THE FUTURE UNDERWATER NEUTRON IMAGING SYSTEM OF THE JULES HOROWITZ MTR: AN EQUIPMENT IMPROVING THE SCIENTIFIC QUALITY OF IRRADIATION PROGRAMS

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ABSTRACT

On-site Non Destructive Examination (NDE) techniques are able to provide valuable scientific information in support to the irradiation process of nuclear fuels and materials in Material Test Reactors (MTR), especially when the sample has strongly evolved or if scientific information would be lost in time.
As the Jules Horowitz (JHR) MTR is intended to be a major European User Facility for sustaining the international irradiation capacity, two photonic imaging benches coupling gamma scanning and X-ray tomography and welcoming full irradiation devices, and an neutron imaging bench are to be implemented in the reactor pools Another coupled gamma – X-ray tomography bench and a multipurpose bench, both in air in hot cell, will check dismounted samples at high resolution.
Following a previous paper focussed on the photonic imaging benches presented at IGORR 13, this paper presents the Neutron Imaging System (NIS) of the JHR. After a reminder on the specific capabilities and addressed scientific needs in the fuel domain of a neutron imaging bench, its mechanical characteristics and integration issues will be reviewed. A focus will be carried out on the design of the detection system. First performance simulation on realistic samples will finally be shown.

1. Interest of non destructive examinations for the irradiation process in MTR

The experimental process in a Material Test Reactor (MTR) mainly consists in the irradiation of an experimental sample (nuclear fuel or material), generally instrumented in order to monitor or quantify on-line the effect of the environment variation on the sample behavior. New irradiation devices are designed to embark a lot of instrumentation and to transmit the various signals properly [1], [2]. However, supplementary and valuable scientific information can also be gained thanks to intermediate non-destructive examination (NDE) on the sample and to specific laboratories that can welcome and analyze fluids in contact with the sample. These techniques are often implemented without specific handling (no supplementary risk for the sample) or detriment on the experiment schedule (see also [3]):

- Initial checking of the sample before starting the irradiation (previous handling or transportation possible effects, precise positioning of sample and instrumentation…),
- Management of the irradiation time history by gaining early results on the sample behavior (power time history fine tuning, detection of unexpected sample behavior…),
- Gain of data not accessible or lost by classical post-irradiation examinations (PIE) in hot cells (maintain of a stress or an atmosphere on a sample, measurement of short half-life fission products…),
- On the spot monitoring of the sample status after a soliciting test (transient or safety),
- Final check to define the “reference state” before transportation to hot cells.

The Jules Horowitz (JHR) MTR, which is under construction at the CEA Cadarache Centre in France and with a target of commissioning by end 2017 [4] will take profit at the best from such techniques. For this aim, two identical underwater photonic imaging benches, coupling gamma scanning and X-tomography, will be installed respectively in the reactor pool and in the storage pool of the JHR, capable of welcoming and checking an irradiation device containing the experimental sample still mounted on the sample-holder and connected [5]. These equipments will be accessible either during the reactor operation or during intercycles. Moreover, an underwater Neutron Imaging System (NIS) will be also implemented in the reactor pool and will check an experimental load after transfer in an evacuated container. At the end of the irradiation process, sample will be unloaded from the device and disconnected from the sample-holder. Then PIE will be performed in the JHR examination hot cells, such as precise X-ray radiography and tomography, or gamma scanning and tomography. A multipurpose NDE bench is also planned in the fuel examination hot cell.

2. Fields of interest for a Neutron Imaging System

Due to different interactions of photons and neutrons with matter, photonic imaging (gamma scanning and X-ray radiography) and neutron imaging are not sensitive to the same chemical elements or isotopes and don't reveal the same details and don't provide the same information. This paragraph focuses on results provided specifically by a NIS, because not or barely visible by photonic imaging. These results are often of great interest for a customer (e.g. decision of accepted / rejected) or they can be used directly as scientific results or in support to the protocol. Such checkings are already implemented in some MTRs (e.g. in the French OSIRIS MTR) [6] and present a high potential interest for future programs in JHR.

2.1 Search for liquid water or hydrogen in very small quantities or divided

When unexpected, such detection has a strong impact on the experiment unfolding or result:

- Sample tightness loss can be a contractual refusal criterion for the sample if detected before irradiation. It can also be used as a "failed / not failed" experimental result (e.g. overshoot of operational margins for a nuclear product in incidental conditions),
- Quantification of hydride concentration in a metallic material (cladding, pressure tube…). After calibration [7], this result can be linked to the maintain of the performance (mechanical properties) of a nuclear material versus ageing or in some accidental conditions,
- Quantification and localization of water ingress in a sample. This can be assessed for water migration or diffusion efficiency determination, or simply for evaluating the possible consequences towards the experiment continuation (see fig. 1).

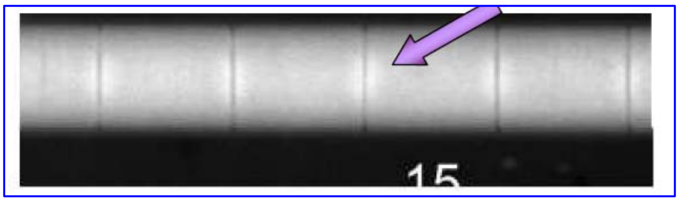

Fig 1. Traces of moisture at pellet-pellet interface

2.2 Detection and quantification of fissile isotopes for thermal neutrons

The application range is wide because X-radiography is only sensitive to the density of the nuclear material, which is very similar for many nuclear fuels (e.g. oxides) whatever the enrichment in fissile nuclei. It can be used for (see fig 2):

- Global checking of a sample after transportation and reception,
- Monitoring of the enrichment evolution versus time during the experiment in MTR,
- Detection and characterization of isolated fissile grains after a fuel release.

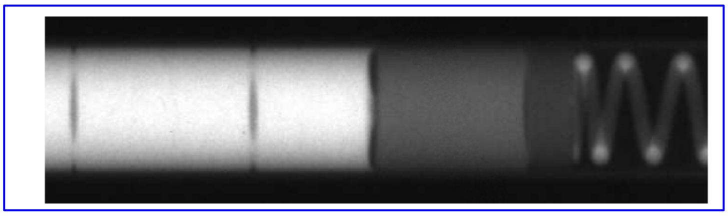

Fig 2. Contrast between MOX pellets (light grey) and one natural UO_2 pellet (dark grey)

2.3 Detection and quantification of isotopes absorbing thermal neutrons

Neutron absorbers are commonly used in MTR experiments, either for changing locally the neutron flux profile or to adapt the neutronic spectrum to the experiment request. In these cases the NIS can quantify the consumption or the homogeneity of neutronic poison introduced in some materials (e.g. cladding), or in a neutronic filter or screen.

2.4 Visualization of light chemical elements sheathed by dense materials

This potentiality uses the relative transparency of most high-Z materials for neutrons, allowing imaging small pieces or components placed inside:

- Monitoring of a liquid level in a vessel (e.g. sodium or NaK),
- Final checking of complex sample holders integrated in hot cells,
- Precise positioning of some sensors (e.g. hot junction of a thermocouple).

3. Description of the JHR underwater Neutron Imaging System (JHR-NIS)

The Neutron Imaging System consists of four parts (see fig 3): a removable nozzle, which defines the size of the neutron source and the beam shape, an evacuated conical structure to allow the best transmission of the neutron beam and to minimize the impact of scattered neutrons, a volume welcoming devices to be examined, and last the imaging device, an activated metal foil disposed in an irradiation cassette.

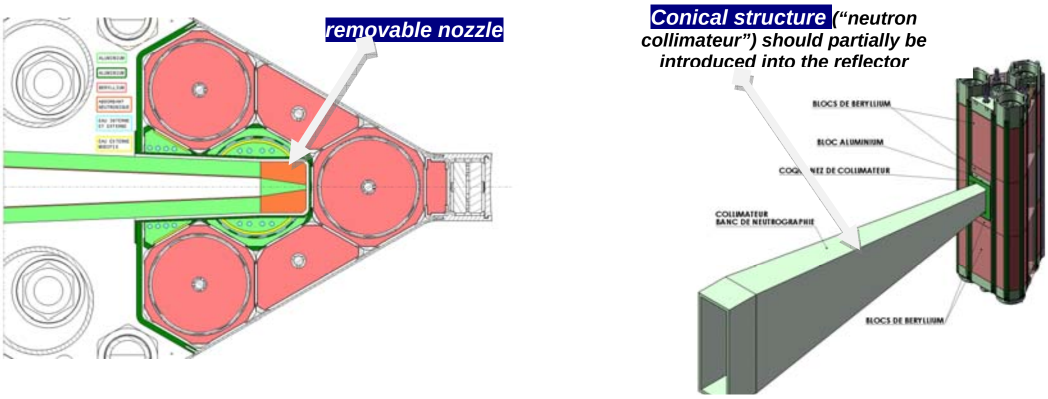

Fig 3. General view of the JHR-NIS collimator and removable nozzle

3.1 The retractable collimator and the welcoming devices

In order to obtain the highest possible neutron flux in the collimator aperture, its tip is introduced into the reflector within a length of 200 mm. The whole nozzle and conical structure may undergo a horizontal retracting movement. The movement avoids unnecessary irradiation of the collimator nozzle outside the examination periods and will be used to perform system maintenance and nozzle replacement. The nozzle of the collimator is a removable piece that will fit the aperture of collimation based on need. At least four different apertures will be available, each providing a different performance from L /D ratio ~200 to L/D ratio ~670. Due to the high radiation level of objects examined and their proximity to the imaging system, the imaging method used is a transfer method.

Fig 4 describes these interfaced components. The retractable process system consists in a great dimensioned metallic bellow (stainless steel) which permits an about 400 mm displacement with a high waterproof function (the 2 views below don't show the interfaces details like training mechanism and welding interfaces). The welcoming device will receive the entire holder irradiation device (yellow tube) and it is equipped to command several monitoring processes (Z and θ movements of the holder, vacuum water inside the welcoming devices). Handling operations and displacement mechanisms are not completely finalized. An aperture with the geometric desirable size of the final image is designed on the back side.

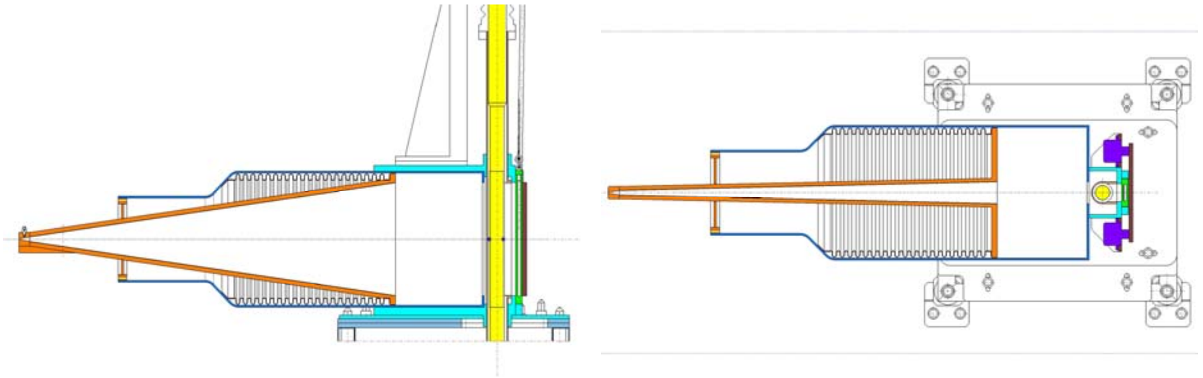

Fig 4. Schematic of the retractable collimator and of the welcoming device
(left: vertical section; right: horizontal section)

3.2 Activable metallic foil housing: design and operation

An activable metallic foil with suitable radioactive period will be located downstream of the examined object. Neutron transmission produces a latent image in the form of beta-emitting isotopes. The metal foil is then removed from the pool for forming an image by contact with a radiographic film, an imaging plate or other conversion system, which finally leads to the production of a digital image. The transfer method has the considerable advantage of being completely free from the gamma-ray flux. The disadvantage of the method is the overall time of production of an image, which makes tomographic examinations inacceptable in routine operations.

The activable metallic foil housing minimizes the geometric size and must be stuck to the welcoming devices aperture before launching vacuum process. After the irradiation phase, the activable metallic foil housing is disconnected and removed from the pool, then transferred to a specific laboratory for forming an image by contact with a radiographic film. Fig 5 shows the principle of interfaces between the bench and the operators.

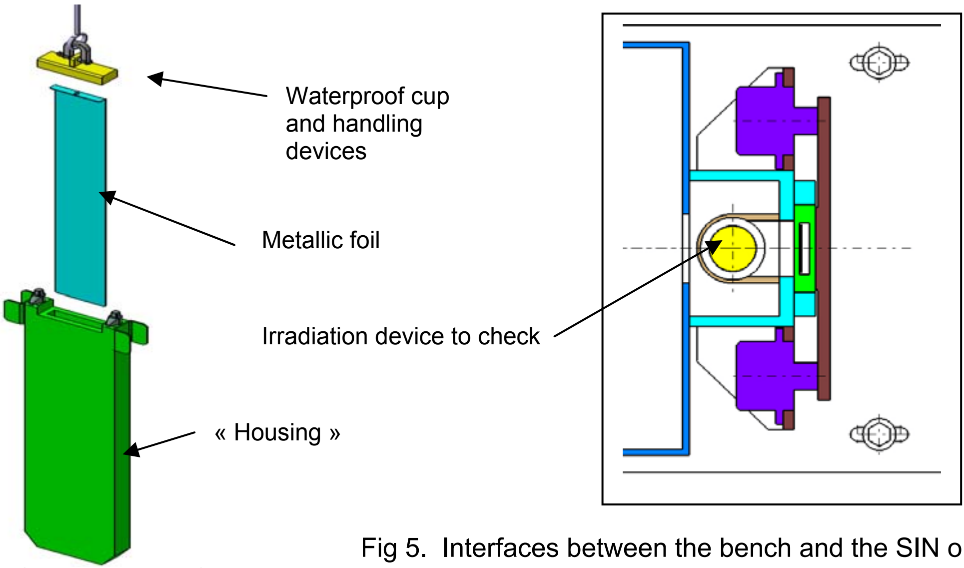

Fig 5. Interfaces between the bench and the SIN operators
(left view: detail of the main structure, right view: horizontal section in irradiation position)

3.3 Interfaces with the JHR pool vessel and reflector

Fig 6 below shows the main principles used to anchor the neutron bench and to guide the sample holder irradiation device under neutron flux in front of the imaging plate.

There is no contact with the reactor pool wall liner, and at the bottom the bench is anchored on a heavy plate (fixed on a stool with seismic guarantees). The part receiving the instrumentation (described in § 4) appears with the retractable collimator and the welcoming devices which must manage the holder irradiation device (vacuum water process, Z and θ movements).The activable metallic foil in its housing will be handled from activation position to surface. At the top a working platform will supervise all transfer operations.

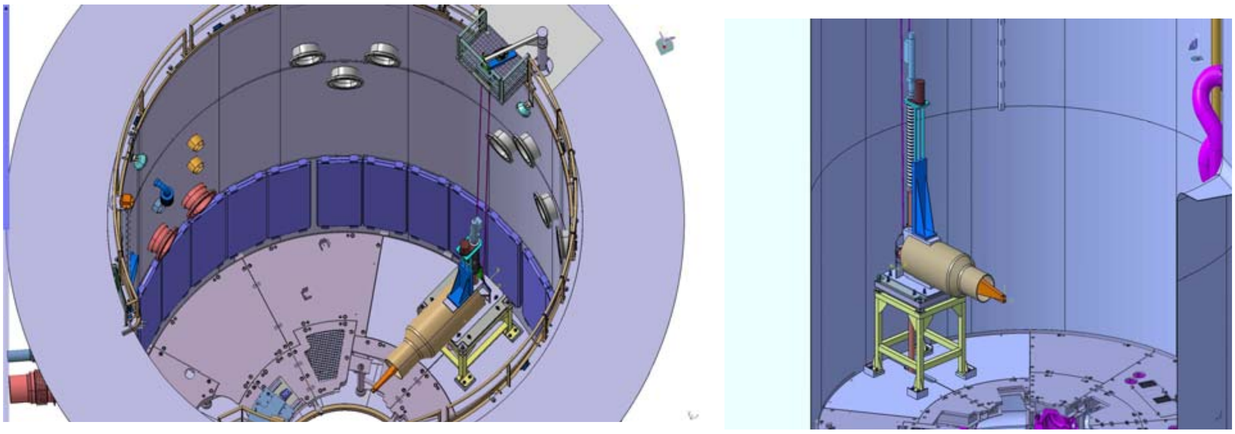

Fig 6. The JHR neutron bench main structures with its vessel and anchors interfaces (these 3D views are in air and all others equipment have been removed)

4. Design of the Neutron Imaging System

4.1 Specifications of performances from future end-users

CEA end-users expressed their requests regarding the use of the bench, along with some specifications of performance in terms of examination length, spatial resolution…, thus providing initial input data for the NIS mechanical design and detection system. Some of them are hardly flexible, but each will be discussed versus the associated technological challenges and cost of the equipment.

The checked object will be generally the sample (e.g. one or a few experimental fuel rods) still connected to its sample-holder, and placed in an empty container. There is also an interest to check a loaded irradiation device if small enough in diameter (less than about 50 mm) and if the coolant still present doesn't interact with the neutron beam (e.g. material samples in a gaseous atmosphere). When the examination is mainly in support to the irradiation process in JHR, the request is to minimize the irradiation interruption (irradiation duration less than 1 hour per view). When the examination goal is to gain scientific results, acquisition time presents fewer constraints.

The acquired information will be in the reference case a 2D image. Two views at 90° are generally sufficient, and expected programs don't point out the need for a neutron tomography. A high spatial resolution will be requested for a large majority of examinations. The target for the minimum size of a so-called "detected" detail is 0.2 mm, and the accuracy of positioning for a component (instrumentation,…) +/- 0.2 mm. Moreover, the JHR-NIS implementation will in practice take profit from the availability of the two photonic imaging underwater benches (see § 1). Depending on the actual performances obtained in the future with this X-Ray benches, the NIS will be operated to provide a complementarity and added value regarding irradiation support and scientific results.

4.2 Performances currently expected by the design

The geometric unsharpness is often a limiting factor for spatial resolution performance. The only geometric parameter for reducing the geometric unsharpness without affecting the duration of examination is the distance from the object to the detector. This parameter is then to be minimized and adapted to the object dimensions.

For the largest objects to check, the object-detector distance will be kept under 50 mm. In order to optimize the resolution for each examination, the concept of the imaging system has retained the ability to change both the distance from the object to the detector plane (l), and the source aperture (D), the length L remaining fixed.

The intrinsic resolution of the detector is divided into two major components: the spatial dispersion of the neutron capture interactions and of emitted electrons within the converter foil on one hand and the spatial dispersion of the emitted electrons interactions in the imager on the other hand. These two components are studied versus the detection efficiency by Monte-Carlo simulations.

The irradiation duration is inversely proportional to the neutron flux on the detector plane and proportional to the square of L/D ratio. To keep some flexibility in choosing either high resolution or fast operation, the proposed solution is modular with the use of multiple values of L/D ratio. Four values of D are proposed to cover a wide range of operation (table 1).

The neutron fluence reference on the detector plane is 4.5 10^{10} $n_{th.}cm^{-2}$ for the production of an image of optical density 3.0 on a radiographic film, after a 900 s irradiation with a thermal neutrons flux of 5 10^{7} $n.cm^{-2}.s^{-1}$, followed by a 30 min transfer delay and a 25 min film exposure. A special large aperture (10 mm or more) will be used for operation at low reactor power (2 MWth reactor operation will be available for short durations during the intercycle phases).

	Nozzle 1	**Nozzle 2**	**Nozzle 3**	**Nozzle 4**
D (mm)	**3**	**4**	**6**	**10**
Geom. Unsharpness (µm)	60	80	120	200
L/D	667	500	333	200
Neutron Fluence rate at object (n/cm²/s)	1.3 10^{7}	2.2 10^{7}	5 10^{7}	13.9 10^{7}
Irradiation duration (min)	60	34	15	5.6

Tab 1: Operation with different nozzles at 70 MW ($\Phi_0 = 10^{14}$ $n.cm^{-2}.s^{-1}$ at inlet aperture)

4.3 Design options for the neutron converter

The converter for recording the latent image must have the following main features:

- A high capture cross section,
- A simple decay chain, preferably a short mean free path (beta emitter) not to degrade the resolution,
- A radioactive decay period between 1 and 4 hours, to allow easy handling in the transfer phase and not prohibitive exposure duration in the image formation phase.

The ideal converter combining these features is the Dysprosium, whose ^{164}Dy isotope with an abundance of 28%, provides a beta decay of ^{165}Dy after neutron capture, with a period of 2.23 h. The dysprosium foil thickness is selected to be thick enough to capture a large amount of incident neutrons, and thin enough to let out a sufficient number of beta-rays and minimize spatial dispersion. The capture efficiency of Dy (production of ^{165}Dy) for thermal neutrons is around 10% for a foil thickness of 100 µm. Such a dysprosium foil has a maximum n_{th}-e- conversion efficiency value of 0.37 keV/n_{th} for a spatial dispersion of energy deposit of about 30 µm (FWHM) in a radiographic film (single coating).

4.4 Design options for the imager

The reference imager for the JHR-NIS is presently the radiographic film, historically used in most MTRs. An alternative, commonly in use for X-rays applications as a replacement to radiographic films, is the imaging plate (IP). A third option, currently under study for the JHR-NIS is a thin high-density scintillator layer, with high light output. Final image is obtained respectively by film development (and optical scanning), by IP scanning, or by low-noise CCD reading.

The desired imaging device for neutron imaging has to combine the best image resolution and a good enough detection efficiency. The three above mentioned options are currently being studied using MCNPX 2.4.0 [8] to perform energy deposit and spatial dispersion calculations of electrons per incident neutron.
The spatial resolution obtained with the imaging plate is twice poorer than that obtained by radiographic film, but with a 10 times greater sensitivity. Applying a thin layer of Gadox scintillator appears to be interesting, with the possibility of a very good intrinsic resolution, even better than the radiographic film, for a similar sensitivity than the film.

5. Neutron radiography images simulations

An effective way to assess the performance of an imaging system is to simulate the image resulting from given test conditions. CEA developed several years ago a simulation toolkit for X-ray radiographic and tomographic examinations: MODHERATO. It has been modified to be applied to neutron imaging examinations, with the name MODHERATO-N. Fig 7 shows the simulation by MODHERATO-N of PWR UO_2 fuel pellets exhibiting typical defects:

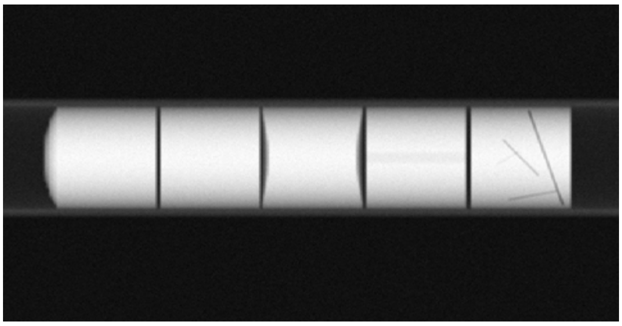

Fig 7. Simulated image of defects in UO_2 pellets: shape, density, cracks (from left to right)

Fig 8 compares images obtained by the Neutron Imaging System (left) and by high energy X-ray system (right) on the same object: a fuel rod associated with structural elements. 3.5 mm in diameter Zy4 disk, 2.8 mm stainless steel, and 8 mm AG3 aluminum alloy.

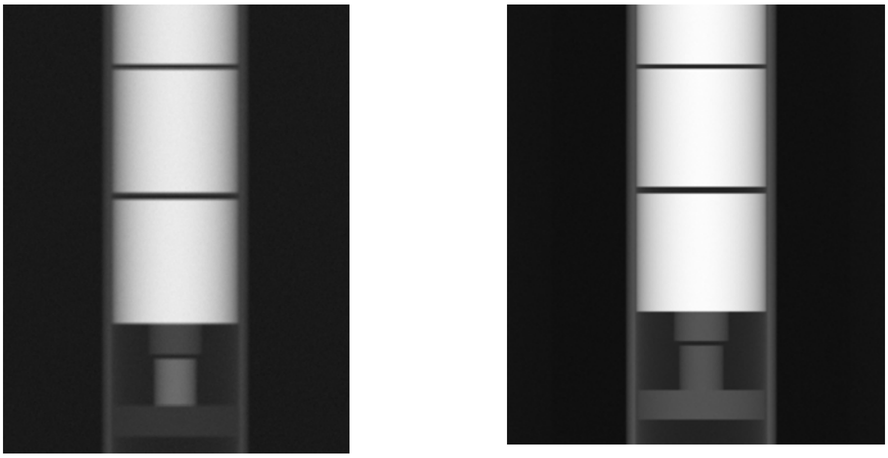

Fig 8. Simulated images with NIS (left) and high energy X-ray (right). See text for details.

MODHERATO-N will be improved in the future to simulate other types of imaging devices. It may be used not only to perform design and sizing studies as is already the case with the classic version for X-Ray imaging benches, but also to produce comparative studies between the different non-destructive technologies available to JHR users.

6. Conclusion

JHR in-pool Neutron Imaging System is in priority intended as part of the JHR service offer on power ramps, together with the ADELINE fuel loop, supported by EDF. It will also contribute to secure and enhance the main JHR imaging capability, which is to be provided by X-rays benches implemented in pool and in the hot cells.

Main project targets are a resolution under 0.2 mm and an improved operation compared to previous neutron benches on French MTRs.

The high gamma-ray background from the reactor core and from the device under examination, most of the time a freshly irradiated fuel rod, was a strong drive for the conservative choice of indirect imaging via a Dysprosium converter. On the other hand, the readout method of this converter is still an open issue, being constrained by the 0.2 mm target and the threat on the global supply of films suitable for neutron radiography. The mechanical design of the retractable collimator with a variable L/D figure is also ongoing, this design being constrained by the harsh operating conditions and nuclear safety requirements for a device in a reactor pool.

The JHR Neutron Imaging System is expected to be operational at the start of the User Facility, in 2018.

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