Development of Neutron Color Image Intensifier for Pulsed Neutron Source

Koichi Nittoh\textsuperscript{a*}, Chikara Konagai\textsuperscript{b}, Mitsuru Yahagi\textsuperscript{b}, Yoshiaki Kiyanagi\textsuperscript{c}, Takashi Kamiyama\textsuperscript{d}

\textsuperscript{a}Toshiba Nuclear Engineering Services Corp., 8 Shinsugita, Isogo-ku, Yokohama 235-8523, Japan
\textsuperscript{b}Toshiba Power systems Inspection Services Co. Ltd., 8 Shinsugita, Isogo-ku, Yokohama 235-8523, Japan
\textsuperscript{c}Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan
\textsuperscript{d}Hokkaido University, Kita 13 Nishi 8, Sapporo 060-8628, Japan

Abstract

We have been developing neutron color image intensifiers (hereafter abbreviated as NCIs) for static neutron sources. With the recent progress of high power pulsed neutron sources, needs for energy selective neutron imaging are increasing. To fulfill such requirements, we have newly developed NCIs having a high-speed blanking (gating) circuit and an output phosphor with shorter decay time. By combining these functions with a selection of input phosphor, measuring neutron energy ranges could be precisely selectable between cold and epithermal region, which extends the NCII utilization area to pulsed facilities.

Keywords: Neutron radiography; Image intensifier; Pulsed Neutron Source; Neutron energy selective imaging

1. Introduction

Image intensifiers (abbreviated as IIs) had been used for dynamic neutron imaging of fuel and lubricant of gas turbine engines at the cold neutron \((0.004\text{eV})\) source of DIDO reactor of AERE and HERALD reactor of AERE...
Harwell, in the late 1970s by Stewart et al. (1987). In those days, X-ray IIIs had been diverted to neutron measurement, because Gadolinium Oxysulfide (Gd$_2$O$_2$S: abbreviated as GOS) phosphor of the X-ray II input surface is also sensitive to neutron. “Neutron-Radiation Image Intensifier Tube” of Thomson Tubes Electronique company had also been using GOS as an input reaction surface, but it isn’t commercially available at present.

Recent X-ray IIIs are generally applying CsI columnar scintillator of high spatial resolution for an input reaction surface, as shown by Washida et al. (1979). By introducing a new Gadolinium or Boron deposition method on the surface of CsI columnar crystal and by combining with “color II” technology of X-ray IIIs, Nittoh et al. (2004) have developed neutron color image intensifiers (abbreviated as NCIIs) of new generation having input reaction layers with higher density, higher reaction rate and higher spatial resolution than those with GOS painted type of the first generation.

NCIIs can be applied for inspection of such materials as boron, lithium or hydrogen in metals, which are difficult to observe by X-rays. Recently, with the progress of high power pulsed neutron sources, time of flight (TOF) measurement such as imaging of Bragg-edge or resonance absorption of isotopes have attracted attention as a powerful tool for materials identification method. To meet such conditions, we have newly developed NCIIs for utilizing at pulsed neutron sources.

2. The system configuration of the neutron color I.I. (NCII)

2.1. Configuration of NCII

The basic configuration of the neutron radiography using NCII is shown in Fig. 1. NCII is installed in a neutron irradiation room in Hokkaido University LINAC. Samples are set in front of the input screen of NCII, and are irradiated with the collimated neutron beam. NCII is remotely operated from the control room outside the shielding wall, by monitoring PC informations and camera images.

NCII, the main part of the system, is constructed as shown in Fig. 2. The main functions of NCII are, efficiently converting the incident radiation to fluorescence light, converting the fluorescence to photoelectrons, amplifying and focusing the photoelectrons onto the output fluorescent screen by the acceleration electric field and the electron lens, and finally getting a brighter visible image. Images are captured by a TV camera or a still camera (hereafter referred to as the color camera) through optical systems such as mirror and lens, and are shown on a TV monitor or on computer display. Major differences of NCII from conventional monochrome I.I. are, using a multicolor scintillator as the output phosphor inside NCII, and incorporating a color camera and a color information processing unit. Europium activated Yttrium Oxysulfide (Y$_2$O$_2$S:Eu abbreviated as YOS), developed by Toshiba
Corp., is applied as the multicolor scintillator by Nittoh et al. (1999) and (2003). YOS emits scintillation by electron beam exposure similarly as that by X-rays. By adjusting the Eu concentration, light emission amounts of red(R), green(G) and blue(B) is controlled so as to match the sensitivity characteristics of imaging elements of the color camera. That is, an incident radiation is converted into RGB signals of different color sensitivities depending on its intensity, which leads to the dynamic range expansion of the imaging. There is only a single characteristic curve of grayscale in a monochrome image. In case of the color, three primary colors of RGB can give three independent characteristic curves as respective grayscales. Each color component has different characteristics, and they can be simultaneously displayed on a color display screen.

2.2. Structure of incident window

Two NCII incident surfaces of different neutron reaction have been developed, as shown in Fig. 2. In either case, it is composed of two-layer structure of the neutron reacting layer and CsI scintillator. In case of Gd(n,γ) type using Gadolinium Oxide (Gd₂O₃) as the reaction layer, high energy gamma rays and internal conversion electrons are emitted, as shown in Fig. 2[i-1]. These internal electrons, and photoelectrons illuminates the CsI scintillator. High energy gamma rays are mostly transmitted through the CsI without any reaction. On the other hand, internal conversion electrons have a range of about 20ȝm in Gd₂O₃ deposited layer and in the CsI scintillator. In case of ¹⁰B(n,α) type using enriched ¹⁰B₄C as the reacting layer shown in Fig.2[i-2], the CsI scintillator is illuminated mainly by the alpha particles from the ¹⁰B(n,α) reaction. Neutron reaction increases with the thickness of B (boron) layer, however, alpha particles are not efficiently incident on the CsI scintillator due to its short range of several micrometers in the B layer. Based on the experiment and calculation, an optimum thickness of B layer was determined to 4 to 5ȝm. In comparison with Gd(n,γ) type, the thicknesses of B layer and CsI scintillator have enabled high-resolution imaging. The columnar crystal CsI scintillator is adopted in both Gd(n,γ) type and ¹⁰B(n,α) type, however, the CsI thickness is kept to 1/8 to 1/20 of that of the conventional X-ray I.I. in order to decrease X-ray(γ-ray) sensitivity. Figure 3 shows the neutron absorption cross section of natural Gd and ¹⁰B isotope for neutron energy. Thermal neutron cross sections of ¹⁰B (19.8% of natural abundance) and natural Gd are 3800 barn and 48890 barn, respectively, which exhibits that natural Gd has about 13 times larger reaction rate than ¹⁰B. However, the absorption cross section of Gd decreases sharply with neutron energy in the region from epi-thermal to fast neutrons. Unlike Gd, ¹⁰B neutron absorption cross section obeys 1/v law without resonance absorption peaks in epithermal region, which leads to the features of easier measurement in wide range of neutron energy. Therefore, two types of NCIIIs developed by Nittoh et al. (2009) are classified as follows depending on the application.
\( ^{10} \text{B}(n,\alpha) \) type is applicable to high-definition measurements in a wide energy range. \( \text{Gd}(n,\gamma) \) type is capable of high sensitive measurements below the thermal neutron energy region.

2.3. Output screen type of NCII

There are two types of output phosphor screen of NCII, the first is a conventional high-intensity and high sensitivity type shown in Fig. 2 [o-1], and the second is a short-persistence type shown in Fig. 2 [o-2] having an improved time resolution corresponding to the time-of-flight measurement characteristics at pulsed neutron sources.

The output phosphor of [o-1] uses YOS which emits light in orange. Since the luminescence rate of YOS decreases in order of R, G, and B, the measurement range of color images consisting of three characteristic curves are expanded. An output screen is an important part in this NCII. Fine phosphor grains of YOS with the average diameters of 1 \( \mu \)m are uniformly coated with the thickness of 3 - 4 \( \mu \)m and an aluminum layer is formed on the surface to prevent reflection of the fluorescence.

A newly developed short-persistence NCII shown in Fig. 2 [o-2] uses a blue-light emitting \( \text{Y}_2\text{SiO}_5: \text{Ce} \) phosphor as the output screen. The dynamic range of \( \text{Y}_2\text{SiO}_5: \text{Ce} \) phosphor is not so large. However, the decay time of its afterglow is much shorter than that of YOS.

3. Results and discussion

3.1. Decay time and blanking characteristics

Experiments were carried out at Hokkaido University LINAC facility for measuring the pulse response of NCIIIs. The LINAC was operated with a copper target, 15MeV acceleration energy, 10nsec pulse width and 50pps repetition frequency.

Figure 4 shows the schematic diagram of the measurement. In order to verify the response of the measurement system, an EJ-212 plastic scintillator of ELJEN TECHNOLOGY was measured with a R928 photomultiplier of Hamamatsu Photonics, as the reference. As a result, afterglow time of 0-90% and FWHM are 26.8nsec and 21.6nsec, respectively. Based on this measurement system, characteristics of the two NCIIIs with different output screen types, [o-1] high-intensity and high sensitivity type and [o-2] short-persistence type, were measured. Measurement results were shown in Fig. 5. Afterglow time of [o-1] exhibited 815\( \mu \)sec 0-90% and 219\( \mu \)sec FWHM as shown in Fig. 5(a). On the other hand, afterglow time of [o-2] exhibited 5.08\( \mu \)sec 0-90% and 1.31\( \mu \)sec FWHM. More than two orders of magnitude faster response could be realized by utilization of the new phosphor. In addition, the measuring results of the blanking characteristics of each NCII incorporating different output phosphors were shown in Fig. 6. It was also confirmed that [o-2] showed much faster response in blanking rise time and fall time.
than [o-1]. Next, we show sensitivity characteristics and image measurement results for different output phosphors, measured at the pulsed neutron source.

3.2. Sensitivity comparison

Sensitivity and image quality of NCIs depending on the difference of the input surface of Gd and B, had already been performed by Ishikawa et al. (2014) using the pulsed cold neutron source at Hokkaido University LINAC.

Neutron imaging was carried out under the condition of tungsten source target, liquid helium cooled moderator, 34.9MeV acceleration energy, 3μsec pulse width and 50pps repetition rate. Neutron radiography
images of ASTM indicators were taken by NCIIIs of the different type under various irradiation conditions. Dimensions of ASTM standard indicators are shown in Fig. 7, and the NCII radiography images are shown in Fig. 8. Raw images of 21.1 megapixels high-definition camera are shown in Fig. 8(a), when its ISO sensitivity is fixed to 800 and the exposure time is varied between 30 sec and 600 sec. A blue emitting conventional scintillator NE426 (ZnS:Ag, 5LiF) is used for the reference to the NCIIIs. The direct NE426 image taken in 1800 seconds of exposure time with the same high-definition camera is shown in Fig. 8(a). The ROI brightness of the same portion of Fig. 8(a) images to the exposure time are shown in Fig. 8(b). The brightness of [i-2] and [o-2] short-persistence type has about 7 times higher sensitivity than the NE426 scintillator. However, it has about 60% brightness of the [o-1] high-intensity and high sensitivity type despite its identical [i-2] input layer.

3.3. Spatial resolution

Figure 9 shows the contrast adjusted images after shading correction using background images, whereas Fig. 8 are 14bit raw images. Despite the relatively low L/D value of about 50 of the collimator to NCII, 25μm groove of the indicator attached on the surface of NCII has been identified.

![Fig.8](image)

Fig. 8. Relative sensitivity comparison of NCIIIs (Irradiated at Hokkaido Univ. LINAC Neutron source)
(a) Image data, (b) Brightness measurement data
For comparison, Fig. 10 shows NCII images taken previously by 7R irradiation port of JRR3 reactor where L/D is higher than 170. The view field of the 4-inch NCII was reduced to 2 inches by the internal electron lens, and the similar high-definition camera of 3.5 μm pixel resolution was used. As shown in Fig. 10, the minimum groove of 12.5 μm SI indicator is clearly recognized.

Currently, the spatial resolution of images has been much improved by applying the latest camera with more than 36 million pixels. A new lineup of NCII is listed up in Table 1 and shown in Fig. 11.

4. Conclusion

In order to adapt the NCII to the TOF measurement, it had to improve energy selectivity, ie, a time response, of the incident neutron. To achieve the fast response time performance, NCII with shorter persistence phosphor has been developed and applied. Afterglow decay time of short persistence NCII using a newly developed $Y_2SiO_5:Ce$ phosphor is 5 μsec (0-90%, FWHM: 1.31 μsec), which attained much faster decay time than 815 μsec (0-90%, FWHM: 219 μsec) of standard NCII with YOS phosphor. In addition, the improved blanking function of high-speed switching operation, along with the improved NCII afterglow time, achieved fast time response NCII. However, the sensitivity is reduced to 60% of the conventional phosphor.

Through this NCII development, the input neutron sensing materials can be selected based on the neutron source energy, and the fast time response type can be selected for using at a pulsed neutron source, which leads to wide selection of NCII depending on the purpose of measurements.
We expect that the developed NCII technologies are widely used in future low-carbon and hydrogen societies, especially for various radiographies in steady-state neutron sources, or for neutron science field application in pulsed neutron sources like J-PARC.

Table 1. Neutron Image intensifier Ultimage™ Line up (Revised 2014/10/01)

<table>
<thead>
<tr>
<th>Type</th>
<th>Neutron Image Intensifier</th>
<th>Optional Image Intensifier</th>
<th>Camera</th>
</tr>
</thead>
<tbody>
<tr>
<td>TON101N 4.2</td>
<td>High sensitivity and high spatial resolution (Capable of epithermal neutron imaging)</td>
<td>5 µ sec</td>
<td>Yes</td>
</tr>
<tr>
<td>TON100B 9.7, 5.5</td>
<td>High sensitivity with wide view field (Capable of epithermal neutron imaging)</td>
<td>Yes</td>
<td>Y$_2$O$_2$Ce</td>
</tr>
<tr>
<td>TON101B 5, 7, 9</td>
<td>High sensitivity in thermal neutron with wide view field</td>
<td>Yes</td>
<td>Y$_2$O$_2$Ce</td>
</tr>
<tr>
<td>TON401B 4</td>
<td>High sensitivity and high spatial resolution in thermal neutron (small view field)</td>
<td>Yes</td>
<td>Y$_2$O$_2$Ce</td>
</tr>
</tbody>
</table>

1: Output phosphor decay time is the afterglow recover time from 0 to 90%. The values are measured by a single X-ray pulse of Hokkaido University Linac accelerator.
2: Camera is exchangeable to different model.

References

Washida, H et al., 1979, Advances in Electronics and Electron Physics, 52, p.201