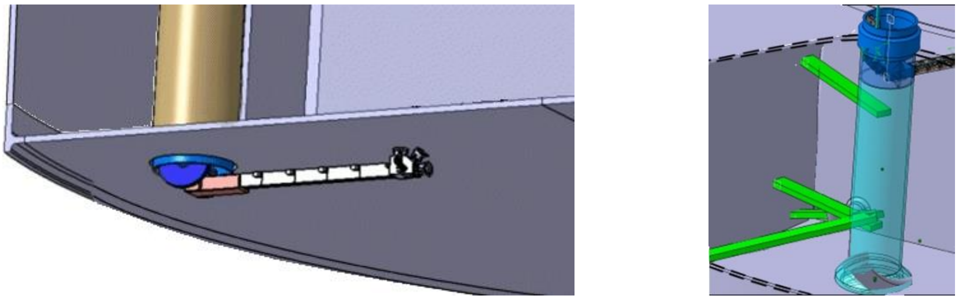

FIG. 2 : Position of the target points (potential inspection)

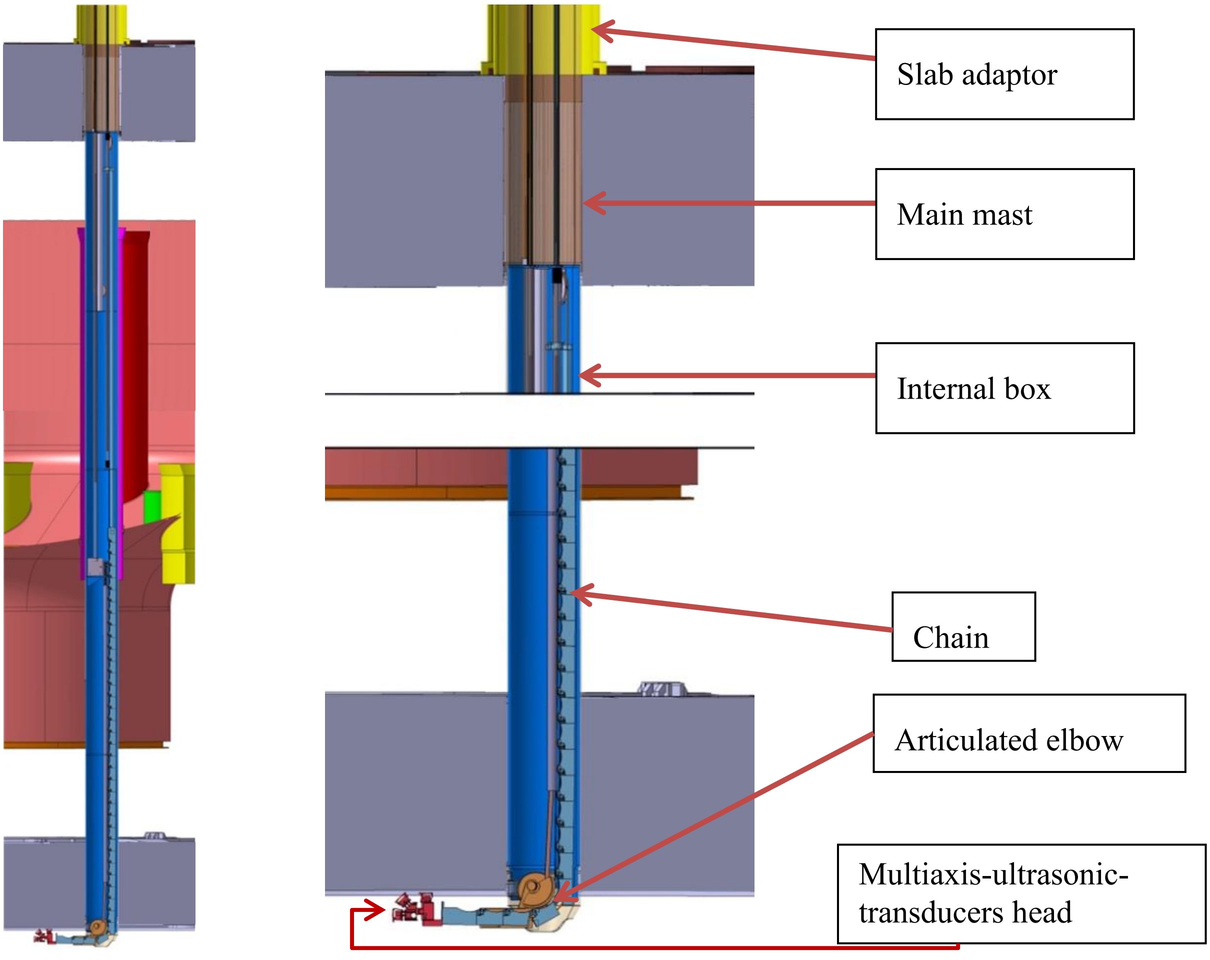

FIG. 3 : First preliminary design of inspection robot

From this design, we can see the parts of the robot will have to be developed and then qualified in realistic conditions: the main technological ’’bricks”, discussed hereafter.

3. In progress R&D studies on technological bricks for under-sodium inspection robot

To develop all the required equipment, tools and ultrasonic transducers (*i.e.* the main technological bricks), some of the activities should be performed in parallel as presented in FIG. 4:

- the Non-Destructive Testing methodology development (NDT method),
- the robot development including each sub-part / technological brick development,
- the integration of the NDT method on the robot,

and later on the industrialization.

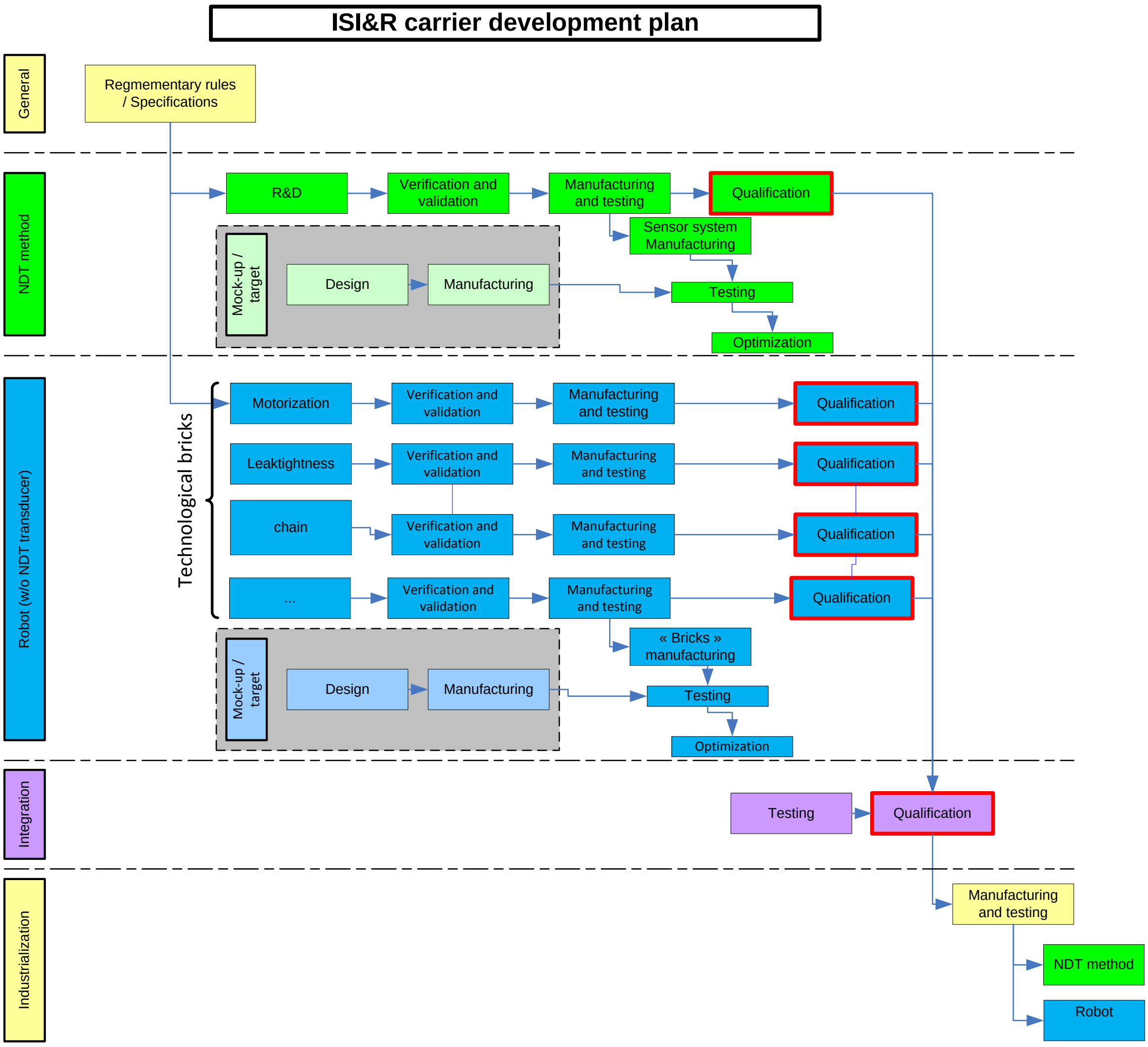

FIG. 4 : Logic diagram of robot and sub-parts / bricks development

The development of the main sub-parts / technological bricks of the robot, is under progress for the following components, and described hereafter:

- the ultrasonic transducers,
- the motorization,
- the sodium resistant seals,
- the chain,

- other bricks such as the sodium resistant plugs, girdles for cables, electronic cards are needed too but won't be detailed in this paper.

3.1 Ultrasonic transducers for NDT (defect detection)

Ultrasonic transducers are an important technological brick for the inspection robot. The R&D progress on under-sodium ultrasonic transducers is described in [1], shown in FIG. 5.

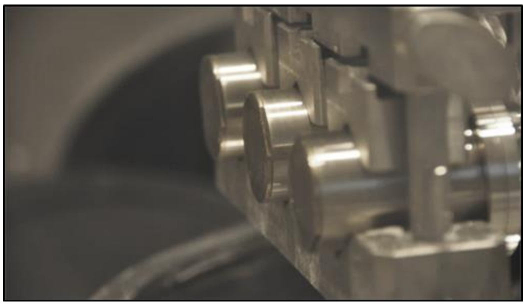

FIG. 5 : Ultrasonic transducers being developed for under-sodium NDT (TUCSS)

3.2 "200°C under sodium" motor and its accessories (reducer, magnetic coupling, bearings)

3.2.1 Motor

For the ASTRID under sodium robotic requirements, CEA develops a « brushless » type prototype motor (see FIG. 6, and [9]), having a 180 W power at room temperature (20°C) and aiming at delivering some power at 200°C. This implies that the electrical coil can withstand at least 200°C temperature. Indeed, the CEA high temperature motor principle is as follows: the temperature difference between the hot source (coil) and the cold source (sodium at 200°C) makes it possible to produce the mechanical power which is proportional to the electrical current in the coil.

Thus, the motor components have been selected in order to ensure a permanent loading at 200°C, with also a ≈100 Gy cumulated radioactive dose specification.

Thermal simulation indicates that the coil temperature will be 260°C. Corresponding copper wire insulation will be made with ceramic based material. Bearings are made of stabilized steel at 250°C. Associated grease, adhesives and resins, and resolver can withstand high temperature.

FIG. 6 : CEA/LIST High Temperature Motor: prototype and thermal simulation

Main components of the high-temperature prototype are:

- coils: insulated copper wire with ceramic coating. Temperature: 400°C, irradiation > 10^6Gy;

- magnets: samarium-cobalt Sm_2Co_{17}. Temperature > 260°C, irradiation >10^6Gy;
- bearings: stiff rollers with high-temperature ball bearings made from steel stabilized at more than 250°C. Operating temperature of 250°C. Grease withstanding 250°C, and 10^4Gy irradiation;

Fatigue test has been successfully performed in an oven at 200°C during 1000 hours. The motor loading was:

- average speed: 1500 revolutions/minute with also some cycles from 0 to 3000 revolutions/minute,
- average torque: 0.08 mN, with some cycles from 0 to 0.11 mN,
- coil temperature remained less than 260°C,
- at 200°C, the delivered power is equal to 60% of the power at 20°C.

3.2.2 Rotating actuator at 200°C (magnetic coupling, resolver)

A rotating actuator has been designed for 200°C under sodium operation, without any cooling (see also [9]). For safety reasons, tightness is performed with static flanges (no lip-type sealing). Two main zones can be distinguished as regards to the environmental constraints (FIG. 7):

- zone 1: components which cannot operate in liquid sodium are placed in leaktight vessels: coders, sensors, electronic cards, electric wires, and also all (or some) robotic activators (electric motors, most reducers and some transmissions). This zone can be cooled;
- zone 2: robotic structures and ISI&R tools which interact with internal structures in the ASTRID main vessel can be immersed in liquid sodium.

Besides thermal and irradiation constraints, the technological complexity results from the force and torque transmission through leaktight vessel walls without using any dynamic sealing with sliding or turning joints.

Zone 1, with adapted cooling for a maximum temperature of 70°C, corresponds to a well-known situation for robotic mechanical components (see MIR robot experience in Superphenix Plant [7]).

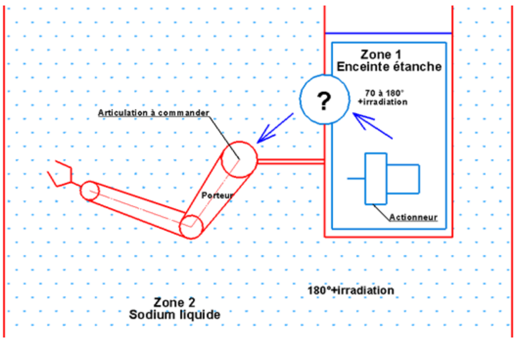

FIG. 7 : Two types of zones with different environmental constraints

Rotation axis is actuated by a harmonic drive geared motor (see §3.2.1) in the leaktight vessel with only static tightness sealing (zone 1). Torque transmission is performed with no contact, thanks to magnetic coupling.

Components of this actuator are made of standard components which have been modified in order to make them compatible with 200°C temperature and also irradiation. Only the resolver had to be specifically developed to withstand ASTRID temperature conditions.

A specific test device has been designed for in sodium testing: two bearings are immerged in liquid sodium. They correspond to articulated bearings for the robot axis. The rotation speed is very low (in the range 10 to 15 revolutions per minute).

Rotating actuator characteristics are:

- nominal speed = 12.5 revolutions/minute
- nominal torque = 12.5 to 23 mN (pull-out torque for magnetic coupling is about 25 mN).

Loading test of a prototype (FIG. 8, left) has been successfully performed in an oven at 200°C during 200 hours.

3.2.3 Bearings

Bearings qualification for ASTRID robotic devices is split two ways, corresponding to the above mentioned two zone requirements:

- zone 1: tight vessel with no sodium for motor and reductor. Bearings speed is high (1 500 revolutions/minute) as they can be used with high temperature grease;
- zone 2: robot segment articulations are immerged in liquid sodium. Bearings speed is low (12.5 revolutions/minute), and no grease is used.

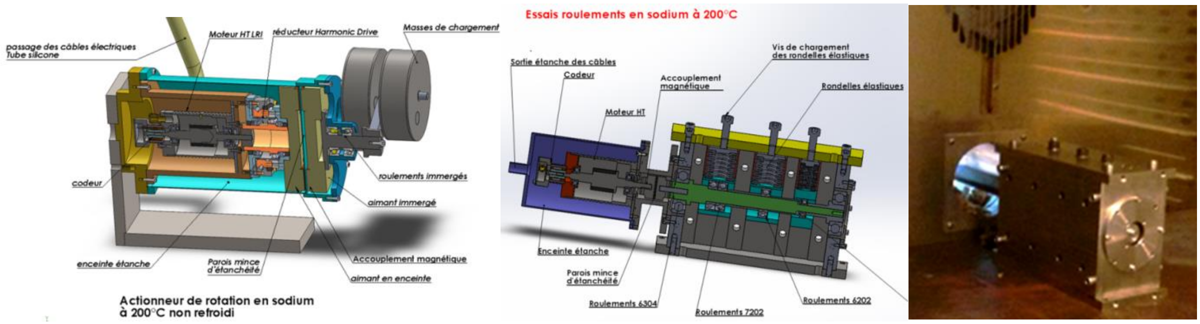

FIG. 8 : Rotating Actuator testing device (left) and in air test bench for bearings (center, right)

Loading tests of a prototype (FIG. 8, center and right) have been successfully performed in air in an oven at 200°C: rotation speed was 1500 revolutions/minute, radial loading on the bearings corresponded to 1/8th of static loading of same size standard bearings (safety coefficient So = 8) and high temperature grease was used.

For under sodium components (zone 2), tests have been successfully performed in air in an oven at 200°C during 250 hours, with no lubricant and under radial loading on the bearings corresponding to 1/8th of static loading. They will be continued with under sodium testing in 2017.

3.3 "200°C sodium leaktight" seals [8]

For under-sodium inspection leaktightening purposes, metallic gaskets and silicone elastomer seals have been considered following a selection process that took into account the application specification (including the constraints: sodium, 200°C, low pressure, short duration…), and the different available sealing technologies.

Many studies on sodium chemical compatibility with this type of elastomers have been conducted since the early sixties [3][4][5][6], and have demonstrated the compatibility of this type of materials for sodium use, with however some reserves regarding the material aging.

Two different silicone based materials compatible with high temperature and with proper mechanical characteristics for sealing applications were selected. Classic mechanical characterization tests were performed, as well as dedicated leaktightness tests, on the materials after aging.

Moreover, irradiation resistance tests were conducted: samples were irradiated (ambient gamma dose rate up to 400Gy/h and cumulative dose up to 10kGy) and then immersed for 15 days in a sodium crucible maintained at 200°C, while 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.

Results show a relatively low influence of irradiation on the material (to be confirmed with complementary tests at higher dose rate and cumulative dose). The effect of the sodium is however more significant and highly dependent on the silicone composition and test duration. One of the two silicone compound had then to be rejected. While still mechanically suitable for leaktightness, the hardening of the material and the surface degradation observed on the samples (FIG. 9) are more bothersome as sealing is concerned.

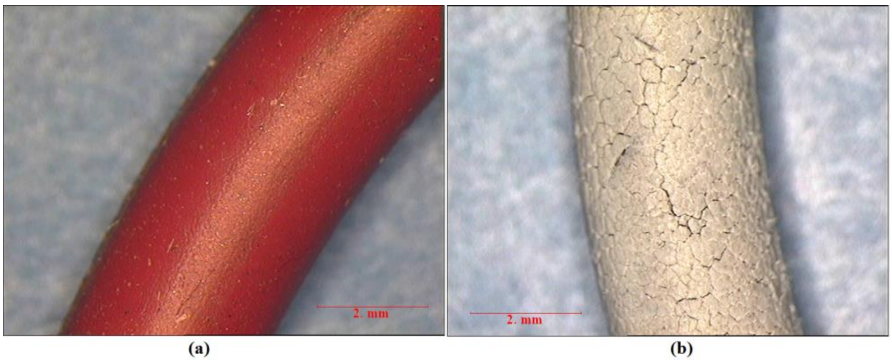

FIG. 9 : Samples of O-ring made of C85MC6-60 silicone: (a) after 30 days at 20°C in air, (b) after 30 days immersed in 200°C Na

Indeed, the degradation of the outer surface of the seal exposed to sodium, strongly affect the sealing performance. 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 cumulative dose 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 compress seal mounted in groove in real assembly. The sealing-tracks created by 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.

3.4 Chain

The main mechanical challenge of this robot, is to manage to reach the middle of the strongback inferior baseplate (horizontally 5 m far from the most distant target), through a vertical slab hole. We needed to transform a vertical motion, into a horizontal motion. This is performed by an articulated chain, illustrated in FIG. 10 (left), which is pushed/deployed by a vertical jack (mechanical motion).

This principle has already been used during inspections in a gaseous environment, and partially tested under sodium conditions [7] for other nuclear applications in previous reactors (cf. FIG. 10, right).

In our case, the development and qualification of the chain will be implemented through mechanical simulation, specific prototype manufacturing and specific test campaigns in order to verify all the main parameters specific to the chain of this robot. Especially, the accuracy of the deployment of the chain under the inferior baseplate will have to be verified.

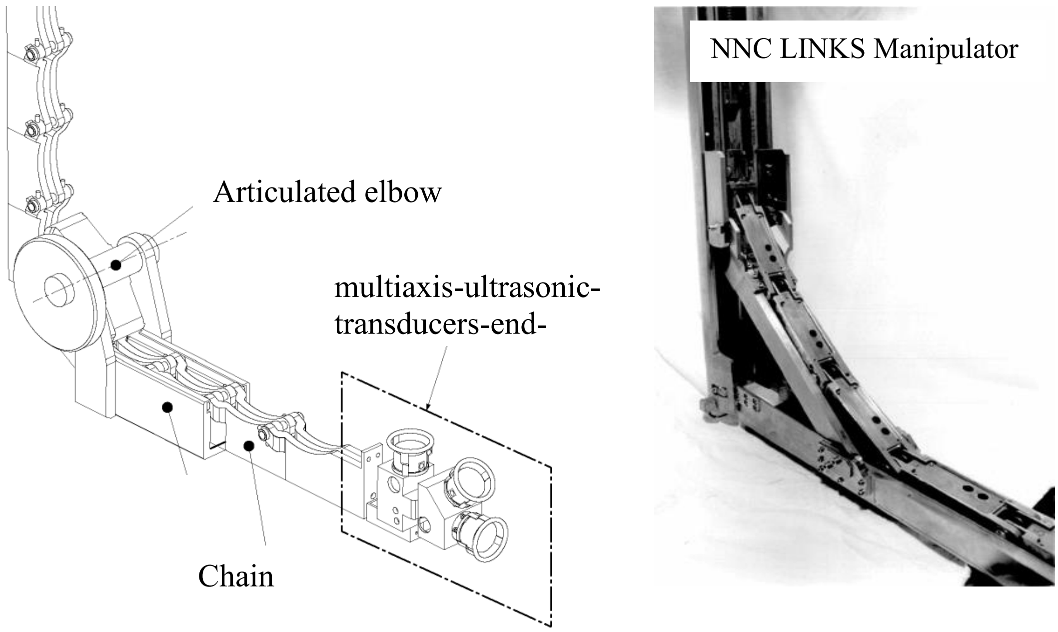

FIG. 10 : Preliminary concept drawing of the chain (left) and LINKS manipulator (NNC) previous example of the use of a chain for under sodium inspection (right) [7]

4. Qualification perspectives

As described in §3, each brick needs to be qualified independently. Afterward, it will be necessary to test and qualify larger assemblies of bricks together, up to the complete robot. After the qualification of the bricks, articulations connecting bricks together will have to be qualified, up to the complete lower part as schematically illustrated in FIG. 11 (left). Test equipment will be necessary at a full scale, such as hot oil/water immersion tank (see FIG. 11, left) or sodium pot if necessary (cf. [10]), or a complete deployment stand with a partial full scale mockup of the strongback (see FIG. 11, right).

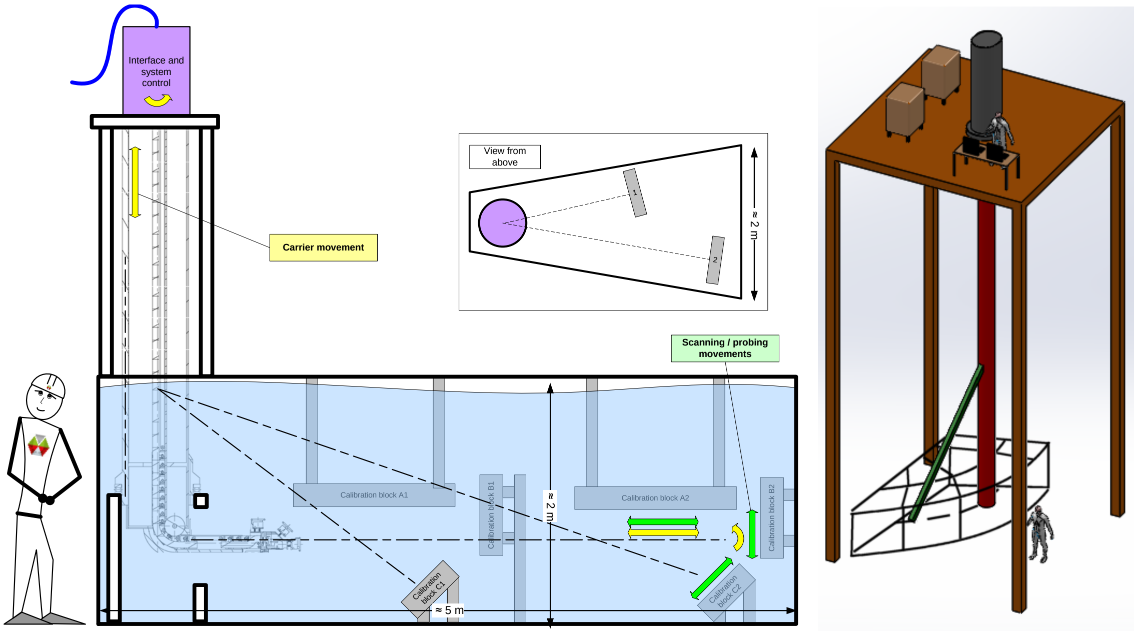

FIG. 11 : Sketch of the immersion test for the lowest part of the inspection robot (left), and of the full scale strongback mockup for final qualification (right)

5. Acknowledgments

The authors wish to thank all the teams involved in the design and R&D of ASTRID ISI&R equipment at CEA, AREVA and EDF.

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