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Development of Two Types of Lightweight Portable Neutron Survey Meter

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Abstract

We have developed two types of lightweight active portable neutron survey meter comprising a proportional gas counter with a mixture of methane and nitrogen for measuring the ambient neutron dose equivalent H*(10). One type without using polyethylene moderator has already been published in Journal of Nuclear Science and Technology. Since no heavy polyethylene moderator is used, this neutron survey meter is only about 2.2 kg in weight causing a weight reduction over 70 % compared with the conventional moderated-type survey meter. The neutron energy response to H*(10) showed very good agreement within about 30% to quasi-mono-energetic and continuous energy neutrons in actual workplace neutron fields over wide energy region from thermal energy up to about 200 MeV. This survey meter can be used in various accelerator facilities. The neutron energy response of this survey meter was however highly deviated from H*(10) to the mono-energetic neutron fields in the keV region. Then, we have developed another type of lightweight neutron survey meter with inserting a thin (2.5 cm thick) polyethylene moderator in the previous gas counter. This new survey meter has a little heavier weight of 3.5 kg, but still lighter than the conventional polyethylene moderated survey meters of about 7 to 11 kg. This survey meter highly improved the neutron energy response in the keV region to the fluence–to-dose equivalent conversion coefficient and can be appropriately used in nuclear power plants where low energy neutrons occupy mostly. These two types of lightweight neutron survey meters are now commercially available and are widely used in various nuclear facilities.

Keywords: Neutron Survey Meter, Neutron Energy Response, Experimental Data, Phits Monte Carlo Calculation, Ambient Dose Equivalent Rate, Neutron Reference Field

Introduction

Active portable neutron survey meters that are widely used in nuclear facilities; however, they have generally heavy weight above 7 kg [1-5]. It is because in those conventional neutron survey meters, a central thermal neutron detector, such as a ^{3}He counter, BF_3 counter, and LiI(Tl) scintillator, is covered with thick (about 10 cm) polyethylene moderator. The handling of these neutron survey meters is therefore quite inconvenient for a person who walks around a large site to survey the neutron dose level by carrying the heavyweight survey meter. Among the three counters, the ^{3}He counter has mostly been used as a central thermal neutron detector due to higher thermal neutron sensitivity [6,7]. However, the recent shortage of ^{3}He gas, so-called ^{3}He crisis, which has been a worldwide serious problem in neutron field measurement

Considering these circumferences, we have newly developed two types of lightweight neutron survey meters using a gas counter with a mixture of methane and nitrogen for dose management in nuclear power plants and accelerator facilities. These two survey meters, NSN3A and NSN3B, are approximately 16 cm x 25 cm x 30 cm in size, and can measure ambient neutron dose equivalent H*(10), directly from thermal to about 20 MeV neutrons. One type without polyethylene moderator, NSN3A, is approximately 2.2 kg in weight, which is 70% or more light weight than the conventional moderated-type neutron survey meters. The detailed information of this survey meter has recently been published in Ref. 8. The NSN3A survey meter has very good energy response to H*(10) only within 25% difference to the continuous energy neutron fields which are close to the actual workplace neutron fields. However, the response to the mono-energetic neutron fields in keV energy region is highly deviated to H*(10). This can bring the underestimation of the neutron dose equivalent such as in a passageway and in a personal airlock in nuclear power plant, which are dominated by low-energy neutrons below 100 keV.

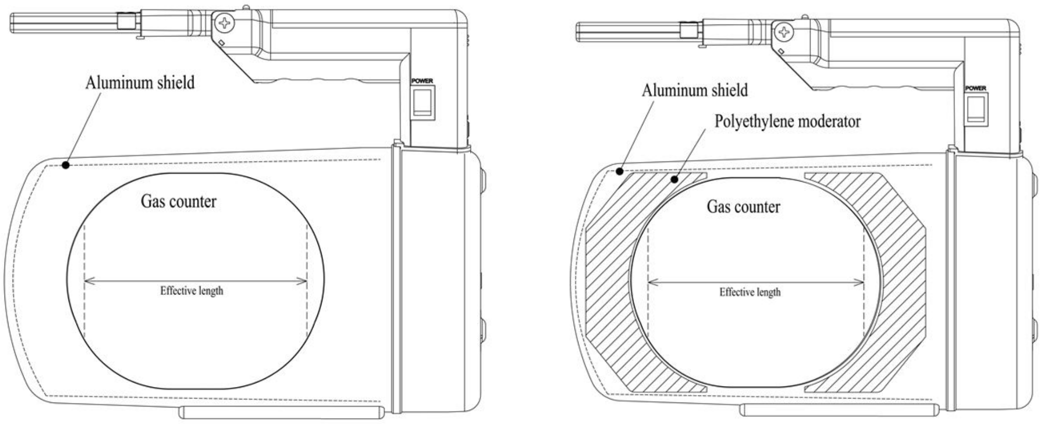
Then we further improved the NSN3A survey meter with inserted thin polyethylene moderator of 2.5 cm thickness in order to increase the sensitivity of neutrons especially in the keV region. This new survey meter, NSN3B, has a little heavier weight of 3.5 kg, but still lighter than the conventional polyethylene moderated survey meters of about 7 to 11 kg. Here in this work, the further development of NSN3B is given by comparing it with NSN3A.

The characteristics of these two neutron survey meters for neutron energy response, angular dependence and detection efficiency were evaluated by measurements at several mono-energetic and quasi-mono-energetic neutron reference fields from thermal energy up to 244 MeV. The neutron energy responses of these two survey meters were also evaluated using the Particle and Heavy Ion Transport Code System (PHITS) code [9].

Neutron detectors of NSN3A and NSN3B survey meters

Outline of neutron detectors

The cross-sectional views of the two survey meters are shown in Figure 1 (a) and (b). The neutron detectors of both NSN3A and NSN3B survey meters are a gas counter consisted of methane gas of approximately 0.4 MPa and nitrogen gas of approximately 0.1 MPa which are encapsulated into thin stainless-steel vessel. It is almost a spherical shape of approximately 13-cm diameter and effective length of 13 cm. The effective volume is approximately 1440 cm^3. The neutron detectors of NSN3A and NSN3B survey meters are both encapsulated into 1 mm thick aluminum shield box, and only for the neutron detector of NSN3B the thin polyethylene moderator of 2.5 cm thickness is inserted between the detector and the shield box.



(a) NSN3A (b) NSN3B

Figure 1: Cross-sectional views of the developed neutron survey meters

The neutrons are measured using the mixed gas of methane and nitrogen. Fast neutrons above several hundreds keV are measured using the recoil proton of elastic scattering reaction of hydrogen, H(n, n)p, in the methane gas and slow neutrons including thermal neutrons are measured using the ^{14}N(n, p)^{14}C reaction of nitrogen gas. The proton energy in ^{14}N(n, p)^{14}C reaction is 626 keV. The electrical pulses are generated from those protons. By using these two reactions the neutron ambient dose equivalent can be obtained from thermal neutrons up to about 20 MeV neutrons. For higher energy region, carbon reactions such as ^{12}C(n, p) and ^{12}C(n, α) reactions, have some contribution to the output pulses.

Evaluation of neutron and gamma-ray characteristics

The neutron energy response and detection efficiency were measured in the continuous energy neutron reference fields and the monoenergetic neutron fields at the National Institute of Advanced Industrial Science and Technology (AIST) [10], the Facility of Radiation Standard (FRS) [11-17] of Japan Atomic Energy Agency (JAEA), the Fast Neutron Laboratory (FNL) [18] and the Cyclotron and Radioisotope Center (CYRIC) [19] of Tohoku University. The fluence-averaged neutron energies in various neutron reference fields are shown in Table 1 for continuous energy neutron fields and in Table 2 for monoenergetic neutron fields. A graphite pile of 150 cm x 164 cm x 150 cm loading a ^{252}Cf source set at the center of graphite pile [11] is used for both thermal neutron field and graphite-moderated neutron field [17]. The graphite-moderated neutron field is produced by using the ^{241}Am-Be source at the shallow position with the thermal neutron absorption sheet made of gadolinium. A concrete moderated neutron field is a neutron field (now defunct) where the ^{241}Am-Be source is transmitted through concrete blocks of 1 m width, 2.85 m length and 1 m height [12]. The neutron detector is fixed at 53 cm height in space and the neutron spectrum can be changed by keeping 60, 110 and 160 cm distance between the source and the concrete blocks. These two neutron fields have wide-spread neutron spectra simulating workplace neutron fields.

Although these neutron survey meters are originally aimed to measure the ambient neutron dose equivalent up to 20 MeV, we further investigated the neutron energy response of the Type A survey meter for higher energy region above 100 MeV for use in high energy accelerator facilities. For this application, neutron detection efficiency was investigated by measurements at quasi-mono-energetic neutron reference fields of 134, 197 and 244 MeV produced from the ^{7}Li(p, n) reaction at Research Center for Nuclear Physics (RCNP) cyclotron facility of Osaka University [20].

The influence of the gamma rays was measured using ^{137}Cs and ^{60}Co sources at 1 mSv h^{-1} and 10 mSv h^{-1} at Fuji Electric Co., Ltd.

Neutron energy response calculation using the PHITS Monte Carlo code

Neutron energy responses were calculated using the Monte Carlo simulation, PHITS (Particle and Heavy Ion Transport code System) 2.64 [9] with JENDL 4.0 [21] neutron cross section data. In this calculation, carbon, hydrogen and nitrogen were installed in the thin stainless-steel vessel of which shapes was almost sphere and the energy deposition distributions from charged particles were obtained by T-Deposit tally named in PHITS using the neutron energy from 0.001 eV to 100 MeV. The neutron energy was divided by 10 energy regions in the log-scale at every digit and neutrons were generated more than 10^7 events in order to decrease the statistical errors. Neutron energy responses were obtained by summing up the counts, which were corrected using spectrum-weight G-function method described in Ref. 8 above the threshold level of gamma-ray cutoff of this detector to be decided at 400 keV.

Table 1: Fluence-averaged neutron energy of continuous energy neutrons

Facility	Source	Fluence-average neutron energy [MeV]
JAEA	Thermal [12]	0.025 x 10^{-6}
JAEA	D_2O moderated [14]	0.55
JAEA	Graphite moderated [18]	0.84
JAEA	Concrete moderated 3 [13]	0.58
JAEA	Concrete moderated 2 [13]	1.5
JAEA	Concrete moderated 1 [13]	2.6
AIST, JAEA	^{252}Cf	2.13
JAEA	^{241}Am-Be	4.16
Tohoku Univ.	Iron moderated [20]	0.33

Table 2: Fluence-averaged neutron energy of monoenergetic neutrons

Facility	Source	Neutron energy [MeV]
JAEA	Sc(p, n) [15]	0.008
AIST	Li(p, n) [11]	0.024
JAEA	Li(p, n) [16,17]	0.144
JAEA	Li(p, n) [16,17]	0.250
JAEA	Li(p, n) [16,17]	0.565
Tohoku Univ.	T(p, n) [19]	1
AIST	T(p, n) [10]	1.1
Tohoku Univ.	D(d, n) [19]	5.0
JAEA	T(d, n) [17]	14.8

Figure 2 gives the calculated results by changing the polyethylene thickness inserted between the detector and the shield box. The neutron energy responses were normalized at 2 MeV to obtain the relative neutron response. With increasing the polyethylene thickness, the calculated neutron energy response in the keV region largely increases and approaches to the fluence-to-ambient-dose-equivalent conversion coefficient, $H^*(10)/\phi$. We therefore decided to have 2.5-cm-thick polyethylene as described before.

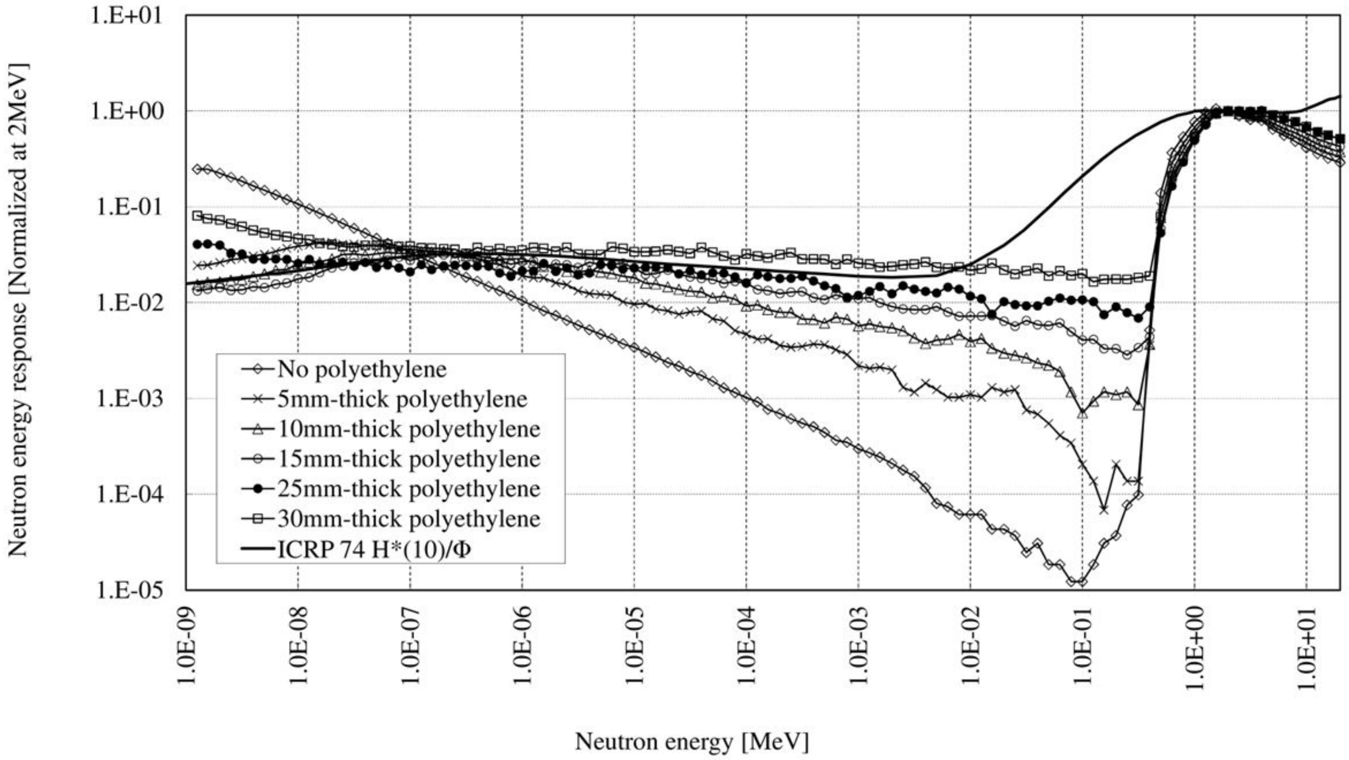


Figure 2: Calculated results of neutron energy response with changing the polyethylene thickness inserted between the detector and the shield box

Experimental Setup

Figure 3 shows the experimental arrangement. Signals from the neutron survey meter after the amplifier unit were fed into an external multi-channel analyzer, MCA600 (Laboratory Equipment Corp.) to obtain the pulse height distribution corrected using the G-function method [8]. The detector was located at the distance of 80 to 250 cm from the neutron source. In thermal neutron irradiation, the detector was located at a closer distance of 40 cm from the graphite pile surface. The room-scattered neutrons were subtracted with the shadow corn method, excluding the thermal neutron field, concrete-moderated neutron field and graphite-moderated neutron field.

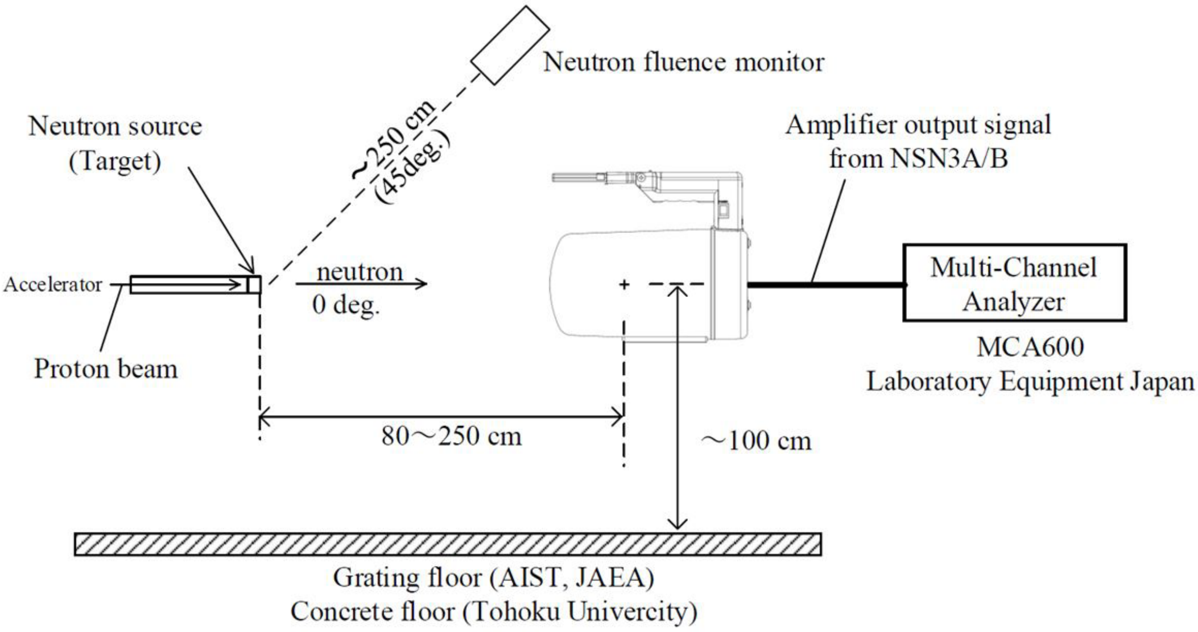


Figure 3: Experimental arrangement at AIST, JAEA and Tohoku University

Results and Discussion

Neutron energy response

The neutron energy responses of NSN3A and NSN3B for neutron fluence were obtained by summing up the counts which were corrected using the G-Function method above the discrimination level of 400 keV. The errors were estimated from statistical errors of the detector total counts, the neutron fluence at the reference field and the uncertainties of source intensities. Statistical errors of the total counts were usually less than 3.5 % (2σ : σ is the standard deviation), however, in the cases of 144 keV and 250 keV monoenergetic neutrons, the statistical errors were more than 95 %, due to the low neutron sensitivity in the energy around 100 keV. Uncertainties of neutron fluence of ^{252}Cf, ^{241}Am-Be sources and graphite-moderated neutrons were expected less than 14 % (2σ). Uncertainties of concrete-moderated neutrons were about 20 % (2σ). The thus-obtained neutron energy responses are indicated in Figure 4 by open circles for NSN3A and open square for NSN3B for comparing with the fluence-to-ambient-dose-equivalent conversion coefficient curve indicated by a bold solid line, $H^*(10)/\phi$, given by ICRP Pub. 74. The solid line and dashed line in histogram are the calculated results using the PHITS Monte Carlo code. The measured results are in good agreement with the PHITS calculation. The measured response of NSN3B becomes much better agreement with the fluence-to-ambient-dose-equivalent conversion coefficient curve indicated by a bold solid line, $H^*(10)/\phi$, about two orders of magnitude higher than that of NSN3A, which verifies much better neutron energy response in keV energy region.

The neutron energy responses at thermal energy and between 1 MeV and 10 MeV give good agreement with $H^*(10)/\phi$ for both neutron survey meters, but the high-energy neutron response at 14.8 MeV gives underestimated values of approximately 40 % to $H^*(10)/\phi$. This is because that the neutron elastic scattering reaction cross section with the hydrogen decreases and the energy deposition of recoil protons decreases, due to decrease of the stopping power of proton with energy, then leads to decrease of the signals which can exceed the discrimination level of 400 keV.

The neutron ambient dose equivalent responses of NSN3A and NSN3B measured for various continuous energy neutron fields given in Table 1 and quasi-mono-energetic high energy neutron reference fields of 134, 197 and 244 MeV at RCNP [20,22], are shown in Figure 5, as response values normalized to that for ^{252}Cf source as a function of fluence-averaged neutron energy. As a result, both NSN3A and NSN3B survey meters have sufficiently good response, within 35 % difference to neutron ambient dose equivalent for fluence-averaged continuous neutron energy in very wide energy range from 0.025 eV up to about 300 MeV. On the other hand, Fuji Electric NSN1, NSN2 [1] and Alnor 2202D which are both polyethylene moderated-type give about one-fifth lower values, while on the other hand, WENDI, which is polyethylene and tungsten moderated-type for higher energy use, gives about 30%–60% higher values at neutron energies over 100 MeV. It was found that NSN3A and NSN3B have much better energy responses than the conventional moderated-type neutron survey meters to be used at accelerator facilities of energy beyond 100 MeV.

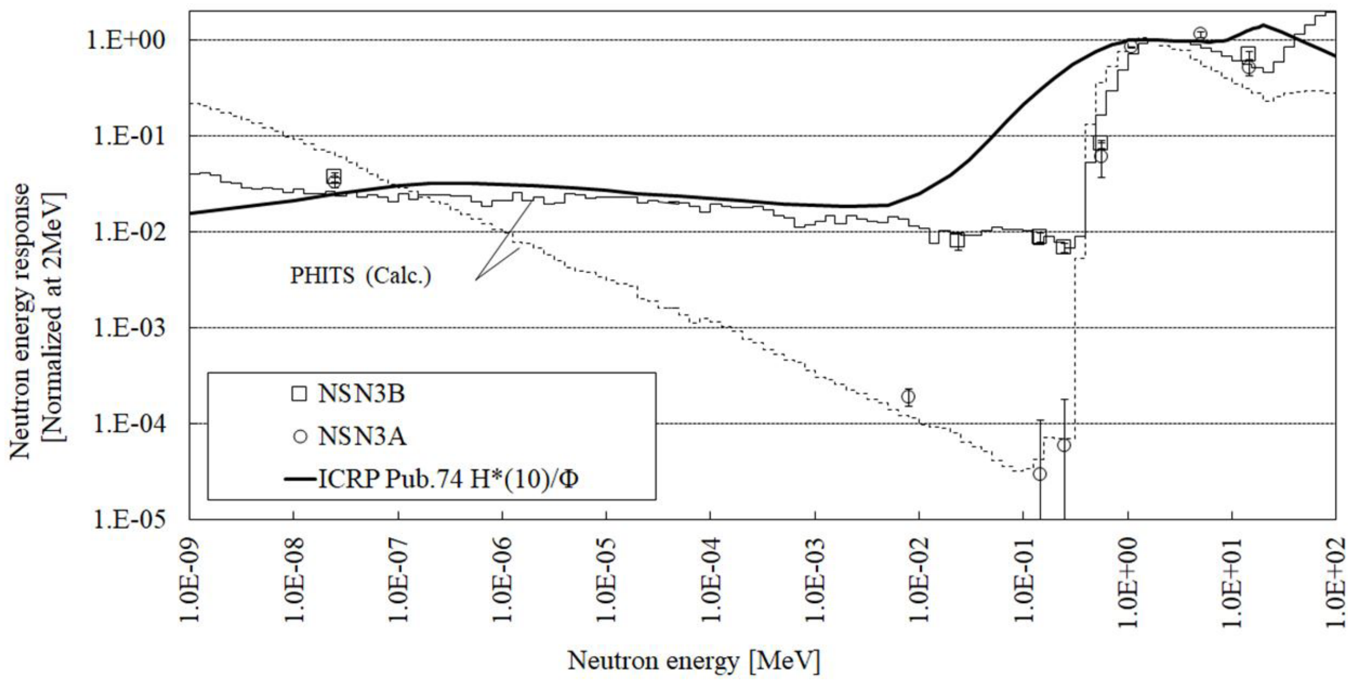


Figure 4: Neutron energy response for neutron fluence of the developed NSN3B neutron detector by comparing with the NSN3A neutron detector. Measured data are open circle, calculated data using PHITS code are solid line of histogram. Bold solid line is the fluence-to-ambient-dose-equivalent conversion coefficient, H*(10)/ϕ, given by ICRP Pub. 74

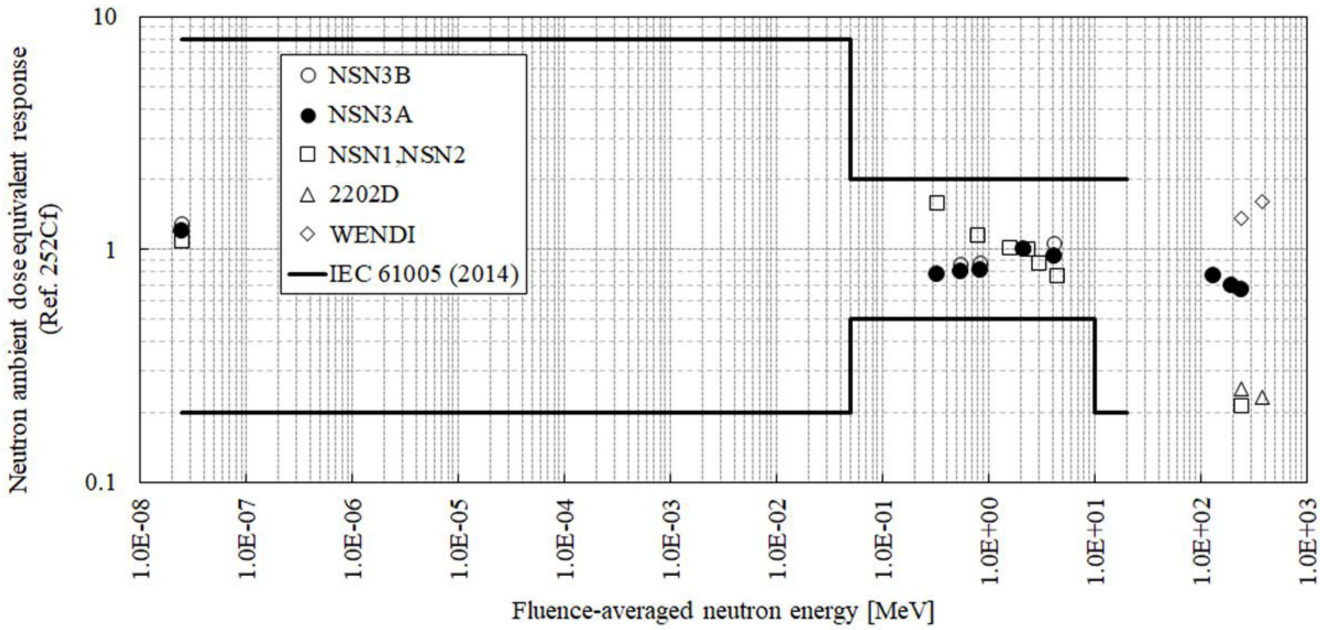


Figure 5: Neutron ambient dose equivalent response of the developed NSN3A and NSN3B neutron survey meters for various continuous energy neutron fields in very wide energy range from 0.025 eV up to about 300 MeV

Angular distribution

Angular distribution of NSN3A and NSN3B were obtained using an ^{241}Am-Be neutron source at every 30-degree from 0 to 180 degrees in the vertical and horizontal directions at Fuji Electric Co. Ltd. The distance between the survey meter and the neutron source was 40 cm. Figure 6 shows the angular distributions of developed two neutron survey meters, the open circle for NSN3A and open square for NSN3B. These are normalized at zero degree of which the direction is shown in Figure 3. The angular distributions are almost constant within 25%, because the sensitive area of these detectors are almost a spherical shape as shown in Figure 1. It is found that these survey meters have a flat angular distribution for neutrons in all directions.

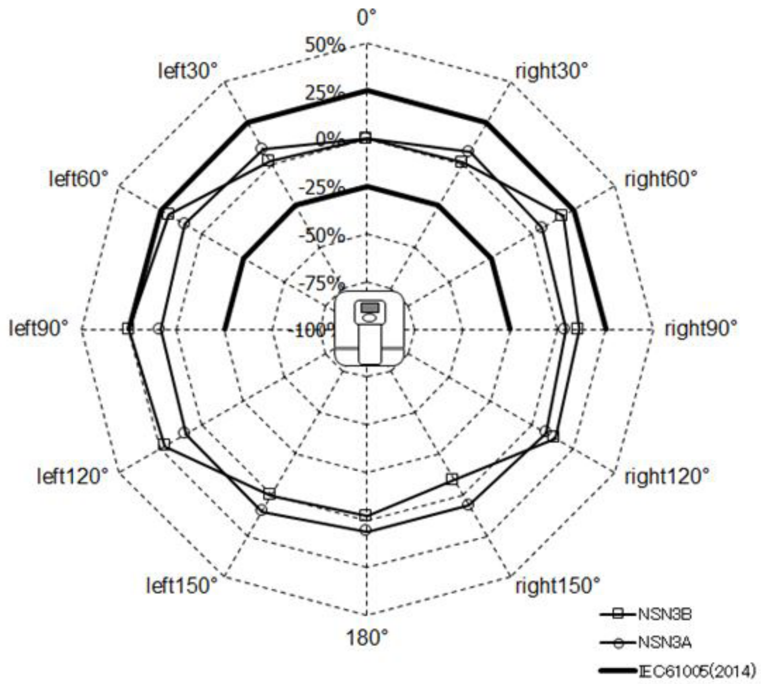


Figure 6: Angular distribution of the developed neutron survey meter using an ^{241}Am-Be neutron source

Figure 7: Outlook of light-weiht portable neutron survey meters, NSN3A and NSN3B

Response of gamma ray

The gamma ray responses of NSN3A and NSN3B were obtained using ^{137}Cs and ^{60}Co sources. These are under 0.01 % at 1 mSv h^{-1} and under 0.1 % at 10 mSv h^{-1}. It is found that the developed neutron survey meters have almost very low sensitivity for photon radiation of dose rate below 10 mSv h^{-1}.

Specifications of two types of light-weight neutron survey meter, NSN3A and NSN3B

The specifications of these two neutron survey meters, NSN3A and NSN3B, are shown in Table 3. The NSN3A survey meter without polyethylene moderator is only 2.2 kg in weight and the NSN3B survey meter with thin polyethylene moderator is 3.5

kg in weight. The NSN3A is over 70 % and the NSN3B is about half lighter than the conventional moderated-type survey meter, NSN1 and NSN2 [1], which are about 7 kg. These survey meters shown in Figure 7 are capable directly to measure ambient neutron dose equivalent H*(10) from thermal to about 20 MeV neutrons. The NSN3A has rather lower sensitivity to neutrons in keV region but has good energy response for continuous energy neutron field simulating actual wok-place neutron fields up to about 250 MeV neutron energy. The NSN3A survey meter is clearly a useful monitoring tool to use in various accelerator facilities over wide energy range. On the other hand, the NSN3B survey meter has much better energy response especially in keV region and is especially very useful to use in nuclear power plants where neutrons in the keV region occupy largely the neutron ambient dose equivalent rate.

Table 3: Specifications of neutron survey meter, NSN3

Measurable energy range		0.025 eV to 20 MeV
Measurement range	Dose rate	0.1 μSv h^{-1} to 100 mSv h^{-1}
	Accumulate Dose	0.01 μSv to 100 mSv
Accuracy	Dose rate	≤ ±20 % at 10 μSv h^{-1}
	Accumulate Dose	≤ ±20 % at 1 μSv
Angular dependence		≤ ±25 %
Neutron sensitivity (^{252}Cf)	NSN3A	0.3 s^{-1}/(μSv h^{-1})
	NSN3B	0.2 s^{-1}/(μSv h^{-1})
Photon sensitivity (^{137}Cs and ^{60}Co)	1 mSv h^{-1}	< 0.01 %
	10 mSv h^{-1}	< 0.1 %

Conclusion

The two types of lightweight portable neutron survey meters have been developed comprising a proportional gas counter with a mixture of methane and nitrogen, the one without and the other with thin polyethylene moderator. Performance tests were carried out using mono-energetic and quasi-mono-energetic neutron fields from thermal energy up to about 250 MeV energy and also continuous energy neutron fields simulating actual work-place neutron fields. The neutron energy responses were obtained from thermal energy to fluence-averaged neutron energy of 4.16 MeV within 25 % difference to neutron ambient dose equivalent. Neutron detection efficiencies for ^{252}Cf source were obtained to be 0.3 s^{-1}/(μSv h^{-1}) for NSN3A and 0.2 s^{-1}/(μSv h^{-1}) for NSN3B. These neutron survey meters have good response to ambient dose equivalent for continuous energy neutron sources simulating workplace and its surrounding environmental neutron fields. The NSN3A survey meter has also much better sensitivity up to about 250 MeV neutrons than the conventional moderated-type neutron survey meters, which becomes a useful monitoring tool in high energy accelerator facilities. The NSN3B survey meter has much better energy response especially in keV region and is especially very useful to use in nuclear power plants where neutrons in the keV region occupy dominantly the neutron ambient dose equivalent rate. Furthermore, these neutron survey meters have very low sensitivity to photons, less than 0.1 % for 10 mSv h^{-1} dose rates.

These survey meters satisfy the angler distribution, energy response and response to photon radiation in IEC 61005 standard [23]. The neutron detection efficiencies of 0.3 and 0.2 s^{-1}/(μSv h^{-1}) of these light-weight NSN3A and NSN3B survey meters are almost the same efficiency of Alnor 2202D having about 10 kg weight, although they are lower than 4.0 s^{-1}/(μSv h^{-1}) of high sensitivity survey meters, NSN1 and NSN2 having 7 kg weight. It can be finally concluded that these light-weight portable neutron survey meters of 2.2 kg and 3.5 kg can make the handling of neutron survey meter easier and be suitable for environmental monitoring around nuclear power plants and accelerator facilities.

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