Measured and Predicted Variations in Fast Neutron Spectrum in Massive Shields of Water and Concrete

E. Aalto, R. Fräki and R. Sandlin
MEASURED AND PREDICTED VARIATIONS IN FAST NEUTRON SPECTRUM IN MASSIVE SHIELDS OF WATER AND CONCRETE

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Abstract

The absolute magnitude, and the variations in form, of the fast neutron spectrum during deep penetration (0.8 - 1.1 metre) in massive shields of water, ordinary and magnetite concrete have been studied by using threshold detectors ($\text{In}(n, n')$, $\text{S}(n, p)$, $\text{Al}(n, \alpha)$). The results have been compared with predictions by two rigorous (NIOBE, Moments method) and two non-rigorous (multigroup removal-diffusion) shielding codes (NRN, RASH D).

The absolute results predicted were in general within 50% of the measured ones, i.e. showed as good or better accuracy than thermal and epithermal flux predictions in the same small-reactor configurations. No difference in accuracy was found between the rigorous and non-rigorous methods.

The changes in the relative form of the spectrum (indicated by variations in the ($\text{Al}/\text{S}$) and ($\text{In}/\text{S}$) reaction rate ratios and amounting to factors up to 3 - 4 during one metre penetration in water) were rather accurately (within 10 - 30%) predicted by all of the methods.

The photonuclear excitation of the 335 keV level used for detecting the $\text{In}(n, n')$ reaction was found to distort completely the In results in water at penetrations > 50 cm.

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<table>
<thead>
<tr>
<th>List of Contents</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>1</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>3</td>
</tr>
<tr>
<td>2. Measurements</td>
<td>4</td>
</tr>
<tr>
<td>3. Calculations</td>
<td>5</td>
</tr>
<tr>
<td>4. Discussion of the results</td>
<td>6</td>
</tr>
<tr>
<td>a) Mode of presentation and the response of the detectors</td>
<td>6</td>
</tr>
<tr>
<td>b) Sources of error</td>
<td>7</td>
</tr>
<tr>
<td>c) Absolute height of the fast spectrum</td>
<td>8</td>
</tr>
<tr>
<td>d) Changes in the form of the spectrum</td>
<td>10</td>
</tr>
<tr>
<td>Summary and Conclusions</td>
<td>12</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>13</td>
</tr>
<tr>
<td>References</td>
<td>14</td>
</tr>
<tr>
<td>Tables I - IV</td>
<td></td>
</tr>
<tr>
<td>Figures 1 - 15</td>
<td></td>
</tr>
</tbody>
</table>
1. Introduction

The magnitude and the form of the fast neutron spectrum in reactor shields are of greatest practical interest close to the core, for instance when determining the radiation damage rates on the pressure vessel. The changes in the spectrum when penetrating the thin regions in question are, however, relatively small, and therefore difficult to measure with a high relative accuracy. On the other hand, spectral changes during a very deep penetration can be large and therefore (at least theoretically) easier to prove and very suitable for checking the basic accuracies of various shielding codes. In practice, the low absolute flux values combined with low detector sensitivities may present some problems further out in the shield.

In this article we present some comparisons between the measured and predicted fast neutron fluxes and their spectral variations in massive shields of water and concrete up to a depth of 1.0 - 1.3 metre. The two main codes used for the calculation are of the non-rigorous multigroup removal-diffusion type. The first is the NRN method developed at AB Atomenergi (1) (2). The second is a code (RASH D) (3) based on the original removal cross section by Spinney (4). We wish to point out that there exists a newer version (RASH E) (12) which has not been published at the time of writing. Besides, some results obtained by numerical integration of the transport equation (NIOBE) (5) will be presented. Finally, in water, some published results by the Moments method (6) are given for comparison.

The range of the shielding materials studied covers both light (water), medium (ordinary concrete), and heavy (magnetite concrete), atomic and specific weights. The study is based on threshold detector measurements.

We have earlier performed measurements of the detailed spectral variations at shallow penetration in laminated Fe-D₂O (7). The range covered was up to a penetration of 0.5 metre. It is known that up to this depth the low-energy fluxes calculated by the removal-diffusion codes are in practice determined by the solution of the diffusion equations. Only at deeper penetrations does the correction for the forward directed flux component, approximated by the uncollided or "removal" flux, have
a more notable effect. Therefore in this study our aim has been to penetrate as deep as possible in the materials.

Spectral studies at deep penetration have recently been published by Veselkin et al. (8) (graphite up to 135 cm, Fe and Pb up to 65 and 74 cm penetrations, respectively). Bokhari and Verbinski have studied the spectrum (including angular distribution) in water out to 50 cm depth and compared their results with those obtained by NIOBE (9).

Measurements out to 30 - 40 cm distance from a Po-Be source in water with and without a Fe or Pb layer around the source have been compared by Barsukov and Avzyanov with calculations by a 25 group removal-diffusion method (10). Using a monoenergetic (3 and 15 MeV) source, During et al. have studied the spectrum behind 5 - 20 cm Fe and 20 cm Al, comparing the results with a Monte Carlo calculation (11).

The aforementioned studies cover the ≤0.5 m penetration range only, excluding the graphite measurements by Veselkin et al. Besides, the last two are very special cases having regard to the source. The only studies directly concerning removal-diffusion methods RASH D and E are those published by Avery and Butler (12)(13). Their work contains mainly comparisons of calculated fast spectra obtained by the RASH, Moments method and NIOBE methods, but threshold measurements have also been performed in H2O (S up to 100 cm and Al up to 40 cm penetration) and in the bulk shield of the Calder Hall Reactor, using a number of detectors [S(n, p), Fe56(n, p), Al(n, α)].

2. Measurements

Measurements for this investigation have been performed at the R2-0 reactor at the Studsvik Research Centre. The configurations studied are, starting from the reactor face:

Config. 1: H2O, 0 to ∞ cm

Config. 2: H2O 20, Al 1 cm, magnetite concrete (ρ = 3.74 g cm\(^{-3}\))

210 cm

Config. 3: H2O 10, Al 2, air 31, ordinary concrete (ρ = 2.43 g cm\(^{-3}\))

≈170 cm
The air space in Config. 3 includes a 1 cm lucite layer.

Of these configurations, No. 3 was studied in the large (N1) window of the reactor and the reaction rates measured have been published earlier (14). The detailed data for the reactor, materials and geometries in question have also been presented in earlier reports describing the measured and predicted thermal and epithermal neutron fluxes and gamma dose rates in the same configurations (15)(16). These results will not be repeated here.

Together with data in refs. (15) and (16) the results given here should enable the reader to test the fast neutron part of his own shielding codes against our measurements.

The threshold detectors used in this study are:

\[
\begin{align*}
\text{Al}^{27}(n, \alpha) & \text{ Na}^{24} \\
\text{S}^{32}(n, p) & \text{ P}^{32} \\
\text{In}^{115}(n, n') & \text{ In}^{115m}
\end{align*}
\]

The indium and aluminium foil activities were measured with a \( \Phi \) 3" x 1.5" NaI(Tl) crystal and a multichannel analyser. Sulphur was measured in a \( \beta \)-detector. The absolute total activities were obtained by using our standard data processing codes.

In the course of the measurements we found that the photoexcitation of \( \text{In}^{115} \) rendered measurements at deeper penetrations than 50 cm in water impossible (see section 4b).

3. Calculations

The calculations by the removal-diffusion methods have been performed according to the standard manuals (1)(4). The removal source was integrated over the true (box-like) core and the solution of the diffusion and slowing-down equations was performed in spherical geometry, with a core radius = 30 cm. The results are based on the sum of the diffusion and the forward collimated (removal) components. The fast spectrum at the core surface (used as a boundary condition in the methods above) was taken from a solution by the NIOBE programme. The NIOBE calculation was also performed with a core radius = 30 cm.
The cosine \( \mu_o(2) \) in the NRN method, defining the angle (in laboratory system of reference) between the "removal" and "non-removal" first collisions, has been given the value 0.6 for all other elements except hydrogen, which has \( \mu_o = 0.45 \) as recommended in a later study (17).

The fluxes and spectrum by the Moments method were given for a point source only. The form of the spectrum presented here was obtained by assuming the point source situated on the face of the reactor \( z = 0 \). The absolute values were obtained by making a geometrical correction assuming \( R = 30 \) cm spherical core, and by normalizing the predicted \( S \)-activity to the observed one at \( z = 30 \) cm.

4. Discussion of the results

a) Mode of presentation and the response of the detectors

The results can be studied from two points of view, viz. a) the absolute agreement between the measured and calculated fluxes and spectra, and b) the agreement between the measured and predicted variations in the relative form of the spectrum.

An approximate form of the spectrum can be obtained from the threshold measurements by the orthonormal expansion method. However, as in a previous study (7), we have here elected to use the measured and predicted reaction rates directly. If, besides, the responses functions of the detectors in the predicted spectrum are considered, the changes in its gross form can be studied.

Fig. 10 shows the response functions of our detectors in a spectrum predicted by NRN in water after a 60 cm penetration. We note that the main energy groups for \( \text{In}(n, n') \) (1.5 to 6 MeV) and \( \text{Al}(n, \alpha) \) (6 to 13.5 MeV) hardly overlap, \( S(n, p) \) (3 to 8 MeV) overlaps both, but the main part of the sensitivity is on the In side. We present only one example of response functions because they were found to be rather insensitive to the spectrum as long as there are no thick iron regions in the configuration. The latter regions can cause an appreciable smoothing of the spectrum, resulting in a change in the response of In towards lower energies (7).
The presentation of the absolute values in the usual way (e.g. Fig. 1 for In\((n, n')\) rate in water) gives only a very rough idea of the agreement and conceals the subtle tendencies which may exist. Therefore we have elected to present the results in a relative form (Figs. 2, 3, 11, 14) to accentuate the deviations between them. These Figures simply give the ratio of other reaction rates to those predicted by NRN.

The changes in the form of the spectrum during penetration cause variations in the ratios of the reaction rates. Therefore, the change in these ratios has been used as a measure of the variation in the spectrum. This is done by normalizing the ratios of other rates to that of Sulphur into one at a certain coordinate (e.g. \(z = 30\) cm in Fig. 4) and giving the ratios at other coordinates after using the normalizing factors thus obtained.

Sources of error

When studying the results, one should observe that the absolute predictions are meaningful only after a penetration of 30 - 50 cm. This is because of the approximations necessary in the translation of the true small reactor geometry into the calculational one \(15\). Because of these approximations, the discrepancies between the results close to the core may amount to rather large values (a factor of two).

Another, and quite unexpected, discrepancy was the marked change in the measured attenuation of the In activity in water (Fig. 1). Starting from the \(z = 70\) cm point, its relaxation length is seen to change to that of the gamma dose rate in water. Therefore the origin of this disturbance must be sought from some reaction induced by photons.

The first explanation possible, the phononeutrons in water, can be disregarded for two main reasons. In the first place, they have an initial energy around 0.2 - 0.4 MeV, or at and below the physical threshold of the \(In(n, n')\) reaction. Secondly, they are known to be the dominating source of lower energy neutrons only after \(z = 170\) to 200 cm under similar conditions \(18\).

Therefore the most plausible explanation is the photonuclear excitation of the In itself. The excited level used in measuring the activity
has a relatively low energy, 335 keV, which is at the same time the minimum photon energy required for excitation. Because of the relatively greater number of lower energy photons present, the relative sensitivity of this detector to gamma disturbance must be quite different from the sensitivities of the elements to photonuclear reactions where a nucleon is emitted, the latter having a threshold energy around 7 - 8 MeV. To find out whether photo-excitation could explain the disturbance in our measurements, a rough estimate was made of the cross section required to quantitatively explain the results. Considering the photons from 1 to 8 MeV, the average cross section obtained is of the order of 50 $\mu$b (microbarns), which sounds quite reasonable for this type of reaction. Therefore we conclude that the disturbance observed must be caused by photonuclear excitation of In. Estimates were made of the possible effect of this disturbance in the other two configurations. The maximum error was approximately 2 per cent and can thus be disregarded. The same applies to the measurements in Fe-D$_2$O configurations published earlier (7).

Other sources of error include the variations in the materials (concretes) and the true coordinates of measurement. These have been discussed earlier (15), and it suffices to say that at the relatively short penetration distances (70 - 100 cm) measurable in concrete, these cause flux discrepancies which are $\approx 15\%$ at most. An exception is Config. 2 (Fig. 11), where a higher-than-predicted attenuation between $z = 35$ and 77 cm has been observed (15).

The errors given are standard deviations, determined by the reproducibility and statistics of the measurements. No possible systematic errors are included. It should be pointed out that, because we have pushed the measurements into extreme penetration depths, the counting statistics at the outermost points are low, as shown in Figs. 2, 11 and 14.

The measured and predicted reaction rates are presented in Tables I - III and in Figs. 1 - 3, 11 and 14. Absolute figures are normalized to 100 kW power level of the reactor.
The first material, water, has often been used as the touchstone of the shielding methods because of the special place of hydrogen among the attenuating elements. We observe that the predictions are generally not more than 50% off the measured values, excluding the regions close to the core. This is actually a better accuracy than the one obtained for the thermal and epithermal fluxes with an earlier version of the NRN system and by the RASH B version of the RASH methods (15)(16). We must point out that the attenuation of \( \text{S} \) activity predicted by NRN in this study does not quite agree with the attenuation of \( \text{P} \) activity in these earlier reports because the boundary angle \( (\mu_o) \) for hydrogen is 0.45 in the present work, while earlier \( \mu_o = 0.6 \) was used for all elements. As for the measured \( \text{S} \) and \( \text{Al} \) values, their relative attenuations agree with the measurements made in the British LIDO facility of similar type (13).

The relative attenuation measured agrees best with the Moments method and RASH D results, while NRN and NIOBE seem to have a built-in safety factor. At least in the case of NRN this has been purposely included while fine-tuning the attenuation.

As to the form of the spectrum, the Moments method seems to be the only one giving high enough fluxes in the lower Indium energies (\( \approx 1.5 - 4 \text{ MeV} \)), see Fig. 2, points 10 - 50 cm. All the other three methods appear to give too hard a spectrum, i.e., the \( \text{In} \) activity is underestimated in relation to the others. Regrettably, the \( \text{In} \) measurements are valueless at \( z \geq 70 \text{ cm} \), and even the value at \( z = 50 \text{ cm} \) may be 5 - 8% too high.

The discrepancy in the relative attenuation in the heavy material studied (magnetite concrete, Fig. 11) was discussed with the error sources. The absolute form of the spectrum is very well predicted by NRN at \( z = 35 \) and 87 cm, while RASH D and NIOBE seem to give too hard a spectrum (high \( \text{Al} \) and low \( \text{In} \) rates). The relative attenuation of the various methods seem to agree quite well here.

In the last configuration (Fig. 14) of ordinary concrete, only the NRN calculation has been performed. The measurements are from an earlier report (14). The predicted values on the front face of the concrete are still within reach of the "geometry disturbances" and thus of
less value. The values at $z = 77$ and $117$ cm show a good spectral and absolute agreement (within 20%).

Changes in the form of the spectrum

Figs. 5 to 8 give the calculated, unnormalized spectra in water, starting from $z = 30$ cm. A relatively good agreement is seen between the various results. The effect of the $3.7$ MeV oxygen resonance is seen in most of the curves, although in the RASH results only at shallow penetration. To give a better idea of the spectral hardening in water, the NRN spectra are plotted in a single figure (Fig. 9). After normalizing at $1$ MeV we see that the form of the predicted spectrum is practically unchanged below $4.5$ MeV. The hardening seems to be greatest from $z = 60$ to $z = 90$ cm. This is the transition region where the attenuation is becoming governed by the "removal" part instead of the diffusion part.

To study how accurately this hardening is predicted by the codes, the results in water are presented in a new way in Fig. 4. The variations in the ratios of the Al to S and In to S activities are plotted after normalizing these ratios to one at $z = 30$ cm. Thus we have effectively eliminated the errors in the absolute height of the spectrum and show the variations as though the predicted spectra at $z = 30$ cm had exactly the same form as the true spectrum at this point. This coordinate was selected because the effects of erroneous boundary conditions have practically disappeared at this penetration and the methods have developed equilibrium spectra.

We note, first, that the variations in $(\text{Al}/S)$ or $(\text{In}/S)$ ratios are much larger (equal to factors 3 and 2) than were the errors (30 - 60%) in their absolute predictions (note that Fig. 4 has a smaller scale than Figs. 2 and 3). In the second place, the hardening of the spectrum, as indicated by an increase in the $(\text{Al}/S)$ ratio, seems to be properly predicted by all of the methods. NRN gives here a higher-than-measured variation (see also Fig. 2) while the NIROBE and Moments method fall slightly below the observed points. The predicted $(\text{In}/S)$-ratios follow one another even more closely. The In measurements show the expected trend from 10 to 50 cm, but the magnitude of the "hardening" is less
than predicted. This should be connected with the already harder-than-observed spectrum on the absolute scale (Figs. 2 and 3), which does not allow increasing hardening with penetration. Regrettably, the photo-excitation discussed makes the measurements unusable at $z > 50$ cm.

In magnetite concrete (Config. 2) the predictions agree well with measurements in the relatively shallow range penetrated (Fig. 12). The change in the spectrum in this heavy ($\rho = 3.74 \text{ g cm}^{-3}$, \approx 50 wt. \% Fe) material is much less than in water. During a 100 cm penetration the (Al/S) ratio changes from 1 to 1.4 - 1.6 (as against 3 in $\text{H}_2\text{O}$) and the (In/S) ratio is practically constant (against 0.5 in $\text{H}_2\text{O}$).

The most remarkable fact is that during the first part of the penetration (35 - 100 cm) the S activity (3 - 8 MeV neutrons) is attenuated relatively more than In and Al. This phenomenon has been measured in thin, pure Fe-regions (7) and is quite apparent also in the concrete which contains only $\approx 50$ wt. \% Fe. Only at $z > 100$ cm does the relative pile-up of low-energy neutrons start to disappear, i.e. the spectrum hardens over the whole energy scale. This is seen in Fig. 13 where the $z = 127$ cm spectrum at $E > 4.5$ MeV is between the lines for $z = 35$ and 87 cm. Fig. 13 should be compared to Fig. 9 which shows a continuous hardening for $z > 30$ cm in water. These different changes are, of course, qualitatively explainable by the different types of cross sections, viz., with the $\sigma$ of hydrogen which decreases with increasing energy and the more constant $\sigma$ (with inelastic scattering) of the heavy elements.

Config. 3 of ordinary concrete is materially somewhere between the previous ones. Because of the non-equilibrium of the predicted spectrum after the air space ($z = 43$ cm, Fig. 15) and the large error limits in measurements at $z = 117$ cm, no definite conclusions can be drawn about the accuracy in predicting spectral variations in this case. The predicted changes (Table IV) are closer to magnetite concrete than to water values.

To give an overall view of the relative gross changes in the spectrum during a 100 cm penetration as indicated by the (Al/S) and (In/S) ratios in all three materials, the results are summarized in Table IV. Of the figures given, those for water and magnetite concrete have been verified experimentally as discussed above.
Summary and Conclusions

To sum up, we have found that

1) The methods studied predicted the absolute fast neutron fluxes ($E \approx 1.5 - 10$ MeV) in three widely different materials (from magnetite concrete to water) normally within 50% of the observed values. This figure applies out to a penetration of 0.8 to 1.1 metre, excluding the spectral and geometrical disturbances very close ($\leq 30$ cm) to the core. For the total penetration distance, the maximum error is about a factor of two. The absolute accuracy is as good or better than that obtained for the thermal and epithermal fluxes by the same methods in the configurations studied.

2) In the small reactor geometry studied, no difference was found in the absolute accuracy between the rigorous (NIOBE, Moments method) and the non-rigorous computer-time-saving methods (RASH D, NRN).

3) Compared with the measurements, the form of the spectrum predicted by three of the methods in water was slightly too hard, the measured In activity being too high in comparison with the S and Al activities. The Moments method here gave the best agreement.

In magnetite concrete the NRN spectrum gave the best agreement with observations, while RASH D and NIOBE produced too hard spectra.

In ordinary concrete only an NRN calculation was performed and the agreement in spectral form was good.

4) The predicted spectral hardening above 4 - 5 MeV in water has been demonstrated out to a depth of 110 cm. This is, to our knowledge, the first time such experimental results have been published beyond a 50-cm penetration.

5) The relative changes in the gross form of the spectrum during penetration (indicated by changes in the $(Al/S)$ and $(In/S)$ ratios) were rather accurately (within 10 - 30% for a 1 metre penetration) predicted by all of the methods.
6) A disturbance in the form of photonuclear excitation was found to dominate over the In(n, n') reaction rate in water at penetrations greater than 1/2 metre. This shows that when using the low-threshold detectors of (n, n') type, one must carefully guard against other sources of excitation.

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Table I

Measured and predicted threshold reaction rates (A) (dis g⁻¹ s⁻¹) in Configuration 1 (H₂O).
(Normalized to 100 kW reactor power. The last figure indicates powers of ten (Z = 0 on reactor face)

<table>
<thead>
<tr>
<th>Z (cm)</th>
<th>MEASURED ( [\text{dis s}^{-1} \text{g}^{-1}] )</th>
<th>PREDICTED BY NNN</th>
<th>PREDICTED BY RASH D</th>
<th>PREDICTED BY NICBE</th>
<th>PREDICTED BY MOMENTS METHOD</th>
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<tr>
<td></td>
<td>( S(n, p) )</td>
<td>( \text{In}(n, n') )</td>
<td>( \text{Al}(n, a) )</td>
<td>( S )</td>
<td>( \text{In} )</td>
</tr>
<tr>
<td>0</td>
<td>7.15 ± 0.05,8</td>
<td>5.60 ± 0.05,8</td>
<td>9.30 ± 0.40,6</td>
<td>6.04,8</td>
<td>4.98,8</td>
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<tr>
<td>10</td>
<td>8.43 ± 0.12,7</td>
<td>6.00 ± 0.04,7</td>
<td>1.42 ± 0.05,6</td>
<td>1.03,8</td>
<td>5.76,7</td>
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<td>30</td>
<td>3.48 ± 0.06,6</td>
<td>2.03 ± 0.01,6</td>
<td>9.16 ± 0.30,4</td>
<td>3.30,6</td>
<td>1.40,6</td>
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<td>50</td>
<td>2.03 ± 0.03,5</td>
<td>1.08 ± 0.01,5</td>
<td>7.90 ± 0.40,3</td>
<td>2.14,5</td>
<td>7.44,4</td>
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<td>60</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.00,4</td>
<td>1.87,4</td>
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<td>70</td>
<td>1.62 ± 0.02,4</td>
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<td>8.58 ± 0.03,2</td>
<td>1.85,4</td>
<td>5.17,3</td>
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<td>-</td>
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a) Point of normalization
Table II

Measured and predicted threshold reaction rates in Configuration 2 (Magnetite Concrete).

<table>
<thead>
<tr>
<th>Z</th>
<th>MEASURED</th>
<th>PREDICTED BY NRN</th>
<th>PREDICTED BY RASH D</th>
<th>PREDICTED BY NIOBE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>In</td>
<td>Al</td>
<td>S</td>
</tr>
<tr>
<td>0</td>
<td>7.15 ± 0.05,3</td>
<td>5.60 ± 0.05,8</td>
<td>9.30 ± 0.10,6</td>
<td>6.94,8</td>
</tr>
<tr>
<td>20</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.77,7</td>
</tr>
<tr>
<td>35</td>
<td>3.52 ± 0.02,6</td>
<td>2.32 ± 0.10,6</td>
<td>5.85 ± 0.10,4</td>
<td>2.77,6</td>
</tr>
<tr>
<td>87</td>
<td>2.27 ± 0.07,3</td>
<td>1.68 ± 0.15,3</td>
<td>4.6 ± 0.15,1</td>
<td>4.44,3</td>
</tr>
<tr>
<td>127</td>
<td>-</td>
<td>1.3 ± 0.4,1</td>
<td>-</td>
<td>3.85,1</td>
</tr>
<tr>
<td>167</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.03,1</td>
</tr>
<tr>
<td>207</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.84,3</td>
</tr>
</tbody>
</table>

1.59,7 | 9.83,6 | 3.64,5 | - | - | - |
5.71,6 | 2.32,6 | 1.33,6 | 5.68,4 |
1.06,2 | 2.24,3 | 1.06,2 | 1.35,0 |
2.17,-1 | 1.73,-2 |
2.04,-4
### Table III
Measured and predicted threshold reaction rates in Configuration 3 (Ordinary Concrete)

<table>
<thead>
<tr>
<th>Z</th>
<th>MEASURED</th>
<th>PREDICTED BY NN</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S</td>
<td>In</td>
<td>Al</td>
</tr>
<tr>
<td>0</td>
<td>7.15 ± 0.05,8</td>
<td>5.60 ± 0.05,8</td>
<td>9.30 ± 0.40,6</td>
</tr>
<tr>
<td>43</td>
<td>2.54 ± 0.05,7</td>
<td>1.85 ± 0.02,7</td>
<td>3.63 ± 0.03,5</td>
</tr>
<tr>
<td>77</td>
<td>6.25 ± 0.10,5</td>
<td>5.05 ± 0.11,5</td>
<td>8.39 ± 0.07,3</td>
</tr>
<tr>
<td>117.6</td>
<td>1.05 ± 0.02,4</td>
<td>8.2 ± 1.6,3</td>
<td>1.4 ± 0.3,2</td>
</tr>
</tbody>
</table>

a) from ref. 14, excluding Z = 0
Table IV

Gross changes in the fast neutron spectrum in various materials during a 100 cm penetration as indicated by the changes in the $(\text{Al}/\text{S})$ and $(\text{In}/\text{S})$ reaction rate ratios. These ratios have been normalized to one at $20 - 40\text{ cm}$ from the reactor face.

<table>
<thead>
<tr>
<th>Material</th>
<th>Regions to the point of normalization</th>
<th>Change in the relative ratios after a 100 cm penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2\text{O}$</td>
<td>$30\text{ cm } \text{H}_2\text{O}$</td>
<td>$(\text{Al}/\text{S})$</td>
</tr>
<tr>
<td>Magnetite Concrete</td>
<td>$20\text{ cm } \text{H}_2\text{O} + 15\text{ cm concr.}$</td>
<td>$3 - 4$</td>
</tr>
<tr>
<td>$\gamma = 3.74\text{ (g cm}^{-3}\text{)}$</td>
<td></td>
<td>$1.4 - 1.6$</td>
</tr>
<tr>
<td>Ordinary Concrete</td>
<td>$\approx 23\text{ cm } \text{H}_2\text{O} + 34\text{ cm concr.}$</td>
<td></td>
</tr>
</tbody>
</table>
Predicted and measured $\ln(n, n')$ reaction rates in water (Config. 1) as a function of penetration. The change in the slope of the measured values, starting at ≈ 70 cm, is most probably due to a photonuclear excitation.
Fig. 2.

The ratio between the measured (or predicted by Moments method) and the NRN-predicted absolute reaction rates in water as a function of penetration. The absolute scale for the results by the Moments method has been obtained by normalizing the $S(n, p)$ rate to the measured one at $z = 30$ cm.

Fig. 3.

The ratio of the NIOBE and RASH D absolute predictions to NRN predictions in water.
Fig. 4.

The change in the ratios \( \frac{A_{Al}}{A_S} \) and \( \frac{A_{In}}{A_S} \) as a function of penetration in water. The ratios have been normalized to one at \( z = 30 \) cm.

Fig. 5.

The predicted neutron spectra in water (given as flux per lethargy unit), \( z = 30 \) cm.
Fig. 6. The predicted neutron spectra in water, $z = 60$ cm

Fig. 7. The predicted neutron spectra in water, $z = 90$ cm
Fig. 8. The predicted neutron spectra in water, $z = 120 \text{ cm}$

Fig. 9. Neutron spectra in water as predicted by NRN at $z = 30$, $60$, $90$, and $120$ cm, on a relative scale. $\phi_u (1 \text{ MeV})$ have been put equal to one.
Fig. 10.

The response functions of the detectors. The spectrum used is that by NRN in water at z = 60 cm.

Fig. 11.

The ratio of the measured and RASH D and NIOBE predicted values to those predicted by NRN, as a function of penetration in Config. 2 (magnetite concrete). For explanation of signs see Fig. 2.
The change in the \((A_{Al}/A_S)\) and \((A_{In}/A_S)\) ratios as a function of penetration in Config. 2. The ratios have been normalized to one at \(z = 35\) cm.

Neutron spectra in Config. 2 as predicted by NRN, at \(z = 35, 87,\) and \(127\) cm on a relative scale. \(\Phi_u (1 \text{ MeV})\) have been put equal to one.
Fig. 14.
The ratio of the measured values to those predicted by NRN as a function of penetration in Config. 3 (ordinary concrete). For explanation of signs see Fig. 2.

Fig. 15.
The change in the \( \frac{A_{\text{Al}}}{A_S} \) and \( \frac{A_{\text{In}}}{A_S} \) ratios as a function of penetration in Config. 3. The ratios have been normalized to one at \( z = 77 \) cm.