

**JHR Project. Irradiation Devices.
In-Service Inspection of Nuclear Pressure Equipment's.
Investigation of Non Destructive Examinations
for inspection purposes.**

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Abstract :

The Jules Horowitz Reactor currently being built at the Cadarache center in the south of FRANCE will be a modern Material Testing Reactor (MTR) designed to perform irradiation experiments while complying with today's safety, quality and regulatory requirements. The JHR Reactor will be used to irradiate fuels and materials samples under experimental conditions representative of current and future nuclear power plants. The facility will also be used to irradiate fuel targets (Mo99) for medical purposes.

The experimental irradiation loops to be installed in the reactor will generally comprise an in-pile section (device, underwater lines, pool penetrations) and an out-of-pile section (hydraulic cooling system, auxiliary systems, vessel, power distribution system, instrumentation & control command). These loops or experimental devices will operate under thermal hydraulic conditions that are representative of the reactor technology being studied (LWR, Gen IV). This implies operating the loop components under specific pressure and temperature conditions (155b, 320°C for PWR).

The use of nuclear pressure equipment's necessarily entails a number of periodic inspections. These inspections often required the prior disassembly of compartments forming this equipment so as to gain access to the different internal and external surfaces to be inspected.

Within the scope of irradiation devices designed for the Jules Horowitz Reactor (JHR) comprising both internal and external irradiated compartments separated by a thin gap filled with gas (5/10 mm), their periodic disassembly and reassembly in hot cells for soundness checks will be a complex operation.

To overcome such problems, the possibility of using non-destructive examination (NDE) techniques are investigated to obtain the data needed to appraise the soundness of such equipment and thus meet the inspection requirements laid out in the regulations.

Key Words: JHR, Irradiation devices, nuclear pressure equipment, In-service inspection, Non-destructive tests.

1. INTRODUCTION:

The Jules Horowitz Reactor currently being built at the Cadarache centre in the south of France will be a modern material testing reactor (MTR) designed to perform irradiation experiments while complying with today's safety, quality and regulatory requirements. This multipurpose reactor will be used to irradiate fuels and materials samples under experimental conditions representative of current and future nuclear power plants. The facility will also be used to irradiate fuel targets (Mo99) for medical purposes.



*FIG.1 : View of the Jules Horowitz Reactor
(CADARACHE, FRANCE, 04-2016)*



FIG.2 : View of the reactor pool

The experimental irradiation loops to be installed in the reactor will generally comprise an in-pile section (device, underwater lines, pool penetrations) and an out-of-pile section (hydraulic cooling system, auxiliary systems, vessel, power distribution system, instrumentation & control command). The loops or experimental devices will operate under thermal hydraulic conditions that are representative of the reactor technology being studied (LWR, Gen IV). This implies operating the loop components under specific pressure and temperature conditions. Some components have to comply with the nuclear pressure equipment regulations and will therefore have to be inspected during their operation (periodic inspection and requalification).

2. REVIEW OF THE REGULATION GOVERNING NUCLEAR PRESSURE EQUIPMENTS

Nuclear pressure equipment's are governed by specific regulations, i.e. the European Pressure Equipment Directive (PED) which has been transposed into French law¹ Nuclear Pressure Equipment is also subject to requirements governing the level of activity inside in the containers².

¹ Decree No. 99-1046 dated 13/12/1999, the Order dated 21/12/1999 (pressure equipment classification and conformity assessment) and the Order dated 15/03/2000 (implementation of pressure equipment).

² French Nuclear Pressure Equipment Order dated 12/12/2005

These regulations cover the potential risks involved in using such pressure equipment and the consequences in the event of their failure (related to the pressure x volume energy contained, the chemical nature of the fluid and its radiological activity).

The maximum operating pressure (OP) of 0.5 bar is the threshold which determines whether the pressure equipment regulations apply or not.

The nuclear pressure equipment category (I to IV) is defined with respect to the

- i) type of equipment (container, pipe),
- ii) type of fluid and its group,
- iii) Pressure and volume of each compartment comprising the equipment.

Nuclear pressure equipment is designed and built by the Manufacturer under its responsibility. The Manufacturer is required to comply with the essential safety and radiation protection requirements stipulated in the regulations, while the conformity assessments of nuclear pressure equipment must be performed by a qualified third party approved by the French Nuclear Safety Authority (ASN), i.e. an agreed notified body (ANB). Once in service, this equipment must be monitored and maintained by the operator, inspected by the ASN, and undergo periodic technical checks by an ASN-approved body.

The Nuclear Pressure Equipment Order also classifies the equipment according to the activity (Bq) it contains:

Nuclear pressure equipment classification by level	Impact in the case of equipment failure
Outside nuclear pressure equipment	Activity released in the case of failure ≤ 370 MBq
N3	Not classified N1 or N2. Activity released in the case of failure ranging between 370 MBq and 370 GBq
N2	Not classified N1. Activity released in the case of failure exceeding 370 GBq
N1	Impact of a failure rendering it impossible to return the equipment to a safe state (according safety report requirements).

TABLE 1: Classification of nuclear pressure equipment by level

The nuclear pressure equipment regulations require, depending on the equipment classification (category, level), the implementation of specific operations and inspections not only during their commissioning phase but also during their operation (periodic inspection and requalification).

Nuclear pressure equipment category	Documentation required for equipment in service	Start-up inspection	Periodic inspection (max. 40 months)	Requalification (max. 10 years)
Reference to the order §	Article 13	Article 6	Article 5	Article 6
Cat 0	N1			
Cat. I	N1	N1	N1	N1
Cat. II	N1, N2, N3	N1	N1, N2, N3	N1, N2, N3
Cat. III	N1, N2, N3	N1	N1, N2, N3	N1, N2, N3
Cat. IV	N1, N2, N3	N1, N2	N1, N2, N3	N1, N2, N3

TABLE 2: Nuclear pressure equipment regulatory requirements per category

The table below lists the documentation and inspection requirements associated with nuclear pressure equipment according to the state of said equipment (start-up, in service, periodic inspection or requalification):

ITEM	REFERENCE	DESCRIPTION	CORRESPONDING INSPECTION
Equipment in service	Article 13	Descriptive file Operating manual Manufacturer's file Programme of maintenance & monitoring operations	Not applicable
Start-up inspection	Article 6	Programme of maintenance & monitoring operations + Declaration of conformity + Conformity with operating rules + Operation of safety devices + Compliance with radiation protection rules	Checked by an independent person approved by an agreed notified body (ANB)
Periodic inspection (max. 40 months)	Article 5	Internal and external inspection + Operation of safety devices	Carried out by a qualified person under the responsibility of the Operator
Periodic requalification (max. 10 years)	Article 6	Internal and external inspection + Operation of safety devices + Pressure resistance test (1.2 x operating pressure or RCC-MRX pressure)	Validated by an independent person Approved by an agreed notified body

TABLE 3: Nuclear Pressure Equipment regulatory requirements

3. APPLICATION TO JHR IRRADIATION DEVICES

In application of the French ESPN Order, the use of nuclear pressure equipment on an experimental loop (e.g. N2/ Cat IV irradiation devices) requires the implementation of maintenance & monitoring programme which is to be defined by the Operator. This programme must include periodic inspections designed to check the soundness of this equipment and to meet the regulatory requirements.

Note: for N2 and N3 nuclear pressure equipment in Category II or higher (see Table 2), the objective of this maintenance & monitoring programme is to maintain the equipment's safety at the level required by design. For N1 equipment, the objective of this programme is to avoid any defects and deterioration capable of leading to the equipment's failure.

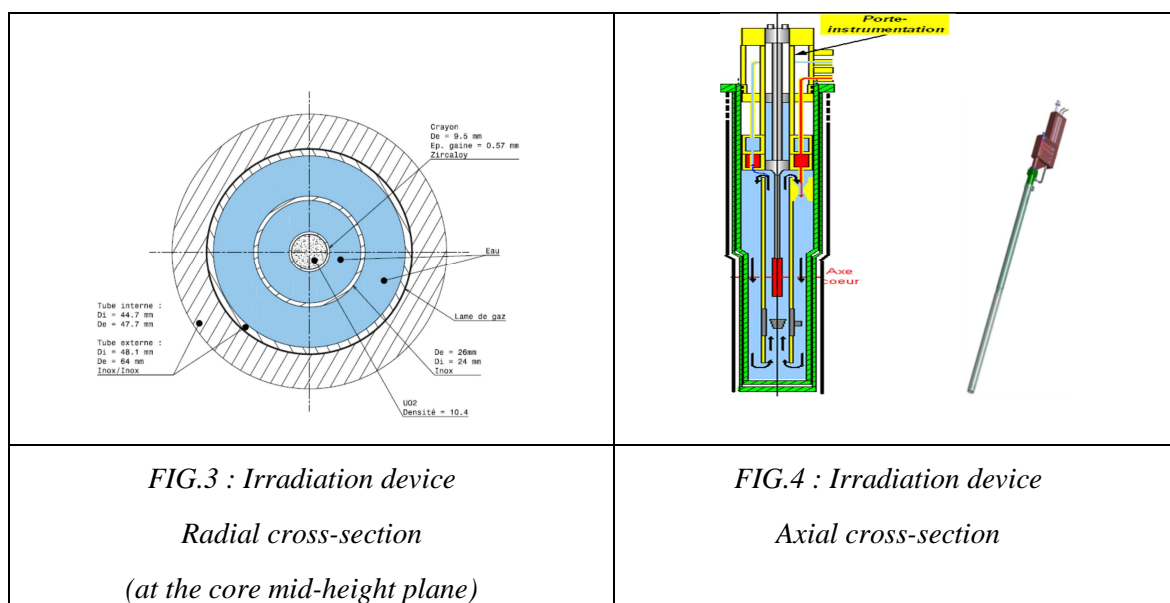
When implementing new experimental loops in the JHR which are governed by these requirements, periodic inspections must be taken into account from the design phase so as to optimise the subsequent inspection phases (configuration, maintenance times) and to limit the unavailability of the experimental loop designed for commercial purposes.

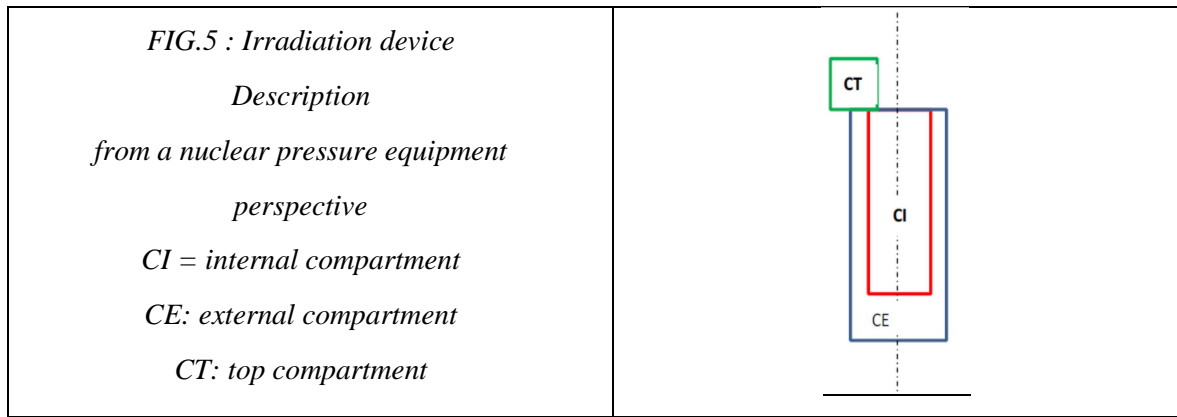
3.1 TYPES OF EQUIPMENT TO INSPECT AND RELATED CHARACTERISTICS

Different types of equipment will need to be checked periodically.

3.1.1 Irradiation device

The irradiation device can generally be described as a container composed of two concentric metal compartments (CI and CE) several millimetres thick, separated by a layer of gas (nitrogen, argon or helium) which provides a thermal barrier (depending on the test requirements) and the online monitoring of the first compartment (safety role). The upper part of the internal compartment (CI) is generally closed by a top compartment (CT) which is used to hold the sample opposite the core by means of an extension, as well as to ensure the withdrawal of instrumentation into the I&C cabinets via leaktight channels.





3.1.2 Other equipment’s of the irradiation loop

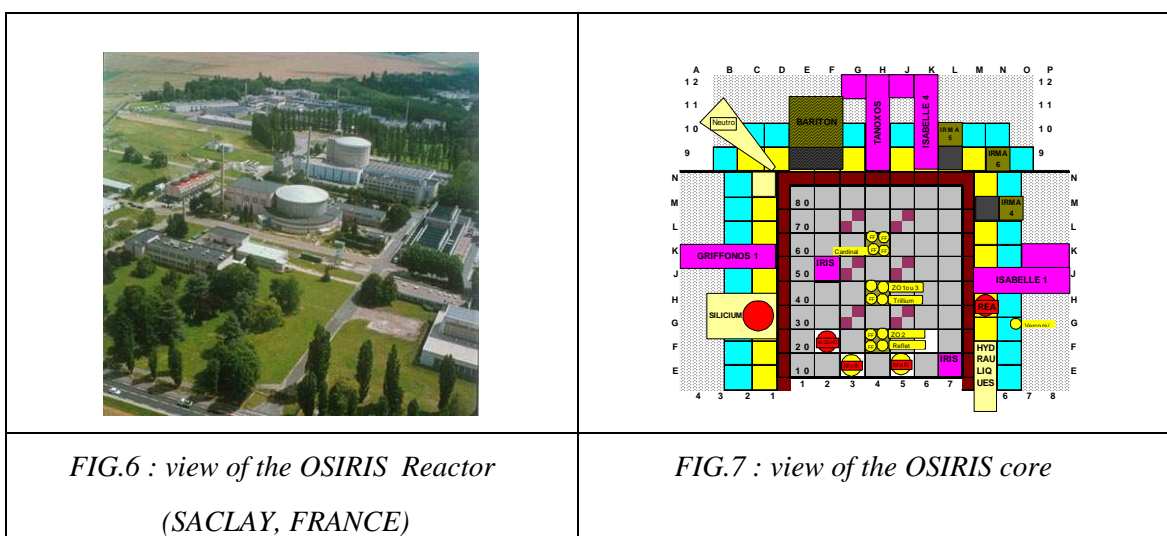
The other parts of the irradiation loop which include, among others, assorted systems (containers, compartments) and nuclear pressure equipment lines are not covered in this report. The periodic inspections required by the regulations for such equipment will entail more standard non-destructive tests (visual checks, ultrasonic inspections, etc.).

3.2 INTEGRATING OSIRIS REACTOR FEEDBACK

3.2.1 Introduction:

The OSIRIS reactor located on the SACLAY site was a 70 MWth pool-type irradiation reactor (shutdown in dec.15). It was used to irradiate fuels and materials, in addition to producing radioelements for medical purposes. The ISABELLE experimental loop and the GRIFFONOS capsule used in OSIRIS both comprise pressure equipment subject to the 1926/1943 Decree, without any regulatory requirements with respect to in-service monitoring.

Since the application of the ESPN order in 2005, some pressure equipment has been reclassified as nuclear pressure equipment and now liable for in-service monitoring. For such nuclear pressure equipment, the presence of internal inspection means or alternative solutions were not a regulatory requirement.



3.2.2 Risk analysis:

To comply with the regulations, each relevant item of equipment must be the subject of a report specifying the risks of failure, the related potential consequences and the preventive measures for limiting risks. The analysis must particularly take into account the following risks:

- **Risk of Equipment Cracking Due To Vibration Fatigue :**

Prevention of this risk is based on building the equipment in compliance with the appropriate construction code (RCC-M, RCC-MX), as well as on performing periodic inspections to check the good working order of the equipment in service.

- **Risk of Faulty Temperature And Pressure Sensors :**

Prevention of this risk is based on checking the good working order of the sensors by means of periodic tests.

- **Risk of Contamination And Irradiation During Inspection And Maintenance :**

Faced with these risks and in compliance with the ALARA principle, all measures making it possible to minimise the received dose should be implemented, in particular by maintaining biological shielding between the irradiating parts of the equipment and workers.

3.2.3 Maintenance & monitoring programme

The file supporting each item of equipment specifies the following information:

- History of use,
- Commissioning,
- Periodic inspections,
- Requalification,
- Incidents,
- Repairs and modifications.

This maintenance & monitoring programme lists the main characteristics of the equipment and all actions required to ensure the integrity of the pressure equipment.

The periodic inspection procedure is described in this document. The purpose is to check the thickness of the materials to make sure there is no damage due to erosion and corrosion, as well as to make sure there are no cracks in the visible parts of the equipment once the accessible parts have been removed.

Considering the geometric characteristics of the equipment, the annular volume of the equipment is not accessible for visual examination of the outer surfaces of the internal compartment and the inner surfaces of the external compartment. These two surfaces are separated by a gap of about 0.5 mm only (case of the ISABELLE device). As this equipment is also used under a neutron flux produced by the OSIRIS reactor core, it is very irradiating. This greatly reduces the possibility of being able to implement specific inspections.

3.2.4 Inspection of the equipment prior to its operation (ISA-1 feedback)

These inspections are performed before commissioning the equipment.

Among others, the following prior checks are required:

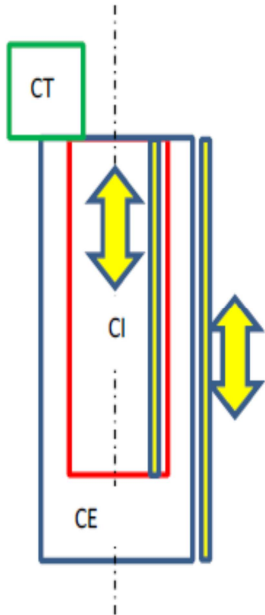
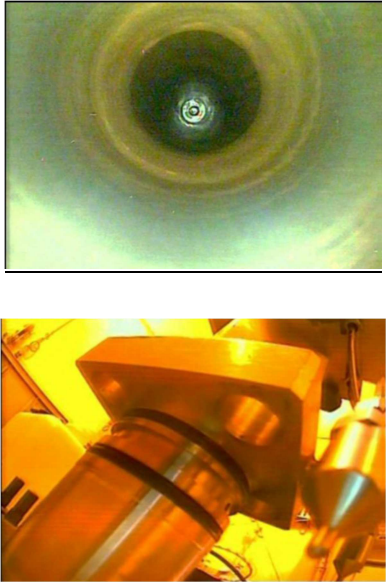
- Leak tight test for the internal compartment in water at 150 bar and ambient temperature,
- Leak tight test for the external compartment in nitrogen at 5 bar and ambient temperature,
- Verification of the pressure sensors and thermocouples,
- Verification of the set pressure (opening and closing pressure) for the safety accessories (relief valves).

3.2.5 Periodic inspection of equipment (pressure tube, container)

Prior to the inspection, the equipment must be prepared for the operation for which it has been designed, e.g. drainage of the device, insulation of a container, stripping and disassembly of all removable parts. The safety accessories must be checked beforehand. The checks are performed on the basis of an inspection standard, e.g. RCC-MX.

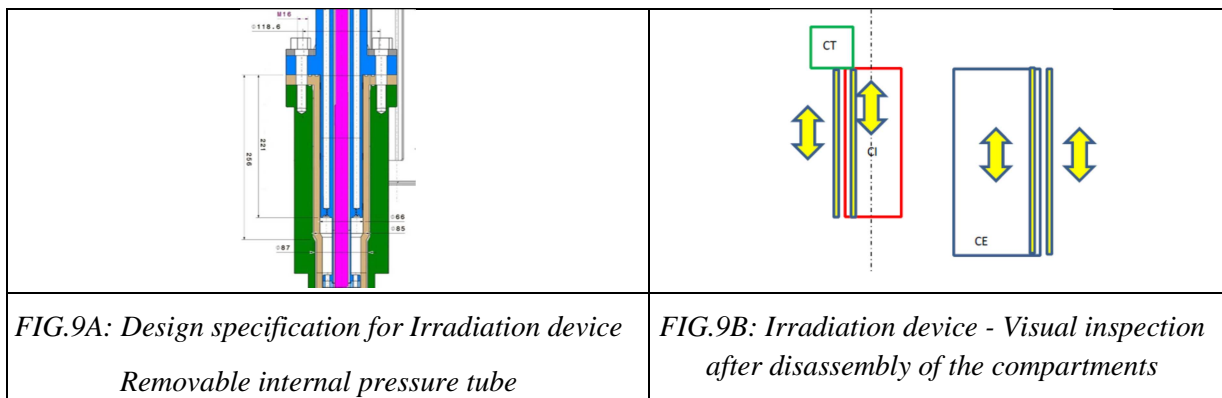
The inspections are performed by a qualified inspector, e.g. COFREND or equivalent.

The inspections concern all visible parts once all the preparatory operations have been carried out on the equipment. Remote visual inspection of internals and externals are performed for each compartment, as defined in the maintenance & monitoring programme.

<p><i>FIG.8: Irradiation device</i></p> <p><i>Visual inspection of the equipment (principle)</i></p> <p><i>N2, category IV</i></p> <p><i>newly subjected to ESPN order</i></p> <p><i>Multi-compartment container (CI-CE-CT)</i></p> <p><i>Pressure tube: Zircaloy</i></p> <p><i>RCCM-N2</i></p>		 <p>Type of inspection: visual in a hot cell</p>
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3.3 INCORPORATING PERIODIC INSPECTIONS INTO EQUIPMENT DESIGN

To meet the regulations requiring the periodic inspection of nuclear pressure equipment, a number of constructive measures have been implemented. Concerning the Adeline irradiation device currently in its design phase, the construction of a removable pressure tube would theoretically make it possible to extract the internal tube and to carry out visual examinations during such periodic inspections.



The difficulties that have so far been identified are listed below:

- operations to be performed on irradiating equipment in hot cell,
- operations requiring the remote disassembly and reassembly of the internal tube (with very little space between the two structures),
- removal and re-introduction after irradiation of the internal tube with respect to the external tube may prove to be difficult or impossible considering the probable deformation of both tubes under flux.

To remedy this difficulty of removing and re-installing the internal tube during periodic inspections in a hot cell, the following scenarios have been devised. These scenarios involve the implementation of non-destructive tests.

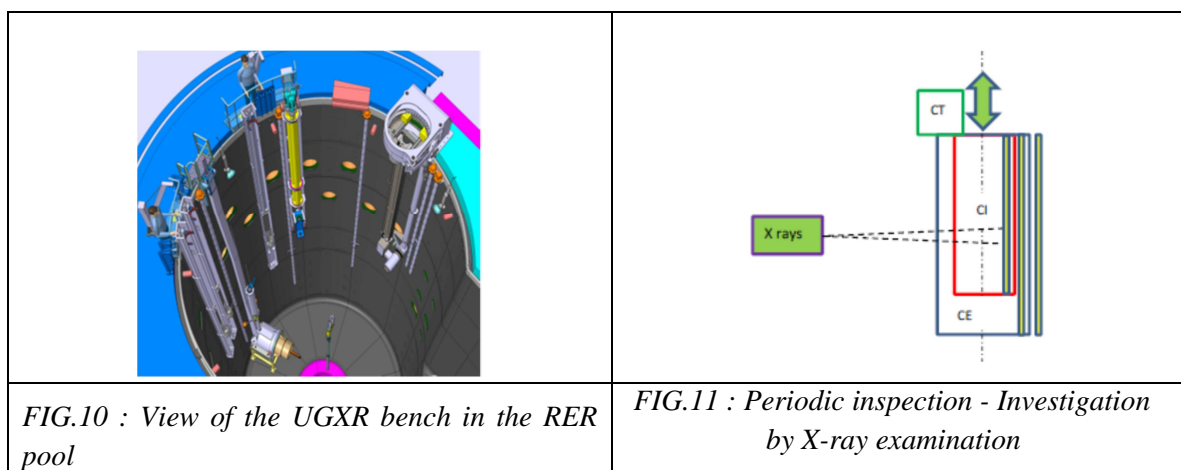
4. INVESTIGATION OF NON-DESTRUCTIVE TESTS IN THE JHR FACILITY FOR PERIODIC INSPECTIONS OF EXPERIMENTAL EQUIPMENT

4.1 X-RAY INSPECTIONS

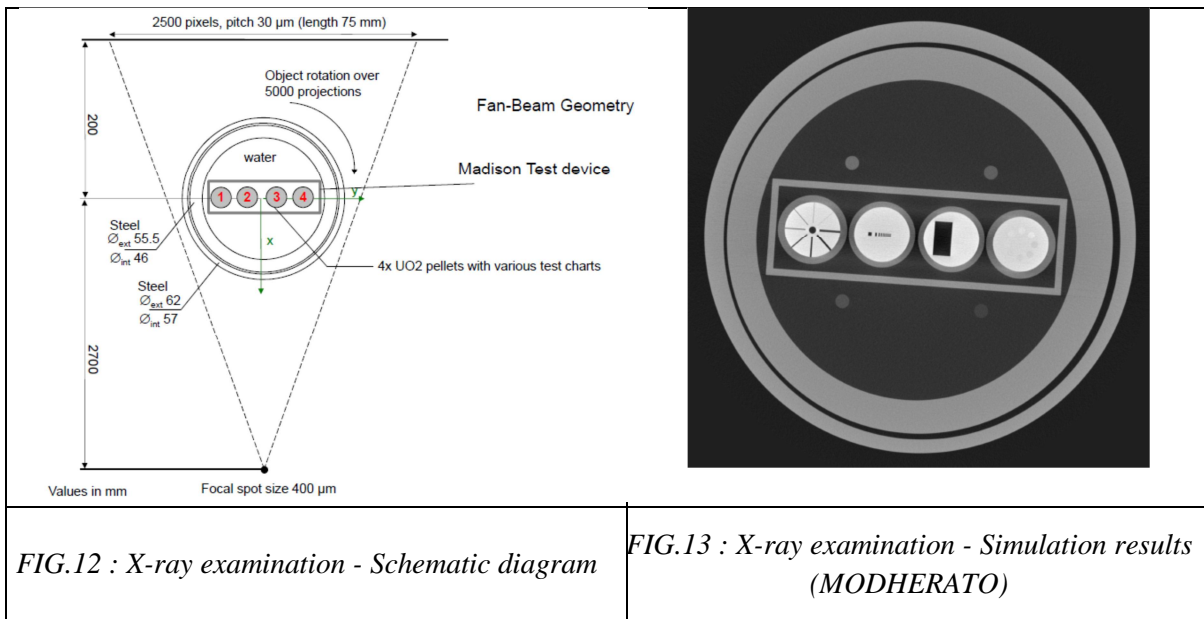
Other than experimental loops designed for irradiation experiments on samples, the JHR facility will be equipped with an examination station making it possible to perform non-destructive tests on irradiated samples (and/or on surrounding structures).

This examination station, called UGXR, will allow us to inspect devices using a high-power X-ray source (6 MeV). The objective of these inspections is to detect defects of about 250 microns in size.

This station makes it possible to examine the structures of a device (according to the position on the bench) without first disassembling the device in a hot cell.



A numerical simulation of an X-ray examination is given below for a structure of device with typical defects (radial cracks of variable thicknesses ranging between 10 and 300 microns).

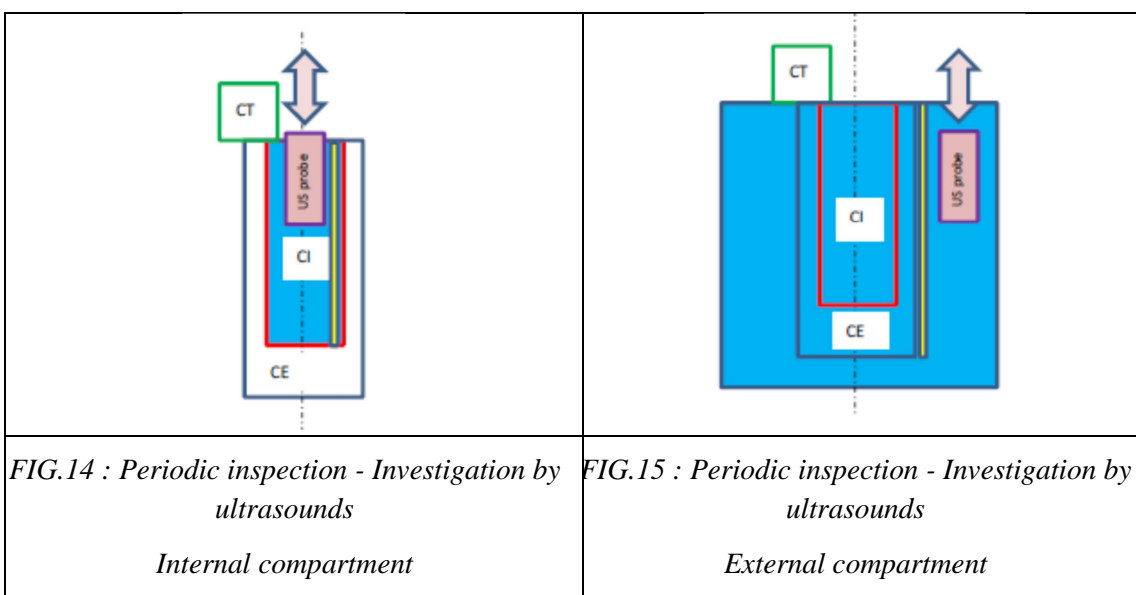


Legend:

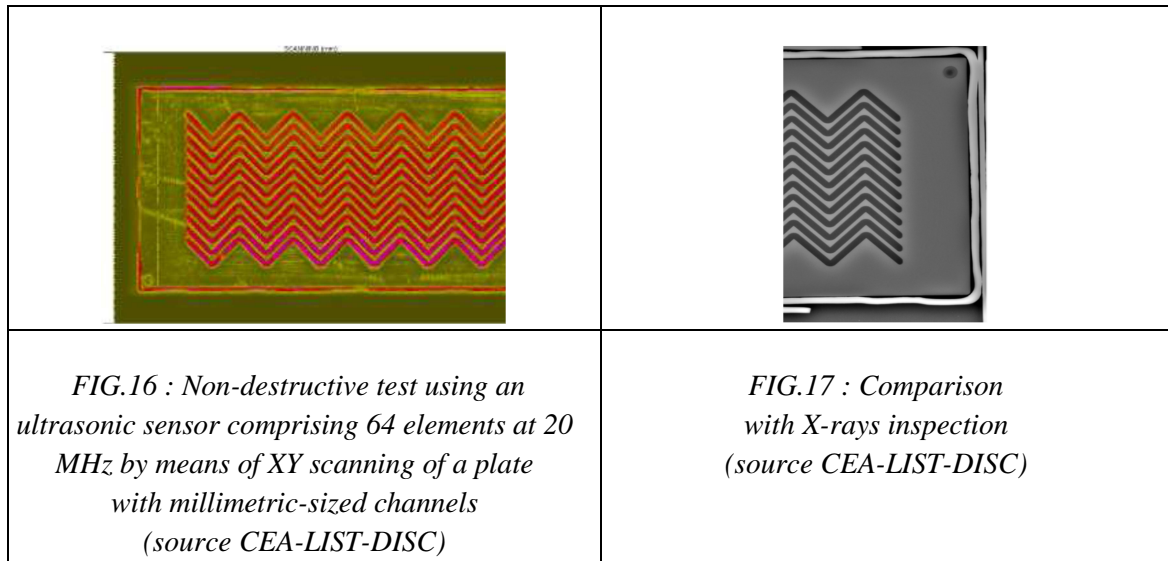
- Radial cross-section of the Madison irradiation device for the JHR.
- Fuel $d = 8$ mm, cladding $d = 10$ mm, density 10.5, hole $d = 1$ mm for instrumentation.
- Variable defect thicknesses between 10 and 300 microns.

4.2 ULTRASONIC INSPECTIONS

This section proposes the implementation of non-destructive tests using ultrasounds to detect defects in the structures of experimental equipment (irradiation devices, containers, etc.).



Examples of NDT using ultrasounds and X-rays on heat exchanger plates (view of the channels):



Note: the typical size of a measurable defect depends on the sensor and the method used. In this case with ESCG³, the frequency is 20 MHz which results in resolution of about 100 microns in the steel.

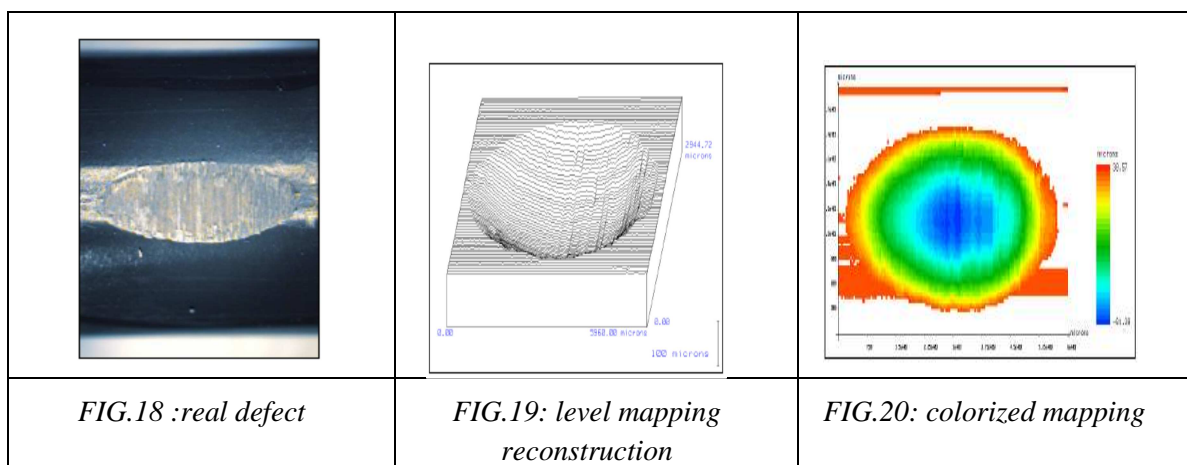
4.3 ANOTHER TECHNIQUE: CONFOCAL OPTICAL MICROSCOPY

Confocal optical microscopy is an interesting alternative technique regarding external defaults screening for the pressure tubes. The main principle is based on multi-spectrum light reflected on the inspected surface and which interfered with emitted light source.

The result obtained (by use of spatial filter & spectrometer) permit to define with accuracy the distance of reflected surface and in consequence the possible defects.

The accuracy of this technic is about few microns.

This technique is already used in cold conditions to characterize the surfaces defects of fuel rods as illustrated in the following pictures (source CEA-CAD DTN).



³ SGHE: Sodium Gas Heat Exchanger

5. DEVELOPMENT PLAN PROPOSAL

This section elaborates a development plan for carrying out periodic inspections on nuclear pressure equipment using non-destructive testing among others.

5.1 INSPECTION REQUIREMENTS AND TYPES OF DEFECTS

The inspections of the equipment must be performed in compliance with the requirements of a design and construction code. The standard chosen for tube inspections is RCC-MRx v12.

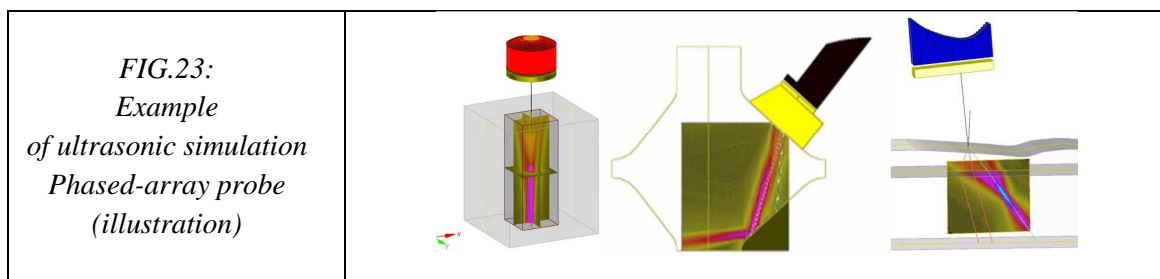
5.2 DEVELOPMENT OF NDT MEASUREMENTS AND CHARACTERISATION OF DEFECTS

Ultrasonic measurements are proposed in principle because they are already used to detect defects in structures, e.g. SFRs (Sodium Fast Reactors).

A sensor and a sample carrier compatible with the geometry of the irradiation devices (long tubular structures with small diameters) are to be developed.

The inspection will be performed by immersion. Water will be used as the coupling medium.

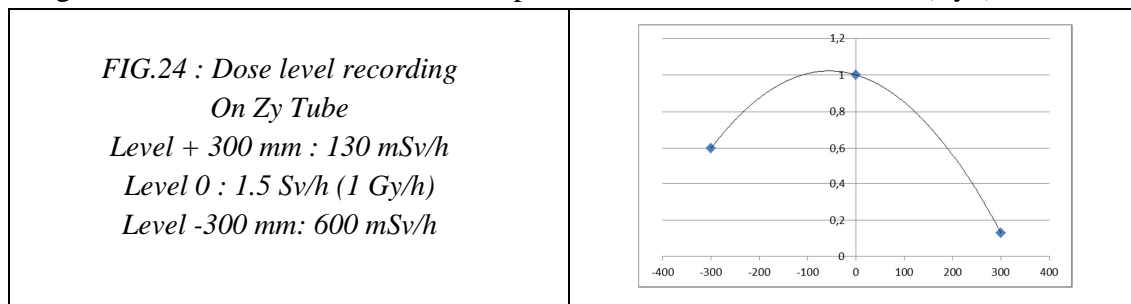
Characterisation tests (according to the geometries, inspection thicknesses and defects) will be performed. At the same time, ultrasonic inspections of various structures immersed in water could be simulated by means of the CEA ultrasonic inspection tool called CIVA⁴.



5.3 TEST TO CHECK THE DOSE RESISTANCE OF THE INSTRUMENTATION USED

The validation programme for the non-destructive inspections must include a test to check that the instrumentation (sensors, electronics, etc.) can resist with the doses received during examinations (activation of stainless steel structures under flux).

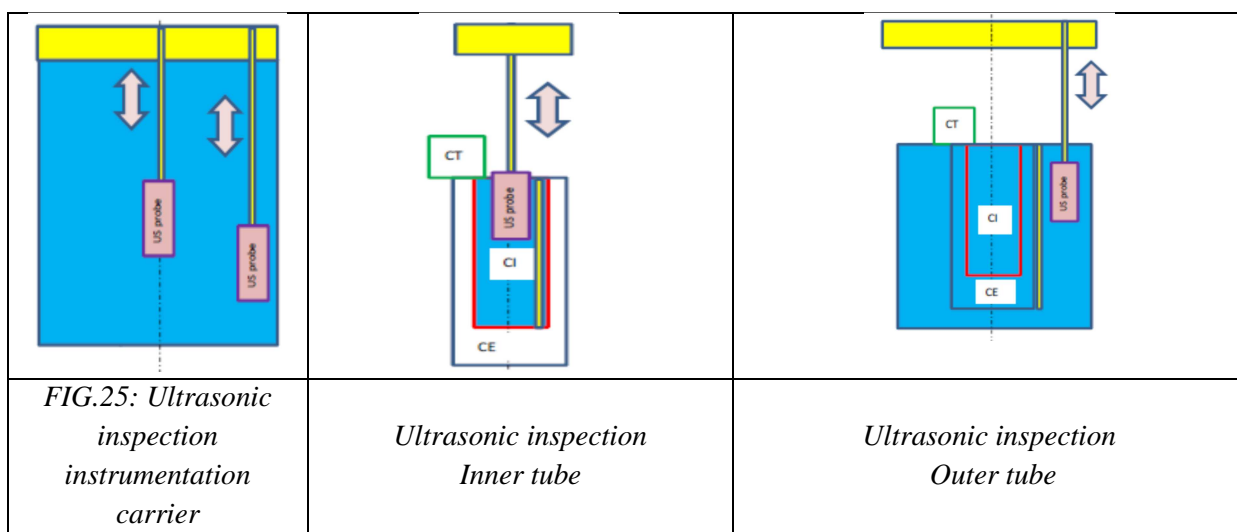
This section provides the CEA data from Osiris feedback. The following graph precise the gamma dose rates recorded outside pressure tube No. 4 underwater (Zy4):



⁴ CIVA: CEA-LIST. Platform for assessing NDTs

5.4 DEVELOPMENT OF A CARRIER EQUIPPED FOR PERIODIC INSPECTIONS

- Detailed design and construction of a non-destructive testing system for inspecting the pressure tubes in the JHR irradiation devices (one or two envelopes).
- Construction of a mechanical holder for ultrasonic instrumentation designed to scan the inner surfaces of the inner tube and the outer surfaces of the outer tube forming the pressure tube, so as to characterise any defects in compliance with the code requirements.
- Implementation of this examination device in the storage pools (EPT) and/or in the hot cells of the JHR for the periodic inspection of irradiation devices concerned by such requirements.



Characteristic of defects to detect:

Inner tube 6.5 mm / outer tube: 5.5 mm	Type of defect	Geometry
inner surfaces outer surfaces	Radial notch	L = 10 mm, w = 1 mm thickness = 320 microns

TABLE 5: Typical data of a defect for NDT on a device

6. CONCLUSION

Periodic inspections are necessary in order to meet the requirements of regulations governing certain pressure equipment and nuclear pressure equipment.

The type of experimental equipment in the JHR (multi-compartment devices, small gaps and irradiation) do not always make it possible to easily visually inspect the different surfaces of the internal and external vessels. In some cases, inspection is impossible.

To counter such difficulties, we have proposed a number of non-destructive inspection techniques (X-rays, ultrasounds and optical techniques).

The implementation of these techniques will first require developing a qualification programme so as to provide the information needed to confirm or refute the relevance of such inspections.

In our proposals, we set out to limit the preparation required prior to these examinations, the related risks, and the resulting unavailability of this equipment.

7. LIST OF REFERENCES

- [1] Decree No. 99-1046 dated 13/12/1999, Order dated 21/12/1999 (pressure equipment classification and conformity assessment) and Order dated 15/03/2000 (implementation of pressure equipment).
- [2] French Nuclear Pressure Equipment Order dated 12/12/2005
- [3] Assessing the compliance of nuclear pressure equipment. ASN guidelines No. 8 Revised version dated 04/09/2012
- [4] RCC-MRx extract
- [5] www.cofrend.com.
- [6] CIVA (CEA-LIST): Platform for assessing NDTs. <http://www-civa.cea.fr/>

