Performance assessment of imaging plates for the JHR transfer Neutron Imaging System

E. Simon, P. Guimbal

***Abstract–T*he underwater Neutron Imaging System to be installed in the Jules Horowitz Reactor (JHR-NIS) is based on a transfer method using a neutron activated beta-emitter like Dysprosium. The information stored in the converter is to be offline transferred on a specific imaging system, still to be defined. Solutions are currently under investigation for the JHR-NIS in order to anticipate the disappearance of radiographic films commonly used in these applications. We report here the performance assessment of Computed Radiography imagers (Imaging Plates) performed at LLB/Orphée (CEA Saclay).**

Several imaging plate types are studied, in one hand in the configuration involving an intimate contact with an activated dysprosium foil converter: Fuji BAS-TR, Fuji UR-1 and Carestream Flex XL Blue imaging plates, and in the other hand by using a prototypal imaging plate doped with dysprosium and thus not needing any contact with a separate converter foil. The results for these imaging plates are compared with those obtained with gadolinium doped imaging plate used in direct neutron imaging (Fuji BAS-ND).

The detection performances of the different imagers are compared regarding resolution and noise.

The many advantages of using imaging plates over radiographic films (high sensitivity, linear response, high dynamic range) could palliate its lower intrinsic resolution.

Index Terms **— Neutron Imaging, Material Testing Reactor, Indirect Neutron Imaging, Non-Destructive Examination, Jules Horowitz Reactor.**

I. Introduction

Among non-destructive examination methods commonly used in material testing reactors, neutron imaging is one of the oldest techniques. The neutron imaging system (NIS) of the Jules Horowitz Reactor (JHR) will follow the one that was used from the 1960s at the OSIRIS reactor, whose JHR will be the successor at Cadarache, France. The design of the neutron imaging bench is guided by the constraints of managing highly radiating objects. As the imaging system must be installed as close as possible to the irradiated fuel rods to be inspected, direct imaging is not an option. No direct imaging system which would be sensitive to thermal neutrons but insensitive to very high gamma-ray flux is applicable.

The underwater Neutron Imaging System to be installed in the Jules Horowitz Reactor (JHR-NIS) is based on an indirect method (transfer method) using a neutron activated beta-emitter like Dysprosium-165. The information stored in the converter foil has to be offline transferred by a specific imaging system to be defined.

Alternative solutions are currently under investigation for the JHR-NIS in order to anticipate the disappearance of historic transfer neutron radiography imagers used at MTR like specific radiographic films. The desired imaging device is the one that offers the best spatial resolution (image resolution performance), and the best detection efficiency (release time of the digital image). One of the objectives is also to improve the imaging process by working with linear response imagers and digital systems. We report here the performance assessment of Computed Radiography imagers (Imaging Plates) performed at LLB/Orphée for neutron imaging by transfer from a dysprosium neutron converter.

Several imaging plate types are studied, first in the configuration involving an intimate contact with the neutron converter: Fuji BAS-TR, Fuji UR-1 and Carestream Flex XL Blue imaging plates, second by using a prototypal imaging plate doped with dysprosium thus not needing any contact with a separate converter foil but having to be exposed to the neutron flux and cope with the associated issues. The results obtained for these imaging plates are compared with those obtained with a gadolinium doped imaging plate designed for direct neutron imaging (Fuji BAS-ND).

The detection performances of the different imagers are compared regarding resolution and noise.

II. Material and Methods

In order to work with a comparable neutron flux as the one expected in the future JHR device, the tests have been carried out at the neutron beam line G3.2 at LLB/Orphée research reactor.

A. Neutron Beamline

The characteristics of the G3.2 neutron beam line at LLB/Orphée are summarized in table I hereafter. The neutrons at G3.2 have an average energy of 3.5 meV (LH_2 source), colder than the expected thermal neutrons from JHR at the location of the imaging plane of NIS. The neutron capture cross section on ^{164}Dy is thus enhanced by a factor 2.45 regarding the configuration of future standard operation at JHR-NIS. The flux of 7.88 10^8 n/cm²/s is also higher than the one expected by a factor 15.8. The overall time scale factor to take into account in irradiation is then of the order of 38.7, leading to exposition times of dysprosium converter of a few dozen seconds to be representative of the JHR-NIS setup.

Manuscript received June 1st, 2017. E. Simon, is with CEA, DEN, Cadarache, Nuclear Measurement Laboratory, F-13108 Saint-Paul-lez-Durance, France, email : eric.simon@cea.fr

P. Guimbal is with CEA, DEN, Cadarache, Jules Horowitz Reactor Service, F-13108 Saint-Paul-lez-Durance, France, email : philippe.guimbal@cea.fr

TABLE I
G32 BEAMLINE CHARACTERISTICS

Quantity	value
Average Flux	7.88 10^8 n/cm²/s
Average energy	3.5 meV
Energy distribution	1.8 meV → 10 meV
Angular dispersion	0.4°
Area	25 × 50 mm²

B. Neutron converter

The neutron converter used is a metal dysprosium foil 100 µm thick. The foil is mounted on a 1 mm aluminum support to facilitate handling. The isotope of interest ^{164}Dy has a natural abundance of 28.18%. Neutron capture produces both ^{165}Dy and ^{165m}Dy with half-lives respectively 2.33h and 1.26 min. Only ^{165}Dy is used for imaging the activation distribution of the foil. A 15 minutes cooling is thus used after each irradiation phase to avoid interference from the metastable isotope. ^{165}Dy is a 100% beta emitter with two main beta levels : 1191.9 keV (15%) and 1286.6 keV (83%). The highest intensity emitted gamma-ray is at 94.7 keV (3.8%).
The intimate contact between the neutron converter and the imaging plate is done by depressurization.

C. Imaging Plates and Readers

To assess the performances of many imaging plate models, two different IP readers have been used, first a FLA7000 reader (Fuji) and next a HPX-1 reader (Carestream) with both a maximum readout resolution of 25 µm.
FLA7000 is however limited to only magnetic imaging plates in our setup (Fuji BAS and Protoype IP), where HPX-1 reader has no such limitations.

D. Image Quality Indicators

The spatial resolution performance assessment is carried out by using gadolinium patterns (Siemens star and bars pattern). The gadolinium bar pattern ranges from 0.5 to 20 line pairs/mm, thus allowing to directly build the experimental modulation transfer function (contrast as a function of spatial frequency). The pattern carrier is set in contact with the surface of the dysprosium foil or of the imaging plate depending on the assessed system.

III. RESULTS

A. Detection efficiency and noise

The detection efficiency is of crucial interest in view of the use of imaging plates as imagers in a transfer neutron imaging system. The response of imaging plates is assessed by forming images of the neutron beam by transfer from the dysprosium neutron converter. The signal is recorded after an irradiation of the converter during a time T_{irrad}, followed by a cooling time T_{cool} of 15 minutes to avoid any interference of the short half-lived ^{165m}Dy gamma emission and next a contact time $T_{contact}$ where the dysprosium foil is put in close contact with the imaging plate. By varying the irradiation times at Orphee neutron beam, a wide range of equivalent JHR neutron flux can be assessed, assuming typical irradiation times.
The equivalent JHR neutron flux range assessed extends from 4.3 10^6 n/cm²/s (2 s irradiation at Orphee beamline) to 4.3 10^7 n/cm²/s (20 s irradiation at Orphee) assuming an irradiation time of 15 minutes at JHR.
The detection efficiency of the different IP is assessed by measuring the signal as a function of the neutron flux by varying irradiation times and keeping a constant cooling time (15 minutes). The contact time is set to 1 hour, and the plates are kept in the dark between contact exposition and reading.
Figure 1 shows the evolution of the signal of Flex XL Blue, BAS-TR and UR-1 imaging plates read by HPX-1 reader in function of the neutron flux when using the highest sensitivity of the reading.

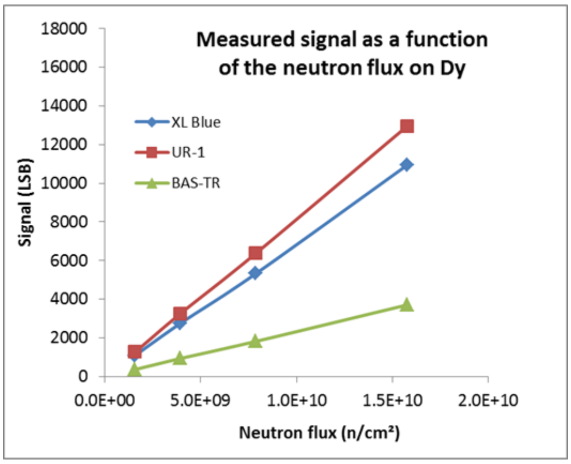

Fig. 1. Evolution of the signal measured on Flex XL Blue, BAS-TR and UR-1 imaging plates in function of the integrated neutron flux.

The dynamic range of the various imaging plate models is of the same order. All models show a good linearity within the signal range. BAS-TR IP however has a lower sensitivity of a factor close to 3 regarding HR Flex Blue and UR-1. This lower sensitivity can be related to the smaller thickness of the active phosphor layer encountered in BAS-TR (50 µm) compared to the phosphor layer of 160 µm in the other two models. This phosphor structure difference will also impact the spatial resolution performance. BAS-TR IP could thus be used up to a JHR neutron flux of 7.5 10^8 n/cm²/s with a 15 minutes dysprosium irradiation time.
The measured signal over noise ratios are as expected increasing as a function of the signal but are almost independent of the reader parameters (photomultiplier gain or laser intensity). The older models (BAS-TR and BAS-ND) show a lower value and lower increase of the S/N ratio than UR-1 or Flex XL Blue models.

B. Spatial Resolution

The intrinsic spatial resolution of imaging plates is investigated by computing their experimental modulation transfer function.
The spatial resolution achievable is defined by a limit of 10% on contrast. An image of Siemens star Image Quality Indicator is shown in figure 2. The computed Modulation Transfer

Functions of different imaging plates are shown on fig 3. The spatial resolution results are summarized in table II, using both readers set at maximum scanning resolution (25 µm).

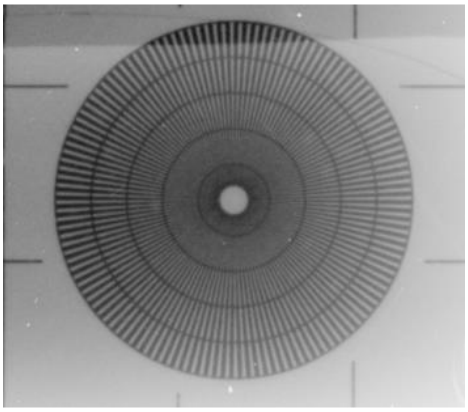

Fig. 2. IQI (Siemens star) image recorded on BAS-TR IP (HPX-1 reader).

TABLE II
SPATIAL RESOLUTION

IP Type	HPX-1 10% MTF (lp/mm)	HPX-1 Spatial resolution (µm)	FLA-7000 10% MTF (lp/mm)	FLA-7000 Spatial resolution (µm)
Fuji BAS-TR	5.4	92	5	100
Fuji-UR1	3.7	135	-	-
Carestream XL Blue	3.7	135	-	-
Prototype Dy-doped	-	-	3.8	130
Fuji BAS-ND	5.8	86	5.5	90

The intrinsic resolution measured on Fuji UR-1 and Carestream Flex XL Blue is similar (135 µm). Fuji BAS-TR imaging plate shows a better intrinsic resolution slightly below 100 µm, thanks to its thinner phosphor layer and the absence of protective layer on top of the active layer. The resolution performance of imaging plates set in contact with an activated foil cannot compete with a neutron detection imaging plate incorporating gadolinium whose resolution is measured around 90 µm. Nevertheless, the prototype IP incorporating dysprosium instead of gadolinium do not show better resolution performances than BAS-TR.

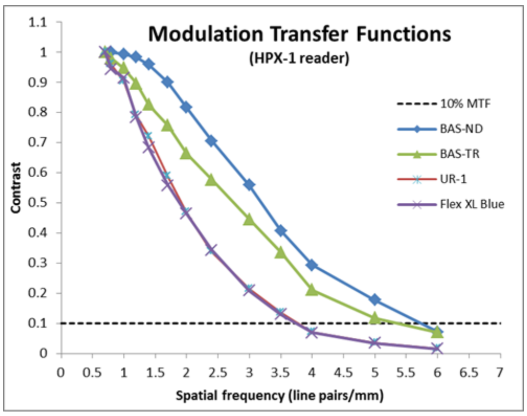

Fig. 3. Modulation Transfer Function computed from the bar pattern image quality indicator for the four imaging plate models assessed using the HPX-1 reader.

IV. CONCLUSION

All imaging plates models assessed show a good sensitivity and a good linearity over a wide signal range. The intrinsic noise appears relatively more important in BAS-TR and BAS-ND IP than in other IP but it remains acceptable even at low signal level (S/N around 50 at 100 LSB), which authorizes the use of such imaging detectors at relatively low flux. The resolution performance obtained with dysprosium doped imaging plate is slightly poorer than those achieved using a Fuji BAS-TR, Carestream HR Flex Blue or Fuji UR-1 in transfer imaging. Even if the intrinsic resolution of imaging plates appears worse than single-sided radiographic films, the impact on the final resolution of the neutron imaging system of JHR may remain low, where the geometrical blurring is the dominant resolution impactor.

Further, the many advantages of using imaging plates over radiographic films (high sensitivity, linear response, high dynamic range) could palliate its lower intrinsic resolution. Nevertheless, in order to get a quantitative response from imaging plates in neutron imaging by transfer, the light exposition between the converter exposition and readout has to be carefully managed.

Imaging plates initially conceived to perform tritium low energy beta imaging like BAS-TR, incorporating the thinnest phosphor layer with no additional protective layer, appears to be a promising on-the-shelf solution to replace a radiographic film-based imager in high resolution neutron imaging by transfer.

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