Recent Activities on Neutron Calibration Fields at FRS of JAERI

Michio Yoshizawa, Yoshihiko Tanimura, Jun Saegusa and Makoto Yoshida
Department of Health Physics,
Japan Atomic Energy Research Institute

1. Preface

Recent activities on neutron calibration fields at the Facility of Radiation Standards (FRS) of the Japan Atomic Energy Research Institute (JAERI) have been focused on the development of mono-energetic neutron calibration fields using a Van-de-Graaff accelerator. This report describes the present status of the mono-energetic neutron calibration fields of FRS of JAERI. In addition, we report our related activities on neutron calibration: renewal of the graphite pile of FRS for thermal neutron calibration fields and the development of a moderated-type neutron detector for establishment of reference neutron field with broad energy spectrum.

2. Mono-energetic Neutron Calibration Fields

Mono-energetic neutron calibration fields have been developed at FRS of JAERI using a 4MV Van-de-Graaff (Pelletron) accelerator. Available energy points are planned to be 10-points between 8 keV and 19 MeV, which cover the energies specified in ISO 8529-1[1]. The energy points and used nuclear reactions are summarized in **Fig. 1**. The fields of 144 keV, 565 keV and 5.0 MeV neutrons have been constructed along the 0°-line with respect to the incident beam, by measuring neutron energy spectra and establishing a neutron monitor method to determine reference neutron fluences. The nuclear reactions employed for neutron production in the fields are ^{7}Li(p,n)^{7}Be for the 144 keV or 565 keV field and ^{2}H(d,n)^{3}He for the 5.0 MeV field. The target for the ^{7}Li(p,n)^{7}Be reaction is made of thin vacuum-deposited LiF on molybdenum backing with 0.5mm in thick. The thickness of the LiF target is ~0.1mg cm^{-2}. The target for the ^{2}H(d,n)^{3}He reaction is a gas cell (15mmϕ × 23mm) with a molybdenum window foil (~5μm^{t}) which separates the gas cell and beam line. The gas pressure is about 1 atm. A platinum beam stopper (0.5mm^{t}) is used to reduce the production of uninvited neutrons. The size of the irradiation room is 16.5m×11.5m×12.3m with an aluminum grating elevated at mid-height of the room. A photograph of the irradiation room is shown in **Fig. 2**.

The neutron energies were measured by time-of-flight (TOF) technique. A BC501A scintillation detector (5.08cmϕ×5.08cm) was used in the measurements. The measurement was performed with two steps: 1) measurement of peak neutron energies, and 2) measurement of source energy spectra. The peak neutron energy of each field was precisely determined from the difference of the flight-time measured at two positions with different distances from the target on the 0°-line. The beam conditions, such as an accelerator voltage, current of analyzing magnet, beam optics, etc., were determined for each field through the measurement. The neutron source spectra were measured by positioning the detector in a collimator to eliminate neutrons coming from other than the target assembly. The measured spectra are shown in **Fig. 3**, compared with the calculated spectra with the MCNP-ANT code system [2]. The measured and calculated spectra are in good agreement for 144 keV and 565 keV, while measured spectrum is broader than the calculated one for 5.0 MeV. This should be explained as follows; the flight-time of incident proton passing through the gas cell (23 mm in length) of ~2 ns spreads the measured neutron flight-time, and this would cause the neutron spectrum broaden. **Table 1** summarizes the measured and calculated energy spreads, full width at half maximum (FWHM), derived from the spectra. For 5.0MeV neutrons, the difference between the measured and the calculated energy spread is 115keV, which approximately corresponds to the 2ns difference of the flight-time of ~5MeV neutrons. Therefore, the calculated spectrum would be the source spectrum of 5.0 MeV neutrons rather than the measured one. The energy spreads of 14%, 2.5% and 3.2% for 144keV, 565keV and 5.0MeV neutrons, respectively, are sufficient energy resolutions to calibrate neutron dosemeters.

The Long counter is used as a monitor to determine the reference neutron fluence at a calibration point. In the case of accelerator-produced neutron fields, reference neutron fluence should be determined with a neutron monitor. We select the Long counter as the neutron monitor because the counter has an appropriate sensitivity and a flat response for wide energy range. The Long counter has been set up at 2.2 m from the target on the 60°-line. The arrangement in the irradiation room is shown in **Fig. 4**. The position of the Long counter was selected from the available positions in the room in consideration of the influence of scattered neutrons from calibrated devices and their supporting materials.

The reference fluence $\Phi(d)$ at a calibration point (placed at d cm from the target) can be derived from the following equation;

$$\Phi(d) = N_{LC} \times \frac{K_{LC}}{d^2} \times S$$

where N_{LC} is the counts of the Long counter, K_{LC} is the conversion coefficient from N_{LC} to $\Phi(d)$, S is the correction factor for in-scattered neutrons from calibrated devices and their supporting materials in N_{LC}. The factor S can be determined from the measurement of the ratio of N_{LC} with and without calibrated devices and their supporting materials.

The traceability of the fields to the primary standard laboratory (AIST) in Japan was established by determining the coefficient K_{LC} with a transfer instrument of AIST. The transfer instrument was a Bonner-sphere of AIST with 24.13cmϕ (9.5-inchesϕ) using a spherical ^{3}He counter, which was calibrated at the primary standard fields. The reference neutron fluence at 1.2m on the 0°-line was measured with the transfer instrument. The conversion coefficient, K_{LC}, was determined from the measured reference fluence (normalized per unit steradian) divided by the counts of the Long counter, N_{LC}, which were simultaneously measured and corrected for the factor S. The shadow cone technique was used to eliminate scattered neutrons. The K_{LC} values obtained by the above method are summarized in **Table 2**. The expanded uncertainties of K_{LC} were calculated according the Guide to the expression of Uncertainty in Measurement (GUM)[4], and estimated to be 5 to 7% (k=2).

3. Renewal of Graphite Pile for Thermal Neutron Calibration Fields.

The Facility of Radiation Standards (FRS) has been equipped with thermal neutron fields using a graphite pile. The graphite pile is set in the irradiation room for RI-neutron sources with a dimension of 12.5m × 12.5m × 11.7m. The old pile had been used over 20 years as a thermal neutron calibration fields in Japan. In 2003, the graphite pile was renewed due to deterioration.

The new graphite pile has a dimension of 1.50m(W) × 1.64m(L) × 1.50m(H), of which the height is 34cm larger than the old one. A photograph of the new pile is shown in **Fig. 5**. The new pile provides, like as the old one, the two kinds of thermal neutron fields: outside-pile and inside-pile (center cavity) irradiation fields. In the case of the outside-pile irradiation field, a ^{252}Cf neutron source (100μg) is placed in the center of the pile, and leakage neutrons from the pile are used for calibration. The calibration is performed at the point of 40cm from the surface of the pile and 75cm from the floor. On the other hand, the inside-pile irradiation fields use a cavity (30cm × 27cm × 47cm) located in the center of the pile. A pair of an ^{241}Am-Be (37 GBq) and a ^{239}Pu-Be (37 GBq) sources are symmetrically placed at either side of the cavity. We can choose one of the four symmetrical source positions for different thermal fluence rates and cadmium ratios.

Reference thermal neutron fluence rates of the fields were determined by the gold-foil activation method. Two gold foils with an aluminum cover and a cadmium cover (1.0 mm^{t}) were simultaneously irradiated for each field. The foil has a diameter of 20mm and a thickness of 20μm. Induced activities of ^{198}Au were measured by the absolute method with the 4πβ–γ coincidence counter that has the traceability to the primary standard of Japan. The reference thermal neutron fluence rates were determined from the saturated induced specific activities, the cross-section of the ^{197}Au(n,γ)^{198}Au reactions for thermal neutrons, and some correction factors for a perturbation effect by the foil and cover. The dose-equivalent rates, H*(10) and H_p(10), were derived using the fluence-to-dose equivalent conversion coefficients for thermal neutrons specified in ISO 8529-3[3].

The reference values of the fields and Cd-ratios are summarized in **Table 3**. The reference thermal neutron fluence rates are 1.75×10^{3} to 4.29×10^{3}(cm^{-2} s^{-1}) for the inside-pile fields and 5.54×10^{2}(cm^{-2} s^{-1}) for the outside-pile field. The expanded uncertainties of the reference fluence rates were calculated according to GUM [4], and estimated to be ~2%(k=2). The traceability of the fields to the primary standard of Japan (AIST) has been kept through the intercomparisons of the ^{198}Au activity and thermal neutron fluence rate measurement between JAERI and the Electrotechnical Laboratory (now AIST). Detailed characteristics of the fields are now under investigation through the measurement and the calculation of neutron spectra and thermal neutron distribution in the fields.

4. Development of a Moderated-type Neutron Detector for Transferring Standard of Calibration Fields with Broad Spectra.

We have been developing a neutron detector to be applied to transferring standard of the calibration fields with broad spectra, such as workplace-simulated neutron fields. The detector consists of a cylindrical moderator and a long position-sensitive ^{3}He proportional counter as shown in **Fig. 6**. The neutrons incident on the surface of the detector parallel to its cylindrical axis loss their energy while penetrating into the cylindrical moderator, and become thermal neutrons. The thermal neutrons diffuse in the moderator and are detected by the thermal neutron counter settled on the central axis of the moderator. Fast neutrons penetrate further into the moderator than slow neutrons until they become thermalized. Therefore, the detected position profile of thermal neutrons with the position-sensitive counter reflects the incident neutron energy distribution, and we can obtain energetic information of the incident neutrons from the profile [5].

The structure and materials of the moderator were optimized by the Monte Carlo simulation with the MCNP-4B transport code [6]. The transport calculations show the moderator of polyethylene needs 30 cm in diameter and 100 cm in length to measure neutrons up to 20MeV. The simple polyethylene moderator, however, was found not to have enough energy resolution in the neutron energy range below 100 keV. This was solved by applying a combination of polycarbonate, which has lower hydrogen density than polyethylene, with 40 cm in length on front side and polyethylene with 60 cm in length on back side, and cadmium sheet as a thermal neutron absorber to reduce undesirable diffusion of thermal neutrons to the moderator. The shape of the Cd-sheet was optimized by calculating thermal neutron distributions in the moderator. **Figures 7(a) and (b)** show the calculated position profile of thermal neutrons in the detector for different mono-energetic neutrons before and after the improvement, respectively. After the improvement, the different position profiles are obtained enough to resolve the energies below 100 keV. We have concluded that the designed detector should be able to measure energy spectrum with neutron energies from a few tens keV to 20 MeV.

References

[1] ISO: ISO 8529, Part 1 (2001).
[2] Yoshizawa, M., et al.: J. Nucl. Sci. and Technol., Suppl. 2, 1240 (2002).
[3] ISO: ISO 8529, Part 3 (1998).
[4] ISO, BIPM, IEC, et al.: Guide to the expression of uncertainty in measurement (1993).
[5] Toyokawa, H., et. al.: Proc. 8th ASTM-Euratom Symp. Reactor Dosim., 263 (1993).
[6] Briesmeister, J. F.(Ed.) : LA-12625-M (1997).

Table 1 Energy spread of 144 keV, 565 keV and 5.0 MeV neutrons

Neutron energy	Energy spread (FWHM)	
	Measured by TOF (keV)	Calculated by MCNP-ANT (keV)
144keV	20	20
565keV	15	14
5.0MeV	275	160

Table 2 Characteristics of mono-energetic neutron calibration fields

Neutron energy (Max. beam current)	Maximum values at 1m		Conversion factor, K_{LC} [sr^{-1} $count^{-1}$] (Uncertainty, k = 2)
	Fluence rate [cm^{-2} s^{-1}]	Dose equivalent rate H*(10) [mSv h^{-1}]	
144keV (50μA)	3×10^3	1.4	2.9×10^4 (7%)
565keV (50μA)	6×10^3	7.4	3.7×10^4 (5%)
5.0MeV (2μA)	5×10^3	7.3	6.0×10^4 (7%)

Table 3 Reference values of thermal neutron calibration fields with the new graphite pile

Field position and sources	Source position	Thermal neutron fluence rate ϕ_{th} (cm^{-2} s^{-1})	Uncer-tainty (%) (k=2)	Dose equivalent rate (μSv/h)		Cd ratio (Au)	Irradiation position	Reference date
				H*(10)	H_p(10)			
Inside-pile ^{241}Am-Be and ^{239}Pu-Be	1	4.29×10^3	1.8	164	Not availa-ble	4.1	Cavity in the center of pile	14 Feb 2003
	2	3.58×10^3	1.7	137		4.9		
	3	2.68×10^3	1.7	102		6.3		
	4	1.75×10^3	1.7	66.8		8.6		
Outside-pile ^{252}Cf		5.54×10^2	1.9	21.1	22.7†	69	40cm from the surface of the pile	8 Feb 2003

† Values when thermal neutrons are assumed incident on perpendicular to the ICRU-slab phantom.

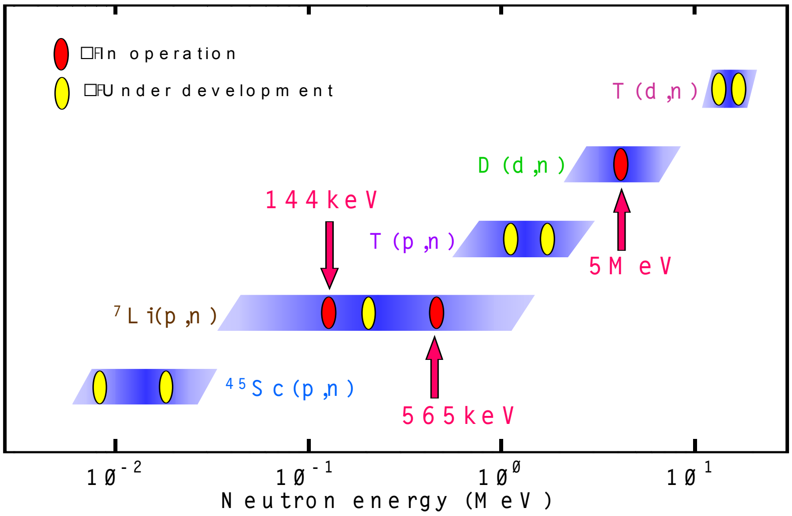


Fig.1 Neutron energies and nuclear reactions to be used for the mono-energetic neutron calibration fields of FRS/JAERI. Broad line shows an available energy range produced by each nuclear reaction, and ellipses indicate the neutron energy points developed or to be developed as calibration energies based on ISO 8529-1. 144keV, 565keV, and 5.0MeV neutrons are in-operation.

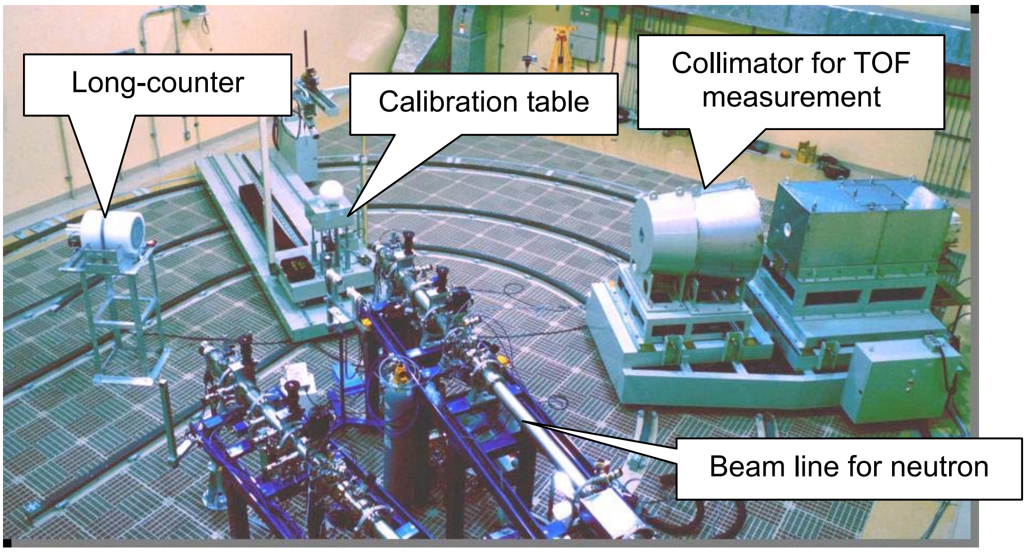
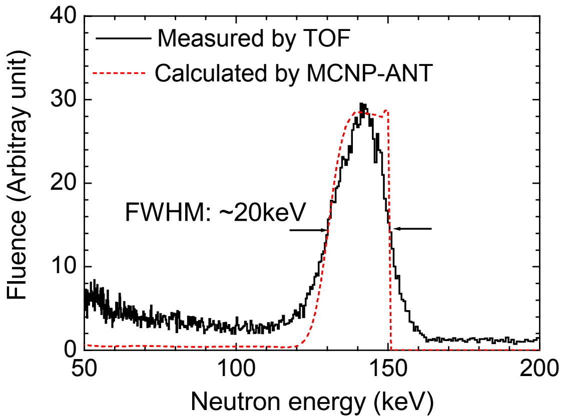
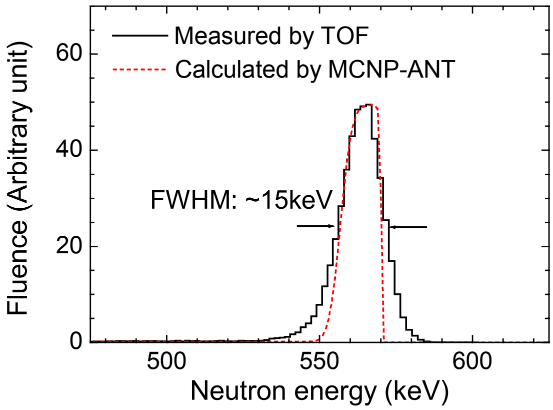


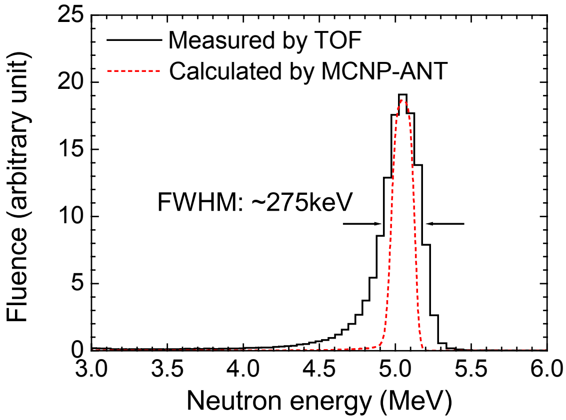
Fig.2 Photograph of the mono-energetic neutron irradiation room. The calibration table and collimator for TOF measurement rotate around a target from 0° to 120°. The Long counter is used as a neutron fluence monitor.



(a) 144keV neutrons



(b) 565keV neutrons



(c) 5.0MeV neutrons

Fig.3 Source spectra of (a) 144keV, (b) 565keV, and (c) 5.0MeV neutrons, measured by TOF (solid lines) and calculated by MCNP-ANT (dashed lines). The deuteron flight time in the D_2-gas cell broadens the measured spectrum of 5.0MeV.

Fig.4 Photograph of the experiment for establishing traceability. The fluence monitor (Long counter) was calibrated with a transfer instrument, which is the 9.5″ϕ Bonner-sphere using a ^{3}He counter, calibrated at AIST, the primary standard laboratory of Japan.

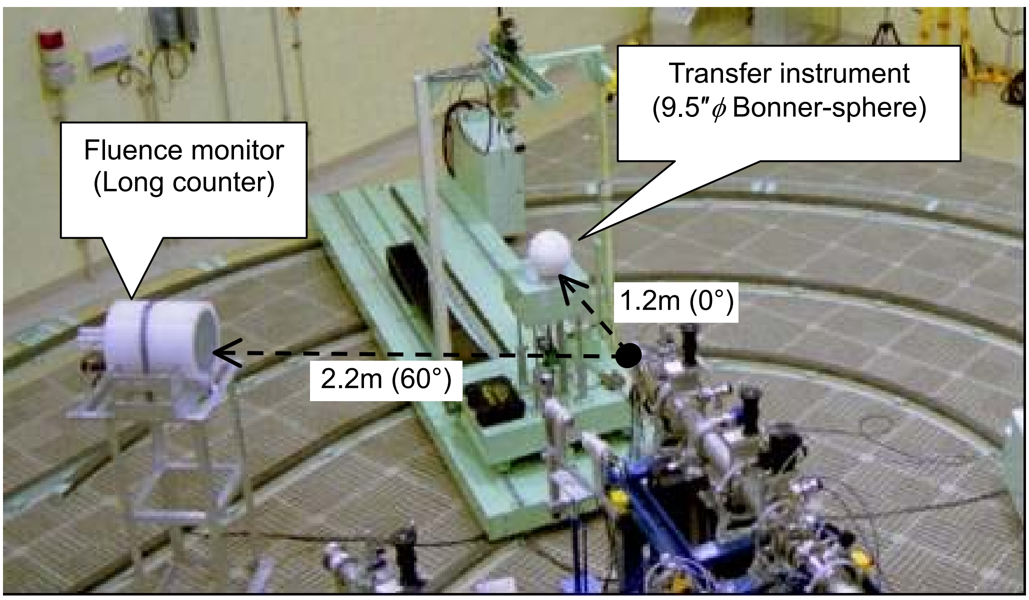


Fig. 5 Photograph of the graphite pile for thermal neutron calibration fields; Inside or outside of the pile is used for calibration.

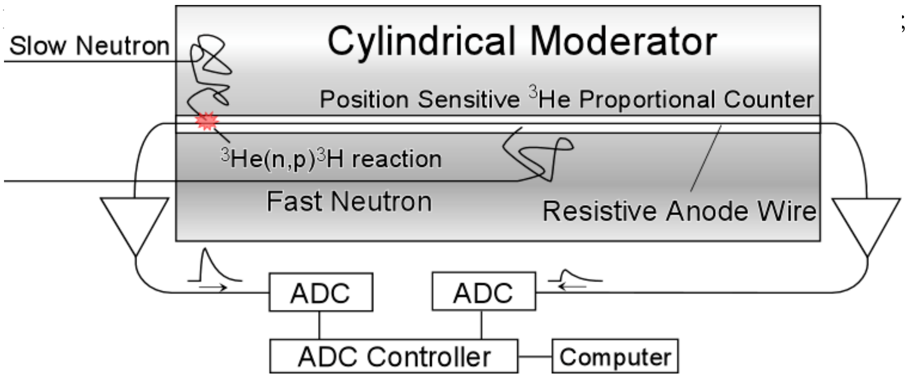
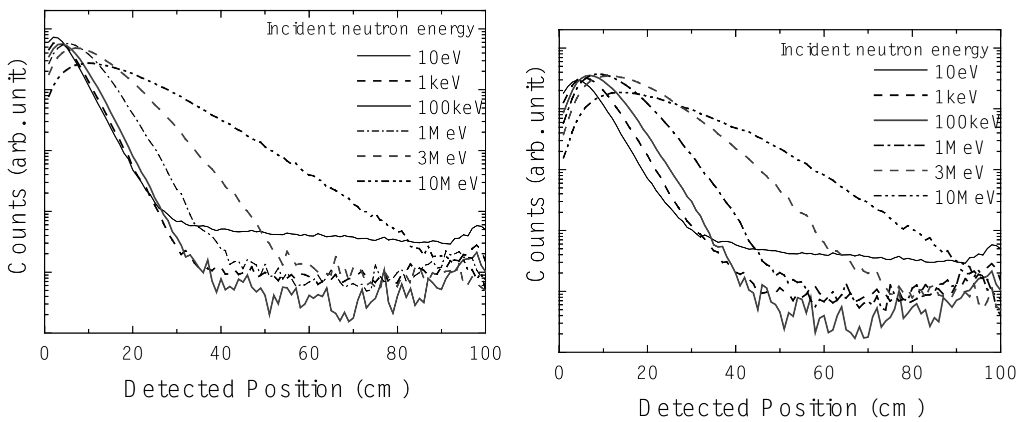


Fig.6 Scheme of the neutron detection principle



(a) Simply polyethylene moderator. (b) Moderator designed by this work.

Fig. 7 Calculated position profiles of the detector for several mono-energetic neutrons.