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J. C. Liu, S. Rokni, V. Vylet and R. Arora

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 9430, U. S. A.

E. Semones and A. Justus

ANL-E, ESH-360, Argonne, IL 60439, U. S. A.

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Abstract - Neutron detection time distribution is an important factor for the dead-time correction for moderator type neutron detectors used in pulsed radiation fields. Measurements of the neutron detection time distributions of multisphere LiI detectors (2”, 3”, 5”, 8”, 10” and 12” in diameter) and AB remmeter were made inside a ANL 20-MeV electron Linac room. Calculations of the neutron detection time distributions were also made using Monte Carlo codes. The first step was to calculate the neutron energy spectra at the target and detector positions, using a coupled EGS4-MORSE code with a giant-resonant photoneutron generation scheme. The calculated detector spectrum was found in agreement with the multisphere measurements. Then, neutrons hitting the detector surface were scored as function of energy and the travel time in the room using MCNP. Finally, the above neutron fluence as function of energy and travel time was used as the source term, and the neutrons detected by ^{6}Li or ^{10}B in the sensor were scored as a function of detection time for each detector using MCNP. The calculations of the detection time distributions agree with the measurements. The results also show that the detection time distributions of detectors with large moderators depend mainly on the moderator thickness and neutron spectrum. However, for small detectors, the neutron travel time in the field is also crucial. Therefore, all four factors (neutron spectrum, neutron travel time in the field, detector moderator thickness and detector response function) may play inter-related roles in the detection time distributions of moderator type detectors.

INTRODUCTION

Electron accelerators are generally operated in pulsed mode with short pulse lengths (< a few μs). Traveling with the speed of light, photon radiation produced in the field is then also pulsed with the same duration as the beam pulse. Therefore, the duty factor of the beam (beam pulse length times beam frequency) is an important factor for the dead-time correction for photon radiation measurements using detectors operated in pulsed mode.

However, for measurements using moderator type detectors with thermal neutron sensors in a pulsed neutron field, the situation and the factors that need to be considered are different. First, neutrons generated have to spend time in traveling from the source position to the detector surface position. This neutron *travel* time in the *field* depends on the field geometry and/or the shielding thickness and composition. Secondly, neutrons hitting the detector surface are moderated/diffused to reach the sensor inside the moderator. The *moderation* time* (defined here as the time between the neutron hitting the detector surface and the slowed-down neutron detected by the sensor) depends on the incident neutron energy and the moderator thickness. The neutron *detection* time (sum of the *travel* time and the *moderation* time) between the neutron generation and its detection is generally around a few tens to a few hundreds of microseconds, which is much longer than both the beam pulse lengths for electron accelerators and the dead-time of the detectors. Therefore, instead of the beam pulse length, it is the neutron detection time

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* It is known that, for a neutron life history, the moderation of a fast neutron takes less time than the diffusion of a thermal neutron. However, this term is still used here to describe the time-delay effect due to the moderator.

distribution (which may depend on the field and detector situations) that needs to be considered in the dead-time correction for moderator type neutron detectors. More discussions of this effect on the dead-time correction can be found elsewhere(1-4).

In this study, measurements of the neutron detection time distributions of the Bonner multisphere detectors and the Anderson-Braun (AB) remmeter have been made inside a 20-MeV electron Linac room of the Argonne National Laboratory (ANL). The detail of the measurements and results has been given in one of the authors' thesis(5). Equivalent calculations were also made using the MCNP4A Monte Carlo code(6). In the paper, measurements are described, followed by details of the calculations and the comparisons. The results, which have significant implications on the dead-time corrections for moderator-type neutron detectors used in pulsed fields, will also be discussed.

MEASUREMENTS

The active moderated neutron detector used for the detection time distribution measurements is part of the Bonner multisphere set (Model 42-5) commercially available from Ludlum Measurements, Inc., Sweetwater, Texas. This set includes a 4 mm x 4 mm cylindrical LiI(Eu) scintillator (96% enriched with ^{6}Li) optically coupled to a photomultiplier tube with a 10 cm long PMMA light pipe and a set of six spherical polyethylene (ρ = 0.95 g cm^{-3}) moderators with 5.08, 7.62, 12.7, 20.32, 25.4, and 30.48 cm diameters (called the 2" to 12" ball, respectively, in the remaining of the paper).

The measurements were conducted at ANL's Electron Linac room (11.7 m long, 9.2 m wide, 2.9 m high), enclosed by 91-cm-thick concrete walls on all six sides (see Figure 1). The 20-MeV electron beam was incident on the center of a copper target (1.91 cm thick in the beam direction, 20.32 cm wide, 9.84 cm high). The width of the accelerator pulses was 4 ns and the pulse repetition frequency was 60 Hz. The average beam current for all measurements was 50 nA, which corresponds to 3.14 x 10^{11} e^{-}/s incident on the copper target. Lead shielding was placed around the detector and in the sideward direction (i.e., 90°) to reduce the photon fluence rate such that significant pile-up of detector pulses due to photon interactions in the detector did not occur. The lead box had an internal cubical dimension of 50.8^3 cm^3 (20.32-cm-thick lead on all sides except the top and bottom were 5 cm). This lead box was located such that the detector position was at 305 cm from the copper target and at 130° relative to the beam direction. The other lead plate (20.32-cm-thick, 61x61 cm^2) was about 30 cm from the target center. The centers of the copper target, lead box and lead plate are at the same height (1.5 m from the floor).

The following steps describe each segment of the signal processing (see Figure 2):

1. A multichannel scaler (Turbo-MCS) is connected to the detector system to count the detector pulses resulting from the detection of neutrons. The Turbo-MCS is triggered to start a counting pass by the Linac trigger signal that is synchronized with the arrival of the accelerator beam pulse.

2. Neutrons produced during each beam pulse are detected in the Li(Eu) sensor via the $^{6}Li(n,\alpha)^{3}H$ reaction (Q = 4.78 MeV). The resulting charge is collected at the anode, extracted by the charge sensitive preamplifier and sent on to the linear amplifier for shaping and amplification.
3. The difference in the heights of the pulses due to neutrons from those due to photons makes it possible to discriminate between the two with the timing single channel analyzer (SCA). The discriminator settings on the timing SCA are set such that it generates a positive NIM-standard (+5 V, 500 ns wide) output pulse for any neutron interaction. This output pulse is then sent to the SCA input on the Turbo-MCS.
4. The output pulses from the SCA are then counted and recorded by the Turbo-MCS in individual time bins (channels) corresponding to the detection time of the pulse after the start of the counting pass (i.e., the arrival of the beam pulse). The time widths of the channels are determined by the dwell time as set in the software that operates the Turbo-MCS. The dwell time of the Turbo-MCS was set at 0.5 μs, with essentially no dead time (<10 ns) between channels. The counting pass length was 16,384 channels, which allowed neutron events to be counted up to 8.192 ms after the arrival of a beam pulse.
5. Each pulse from the linear amplifier corresponding to an output pulse from the SCA could also be displayed with a PHA (PCA-II). This was done by gating the analog-to-digital converter (ADC) input of the PCA-II with the output pulses from the timing SCA. A delay of 2 μs was added between linear amplifier and the ADC input of the PCA-II with a delay amplifier. This was necessary because the gating signal needs to be applied at least 1 μs

before the arrival of the ADC input to allow the ADC to accept the input. Any signal from noise pickup that might disturb the resulting detection time distribution can thus be identified by displaying the pulse height spectrum from the linear amplifier. If there were any anomalies in the pulse height spectrum due to spurious pulses, the cause could be identified and eliminated. The detection time distribution measurements were made only if the pulse height spectrum is free of anomalies.

CALCULATIONS, RESULT, AND COMPARISON

The calculations of the neutron detection time distributions were divided into three steps. First, the neutron energy spectra from the *target* (i.e., *source*) and at the *detector* positions in the Linac room were calculated using the coupled EGS4[(7)]-MORSE[(8)] code. Secondly, with the calculated *source* spectrum, neutrons hitting the detector surface were scored as function of energy and the field travel time in the room using MCNP4A. Thirdly, the above neutron fluence as function of energy and travel time was used as the source term, and the neutrons detected by ^{6}Li or ^{10}B in the sensor were scored as a function of detection time for each detector. These three steps and the results are described in more details in the following sections.

Neutron Spectral Calculations Using EGS4-MORSE

Neutrons from a 20-MeV electron beam are produced by the giant-resonant photoneutron (GRN) reaction. Currently, there are no general purpose Monte Carlo codes that incorporates the production of photoneutrons. A giant-resonant photoneutron generation scheme has been implemented and validated[9] in a coupled EGS4-MORSE code. The scheme utilized EVAP4[10] and an empirical algorithm to determine the fractions and energies of the evaporation neutrons and direct neutrons, respectively. The angular distribution of the emitted neutrons was also accounted for. The coupled EGS4-MORSE code was used to calculate the *source* spectrum for neutrons generated in the copper target and the *detector* spectrum in the center of lead box (which was assumed to be the same as the spectrum hitting the detector surface). Exact geometry of the Linac room with target and lead shielding as those in Figure 1 was modeled.

Figure 3 shows that the calculated source spectrum has an average energy of 1.085 MeV, which agrees well with the nuclear temperature of 1 MeV for copper. However, due to the lead shielding and concrete wall reflection, the detector 'see' an incident spectrum with an average energy of only 0.284 MeV. Note that the thermal neutrons were not included in both spectra. To further validate the spectral calculations, the calculated detector spectrum was compared with the multisphere measurements (unfolded with the BON code). Figure 4 shows that the relative comparison has a good agreement on the spectral shape and average energy value.

The total neutron fluences at the detector position per unit incident electron were also given in Figure 3. A source neutron fluence of 2.22×10^{-10} cm^{-1} $electron^{-1}$ at 305 cm away corresponds to a neutron yield of 2.6×10^{-4} (assuming an isotropic neutron emission from the copper target). This number agrees well with Barber's measurements[11].

MCNP Calculations of Energy And Time Distributions for Neutrons Hitting Detector Surface

From the agreement of the spectral comparison, the photoneutron generation scheme has been shown to work. The MORSE-calculated source spectrum in the copper target can now be used in MCNP4A as the source term, and the neutrons that travel to reach the cubical space inside the lead box are scored as function of energy and the travel time in the room. Instead of scoring the three dimensional energy-time distribution, the neutron travel time was scored into 37 energy bins (to correspond to the MORSE multi-group binning). This assumed that the neutrons within the same energy bin have the same travel time distribution. Exact geometry of the Linac room with target and lead shielding was again simulated in the MCNP calculations.

The MCNP-calculated travel time distribution results are shown in Figure 5. The energy and the number inside the parenthesis are the upper energy and the fractional neutron intensity (in %) of each bin, respectively. As expected, the lower the energy of the neutron hitting the detector surface, the longer the travel time after its generation in the copper target. Thermal neutrons (< 0.414 eV, the cadmium-cutoff) have travel time more than 200 μs and many thermal neutrons arrive at the detector surface after 300 μs. On the other hand, neutrons between 21.88 keV and 10 MeV (~57% intensity) have similar time distributions and, therefore, are grouped into one curve only. These faster neutrons hit the detector surface within 10 μs (most of them arrive within a few μs).

Note that the travel time distributions in Figure 5 depend only on the radiation field's environments (in this case, it is the 20-MeV Linac room). It can be anticipated that, because of the long travel times of neutrons < 100 eV (to which the 2" and 3" Bonner detectors are most sensitive) in the ANL room, the detection time distributions of the 2" and 3" balls can be affected by the travel times in the field. This will be demonstrated later.

MCNP Calculations of Detection Time Distributions for Neutrons Recorded by Detector Sensor

Neutrons with the energy and the travel time distributions in Figure 5 were assumed to be incident parallel on the detector surface from one direction perpendicular to the sensor axis. Detectors included the common multisphere detectors (^{6}LiI crystal sensor of 4 mm height and 4 mm diameter with polyethylene moderators) and the AB remmeter ($^{10}BF_3$ tube). In the MCNP calculations, detector geometries were simulated in great detail and the composition was modeled closely. For example, the ^{6}LiI crystal, the acrylic light pipe, the aluminum housing, and the polyethylene ball (0.955 g cm^{-3}), etc., were all modeled for multisphere detectors. However, to simplify the geometry input, the perforated borated plastic layer of the remmeter was simulated by a ^{10}B-plastic layer without holes (but with a reduced density of 0.78 g cm^{-3}).

While being moderated/diffused in the detector, neutrons reaching the sensor were scored as a function of their detection times, after weighted with the appropriate absorption cross sections ($^{6}Li(n,\alpha)^{3}H$ for the LiI sensor and $^{10}B(n,\alpha)^{7}Li$ for the BF_3 tube) of the neutron energies. Figure 6a shows the good agreement between the calculated and measured detection time distributions of the 2"-diameter Bonner detector. It should be pointed out again that this is the time between the neutron generation in the copper target and its detection by the sensor, which depends on both the radiation field and the detector.

Figure 6b shows three calculated detection time distributions of the 2" ball. The curve with solid circles is the same as that in Figure 6a. The curve with open circles was calculated by setting the travel times for all neutrons hitting the detector surface to be zero. Therefore, this curve actually corresponds the moderation time distribution of the 2" detector for the incident ANL spectrum (an average energy of 0.284 MeV). A comparison between the two curves (with and without the travel time distributions) clearly shows the effect of the long travel times in the ANL room for the low-energy neutrons (see neutrons around a few eV in Figure 5a), to which the 2" ball was most sensitive.

The curve with triangles in Figure 6b was calculated by using a GRN spectrum hitting the 2" ball surface with a zero travel time. The GRN spectrum was obtained by applying a nuclear temperature of 1 MeV to the evaporation spectrum formula in MCNP4A. The time distributions between the GRN and the ANL spectrum (the one with zero field travel time) are similar. The 2" detector response (i.e., the total area under the curve) is much higher for the ANL spectrum, as expected.

Another important observation from Figure 6 is that all detection time distributions are similar to exponential curves. Actually, the two *moderation* time distributions (i.e., the one with zero travel time in the field) are closer to exponential curves. In the figure, the number inside the parenthesis is the corresponding mean detection (or moderation) time value in units of μs. These values were obtained from the best exponential fits to the curves within certain time intervals (e.g., 20-100 μs for the 2" ball). The mean detection time (i.e., the inverse of the slope of the fitted exponential curve) for ANL neutrons is 45 μs, whereas the mean moderation times for

GRN and ANL neutrons are the same (25 μs). Therefore, in the ANL case, the field travel times in the Linac room dominate over the detector moderation time of the 2" ball. Although thermal neutrons were not included in the calculations, the detection time distributions in Figure 6 are still valid, because thermal neutrons in the Linac room reached the detector only after 200 μs (see Figure 5a).

Figure 7a shows the good agreement between the calculated and measured detection time distributions of the 12" ball. Figure 7b shows three calculated time distributions of the 12" ball, similar to those in Figure 6b. Contrary to the case of the 2" ball, the detection time distributions of the 12" ball (with and without the travel time distribution in the field) are the same. This is because that fast neutrons above a few tens of keV, to which the 12" ball was more sensitive, had very short travel times in the ANL room (see Figure 5c). Therefore, the detection time distribution depends mainly on the moderator thickness (not on the field conditions), and the detection time of the 12" ball is dominated mainly by the detector moderation time.

Compared with the 2" ball, the slope of the fitted exponential curve of the 12" ball is much less steep. This can be expected because of 12" ball's larger moderator. This also results in a much larger mean moderation time for the 12" ball (455 μs for the ANL spectrum). However, the mean moderation time of the 12" ball for GRN is only 192 μs. This indicates that the moderation time of the 12" ball has a stronger dependence on the incident neutron spectrum, compared with the 2" ball. The inclusion of thermal neutrons will again only have minor influence on the curves, due to the 12" ball's low sensitivity to thermal neutrons.

The comparisons among the curves in Figures 6b and 7b strongly demonstrates the important and inter-related roles played by the neutron spectrum, radiation field, detector response function, and the moderator thickness on the neutron detection time distribution. It can be expected that the Bonner detectors of 3”, 5”, 8” and 10” would behave between the two extreme features of the 2” and 12” balls.

Figure 8 shows the MCNP-calculated and the measured detection time distributions of the 3” ball. The conclusions drawn above for the 2” ball are applicable to the 3” ball. The mean moderation time for the ANL neutrons and GRN are the same (47 μs), and they are smaller than the mean calculated detection time of 67 μs.

Figure 9 shows the calculated and the measured detection time distributions of the 5” ball. Because the 5” ball has a higher response to neutrons above 10 keV, the time distribution is no longer dependent on the field parameters. Therefore, the mean detection time equals to the mean moderation time (150 μs for ANL neutrons). However, the mean detection time of the 5” ball is spectrum-dependent (85 μs for GRN).

Figures 10 and 11 show the calculated and the measured detection time distributions of the 8” and 10” balls, respectively, for the GRN and ANL neutrons. The characteristics of the time distributions for the 8” and 10” balls are similar to those of the 5” and 12” balls.

Figure 12 shows that the calculated detection time distribution of the AB remmeter is different from the measured one. The disagreement could be due to that the AB remmeter does not have an isotropic angular response (whereas we assumed mono-directional incidence in the calculations) and/or the no-hole assumption used in the detector geometry simulation. The reason is under further study. The mean calculated detection time (equals to the mean moderation time in this case) for ANL neutrons is 56 μs.

The time distributions for Bonner detectors with a LiI sensor have spikes with a steep slope within ~10 μs. The spike is obviously caused by, and thus dependent on the probability of, incident neutrons detected by the sensor with little interaction in the moderator. Note that the AB remmeter with a BF_3 sensor does not have a spike. This difference suggests that the cause of the spike may be revealed from the difference in the fast neutron cross sections of $^{6}Li(n,\alpha)^{3}H$ and $^{10}B(n,\alpha)Li$. The $^{6}Li(n,\alpha)^{3}H$ reaction has a resonant peak at ~0.2 MeV, while the cross section of $^{10}B(n,\alpha)Li$ is nearly a 1/v function. Figure 13 shows that the moderation time distribution of the 8" ball hit by GRN has a spike, while that of the 8" ball hit by monoenergetic neutrons of 0.1 MeV (below the resonant region) does not. This result and the other study in one of the authors' thesis(12) have verify that the spike is caused by fast neutrons and the resonant cross section of ^{6}Li helps in producing a more pronounced spike.

Summary

The mean detection times (denoted as *T*) for multisphere detectors are plotted as a function of the moderator volume in Figure 14. The two curves labeled with ANL are *T* values from the detector results in the ANL Linac room, with and without the effect of neutron travel time in the field. Because of the long travel times of the slow neutrons (to which the 2" and 3" detectors are most sensitive), the *T* values of the 2" and 3" detectors with the field travel times are larger than those without the field travel times. On the other hand, the detectors with 5”-12” diameters are not affected by the field travel times.

In addition to the ANL spectrum (average energy 0.284 MeV), the calculated *T* values for GRN (average energy 1 MeV) without field travel time is also shown. A comparison between the two curves of “ANL-NO-TIME” and “GRN” shows that the *T* values of the 2” and 3” detectors are not affected by the neutron spectra, whereas the larger detectors are.

Dinter and Tesch(2,13) have measured the so-called 1/10 values from the exponential time distribution curves of multisphere LiI detectors irradiated in a DESY neutron field, generated from a copper target hit by 300 MeV positrons. The corresponding *T* values can be estimated from their 1/10 values divided by 2.303. Their *T* values (labeled as DESY) can be compared with our calculated *T* values for GRN in Figure 14. As expected, because of the similarity between the DESY and GRN spectra below 20 MeV, the *T* values of 5”-12” balls for two spectra are also similar. The differences in the cases of the 2” and 3” detectors are likely again due to the neutron travel times in the DESY field.

The mean detection time *T* (μs) of a LiI Bonner detector (those not affected by field travel time) as a function of the moderator volume *V* (cm^3) in Figure 14 can be parameterized as:

$T = 7.04\ V^{0.438}$ for ANL spectrum (1a)

$T = 11.78\ V^{0.284}$ for GRN (1b)

Since only two neutron spectra were studied, it was not attempted to parameterize *T* against the average energy of the spectrum.

DISCUSSIONS AND CONCLUSIONS

The detection time distributions of moderator type detectors are close to exponential curves (particularly when the effect of field travel time is minimal). This exponential behavior has been found before[1-3]. The implication is that a mean detection time (corresponding to the inverse of the slope of the fitted exponential curve) may be appropriate to describe the main portion of the time distribution curve (i.e., neglecting the spike and tail). A single exponential function with a mean detection time can then be used in the models of dead-time correction[3,4]. To account for the spike and tails, a summation of two or more exponential functions may also be used, at the expense of a more complex dead-time modeling.

This study has shown that the neutron detection time distributions of moderator-type detectors used in a pulsed radiation field depend on four factors: the energies and field travel times of the neutrons hitting the detector surface (source and field parameters) and the moderator thickness and response function of the detector (detector parameters). The 2" and 3" Bonner detector belong to an extreme case in which the long travel times of the slow neutrons in the field, to which the detector is more sensitive, may dominate over the short moderation times in small moderators. Therefore, the detection time distributions of the 2" and 3" balls depend mainly on the field parameters. The 5"-12" Bonner detectors and AB remmeter are the other extremes in which the detectors are more sensitive to fast neutrons, whose travel times in the field are shorter than the moderation times in large moderators. At the same time, the detection time distributions for the 5"-12" balls are also spectrum-dependent. Therefore, the detection time distributions of the 5"-12" balls and AB remmeter depend on both the source and field parameters and the detector parameters.

From the conclusions drawn above, if calculations or measurements considering both the detector and the field were not made, it seems then very difficult, if not impossible, to know the detection time distribution of a detector in a specific pulsed neutron field. Fortunately, this is not always true. Because the pulsed neutron fields exists generally in accelerator facilities and the fields of interest are also generally outside biological shields, there may be fixed patterns of the spectral and travel time distributions of the neutrons in these fields. For example, at high-energy (> 1 GeV) electron and proton machines, the spectra outside thick shields (say > 1 m) are nearly the same (called the equilibrium spectrum). Most neutrons in the low-energy (< 20 MeV) portion of the equilibrium spectrum are produced by high-energy (around a few hundred MeV) neutrons in a outer layer of the shield. Therefore, regardless of the beam energy and shielding thickness, the travel time distributions for neutrons (< 20 MeV) outside the thick shield should also be the same, if the equilibrium spectrum exists. This means that there is also an equilibrium time distribution. In these case, the source and field parameters are constant. Therefore, the energy and travel time distributions of a detector for the equilibrium spectrum outside a thick shield need to be measured and/or calculated just once, and the results can then be applied to other thick shields which also have the equilibrium conditions. Actually it has been shown in one of the authors' thesis(12) that the detection time distributions for detectors exposed to an equilibrium spectrum are very close to those for GRN.

In accelerator facilities, thick shields generally exist for high-power facilities. For low-power facilities, e.g., the synchrotron radiation facilities, the shields are thinner and the equilibrium spectrum may not exist. In this case, the detection time distribution of a detector in the field may need to be measured/calculated, if dead-time correction is desired.

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Figure Captions -- Contact author for figures.

Fig. 1 Geometry of the ANL 20-MeV electron Linac room with a small copper target, a lead box enclosing the detector for the timing measurement and an intervening lead gamma-shield plate.

Fig. 2 Schematic for the measurement of the neutron detection time distribution in ANL.

Fig. 3 MORSE-calculated neutron source spectrum in the copper target (an average energy of 1.085 MeV) and the spectrum incident on the detector with an average energy of only 0.284 MeV. Thermal neutrons were not included in both spectra.

Fig. 4 Comparison between the MORSE-calculated detector spectrum with the multisphere measurements.

Fig. 5 Neutron energy and travel time distributions in the 20-MeV Linac room, calculated with MCNP4A.

Fig. 6 a) Comparison between the MCNP-calculated and measured detection time distributions of the 2”-diameter Bonner LiI detector.

b) Three calculated detection time distributions of the 2” ball; one with travel time distributions in the Linac room and one without (both saw the same ANL spectrum with an average energy of 0.284 MeV), and another using a giant resonance neutron spectrum with no travel time distribution.

Fig. 7 a) Comparison between the calculated and measured detection time distributions of the 12” detector.

b) Three calculated detection time distributions of the 12” detector; one with travel time distributions in the Linac room and one without (both saw the same ANL spectrum with an average energy of 0.284 MeV), and another using a giant resonance neutron spectrum with no travel time distribution.

Fig. 8 Calculated and measured detection time distributions of the 3" ball for GRN and ANL neutrons.

Fig. 9 Calculated and measured detection time distributions of the 5" ball for GRN and ANL neutrons.

Fig. 10 Calculated and measured detection time distributions of the 8" ball for GRN and ANL neutrons.

Fig. 11 Calculated and measured detection time distributions of the 10" ball for GRN and ANL neutrons.

Fig. 12 Comparison between the calculated and measured detection time distributions of the AB remmeter.

Fig. 13 The moderation time distribution of the 8" detector hit by GRN has a spike, while that of the 8" detector hit by neutrons of 0.1 MeV (below the resonant region of the $^{6}Li(n,\alpha)^{3}H$ reaction) does not.

Fig. 14 The mean detection time *T* as a function of the moderator volume of multisphere LiI detectors (2" to 18" diameters) for two neutron spectra (ANL spectrum and GRN).