D.V. Gorbatkov\textsuperscript{1}, V.P. Kryuchkov\textsuperscript{2}

\textbf{A COMPARISON OF COMPUTATIONAL DATA OBTAINED WITH A VARIETY OF WELL-KNOWN RADIATION TRANSPORT CODES (MCNP, ANISN, FLUKA, ROZ6H)}

Submitted to \textit{AE and NIM}

\textsuperscript{1}E-mail: gorbatkov@mx.ihep.su
\textsuperscript{2}E-mail: kryuchkov@mx.ihep.su

Protvino 1995
Abstract

A verification of the calculational data, obtained with different well-known radiation transport codes and nuclear cross section sets (MCNP + ENDF/B, ANISN + HILO, FLUKA92) has been made by comparison with the results of precision ROZ6H + SADCO calculations and available experimental data. The results obtained with the MCNP + ENDF/B-5 package and ROZ6H + SADCO-computed data for neutron penetration in iron at energies $E \leq 14\ MeV$ are in good agreement. For the calculations using ANISN at energies $\leq 400\ MeV$ and FLUKA at energies $\leq 200\ GeV$, there are significant discrepancies both from the ROZ6H calculations and experimental data. Differences are discussed.

Аннотация

Проведена верификация результатов расчетов переноса излучений, полученных по известным транспортным кодам и константным библиотекам (MCNP + ENDF/B, ANISN + HILO, FLUKA92), путем их сравнения с результатами прецизионных расчетов по программному комплексу ROZ6H + SADCO и с экспериментальными данными. Показано хорошее согласие с данными пакета MCNP + ENDF/B-5 для диапазона энергий $E \leq 14\ MeV$. Проведен анализ расхождений результатов, полученных с помощью пакета ANISN+ HILO для $E \leq 400\ MeV$ и программы FLUKA92 для $E \leq 200\ GeV$, с нашими и с экспериментальными данными.

© State Research Center of Russia
Institute for High Energy Physics, 1995
Introduction

Particle transport through shield materials has been important since the early days of accelerator physics. Examples include shielding for high-energy accelerators, radiation safety and background problems, accelerators for fusion reactor materials studies and cancer therapy.

Recently, a lot of transport codes and program packages (for example, [1–4]) have been developed to investigate radiation and physical problems on charged particle accelerators. But none is universal: there are limitations on the energy range, particle types, and attenuation depths. Applying transport code with no regard for these limitations can lead to large uncertainties.

For this reason, any calculational method used must be shown through measurements to be as accurate as the current technology allows. However, experimental measurements are usually difficult to model calculationally due to multidimensional geometries and complex source and detector characteristics. The available experimental data provide a verification of transport codes only over a limited range of particle energies, target sizes, materials and attenuation depths; nevertheless, good integral measurements are extremely important since they allow a check on the overall adequacy of calculational techniques.

The use of special "precision" code calculations for checking on the adequacy of a variety of transport computer codes seems to be the best way. One of such "precision" codes is represented by the discrete ordinates code ROZ6H [5,6] with nuclear cross section set based on the SADCO–2 system [7], which has been extended to provide the transport calculations of neutrons, protons, pions, kaons, muons and photons through matter in a wide energy range with estimated and small errors.

The purpose of this paper is to compare the data obtained using some well-known transport codes (MCNP, ANISN, FLUKA) with the data, calculated by the ROZ6H + SADCO program complex for the three ranges of the primary particles energy: E<20 MeV, E<400 MeV, E<200 GeV. Discrepancies have been observed and will be discussed below.
1. Methods for high-energy hadrons transport calculation

Almost all codes developed for practical accelerator shield design are based on an analogue simulation of particle trajectories by the Monte Carlo method. The choice of the Monte Carlo method in the high-energy range is connected with its advantages. They are:

- simplicity of the particle transport simulation algorithm;
- possibility and simplicity of any physical processes inclusion into a calculation scheme;
- capabilities to solve the transport problem for complicated three-dimensional geometries.

At the same time the main deficiency of Monte Carlo, that determines admissible areas of its application, is the restriction on the attenuation depth (it is the so called "deep penetration problem"). As has been mentioned in [8], another difficulty lies in the fact that most high-energy transport programs are not provided with variance reduction algorithms, and therefore require prohibitive computing times to carry out deep penetration calculations.

Really, it can easily be shown that the calculation time depends on a material thickness as an exponent: \( T \sim T_0 e^{d/\lambda} \varepsilon^2 \), where \( T \) is the calculational time, \( T_0 \) is the average time of one history calculation, \( d \) is the shielding thickness, \( \lambda \) is the attenuation length, \( \varepsilon \) is the statistical calculation error.

From this relation it is clear that for the particle fluence calculation with 30% error behind the shielding 15-\( \lambda \) thick using the transport code with \( T_0 = 0.1 \)c about 1000 hours of processor run time are required. The solution of the same task for the shielding thickness more than 20\( \lambda \) is impossible even using supermodern computers with multiprocessor parallel architecture.

One more difficult problem of the Monte Carlo method is a particle trajectory simulation in slightly absorbing medium and in medium with the generation of a great number of secondary particles.

The well-known variance reduction algorithms application (for example, "splitting" for highly absorbing medium or "Russian roulette" for medium with generation of numerous secondary particles and etc.) is the most effective and correct with the use of a priori information about radiation fields. This information can be obtained either from special experiments or from calculations with a "precision" code. We believe the ROZ6H + SADO program package [6] is best suited for those purposes.

The developed program complex consists of the SADCO-2 modular code system [7] for generating coupled nuclear data libraries to provide high-energy particle transport calculation by multigroup methods and the discrete ordinates cascade particle transport code ROZ6H [5].

The SADCO-2 system prepares multigroup cross sections for neutrons with energies ranging from 0.01 eV to 10 TeV, protons, pions, kaons and muons (20 MeV ÷ 10 TeV) and photons (0.01 MeV ÷ 20 MeV). The multigroup data processing is described in [7]. Here, we emphasize that the SADCO-2 system allows one to obtain the total cross sections
with the error less than 10% and the uncertainty of the double differential cross sections calculated using method [9] can come up to 50% at most.

The program ROZ6H is developed for the solution of multigroup kinetic equation of \((n, p, \pi, K, \mu, \gamma)\) particle transport in the one-dimensional geometry by the discrete ordinates method for different sources, involving problems with fission and cascade processes. The angular distribution of scattering is represented either by the Legendre expansion, or by the "discrete points type" approximation.

To approximate a spatial derivative one of the following schemes is used: a) the Adapted Weighted Diamond scheme; b) the method of characteristics. The energy derivative describing ionizing energy losses in a continuous slowing-down approach and diffusion dilution in energy are approximated with a second-order accuracy scheme. The angular dependence of Boltzmann's operator with a high anisotropic scattering is described in a Fokker-Planck or in a \(\delta\)-function approximation.

A systematic error of numerical schemes, as realized in code ROZ6H, is less than 1%. The total uncertainty of calculations is determined by errors of multigroup data from the SADCO-2 system and amounts about 30%.

A developed algorithm makes it possible to calculate different functionals of radiation field in deep penetration problems with a highly anisotropic scattering.

The ROZ6H + SADCO program complex presented in [6] allows one to calculate the transport of neutrons \((0.01 \text{ eV} < E < 10 \text{ TeV})\), protons, pions, kaons, muons \((20 \text{ MeV} < E < 10 \text{ TeV})\), and photons \((0.01 \text{ MeV} < E < 20 \text{ MeV})\) in the one-dimensional geometry with a high accuracy \((\text{error} \leq 30\%)\) by the discrete ordinates method. It may be used to investigate stationary and nonstationary radiation fields formed behind a high-energy accelerator shielding.

2. Calculation and comparison of neutron penetration through a slab of iron for the 2-, 14- and 40-MeV sources

A comparison of the calculated results with the benchmark data is very important to evaluate the adequacy of methods and nuclear data libraries in use.

A lot of examples of the ROZ6H-calculated data comparison with the results of base and integral experiments are available (for instance, [10]), which has convincingly demonstrated a high accuracy of the code ROZ6H.

The results of calculational benchmark presented in [11] have been chosen to compare space-energy distributions of neutron fields at source energies of 2, 14, 40 MeV in the iron shield up to 3-m thick. The benchmark calculations were carried out by the Monte Carlo method using code MCNP [12] with neutron cross section sets based on both ENDF-B/4 [13] and ENDF-B/5 [14]. To calculate the transport of neutrons with source energy 40 MeV in [11] the "extended library" consisting of ENDF-B/4 for the neutron energy \(E < 20 \text{ MeV}\) and the data calculated using the cascade-evaporation model for the energy range \(20 < E < 40 \text{ MeV}\) [15] were used.
The deep penetration calculation (up to ~10 attenuation lengths) was carried out by the Monte Carlo method using a special weight technique ("Russian roulette") with checking the results on the integral experiments.

The comparison of our calculated neutron spectra at 100 and 200 cm in the pure iron slab for the 2- and 14-MeV sources with those from [11] are presented in Figs.1-4. It is worth noting that the results obtained by different methods and nuclear data libraries (Monte Carlo in MCNP + ENDF-B/5 and discrete ordinates in ROZ6H + SADCO) are in a good agreement well (within a 10% error).

The calculational-to-benchmark comparisons of neutron spatial distributions are shown in Fig.5 for various source energies. One can see that the integral characteristics of neutron fields for the energies 2 and 14 MeV calculated by MCNP + ENDF-B/5 conform with ROZ6H + SADCO-calculated results within 5%.

At the same time we call attention to the strong discrepancy between our results and benchmark data obtained at the big iron depths and with 40-MeV source. The reasons of this disagreements can be both the inadequacy of "extended library" and the difficulty to calculate neutron deep penetration by the Monte Carlo method.

The neutron spectra calculated by ROZ6H + SADCO with 40-MeV source are presented in Fig.6 and can be used as benchmark data in parallel with the spectra for the 2- and 14-MeV sources.

3. Calculation of space-energy characteristics of neutron fields in the thick iron layer for the 400-MeV source

For the neutron energy range E<400 MeV the most famous nuclear data system is the multigroup library HILO [16]. This library is in common use to provide a numerical solution of the multigroup kinetic equation by the discrete ordinates method, as realized in the ANISN transport code [17].

Neglect of charged particles transport in the numerical scheme of ANISN (data for charged particles in the HILO library are absent too) has little or no effect on the calculational error for the above energy range. An inadequate description of the indicatrix in HILO (\(\beta\)-approximation) does contribute to the error, essentially.

In addition, the ANISN numerical scheme is not designed to calculate a high anisotropic neutron flux, that is typical for this energy range. This circumstance could make appreciable contribution to the calculation error.

The calculations reliability analysis of the ANISN + HILO package has been carried out using data [16] and calculations with the ROZ6H + SADCO program complex. The calculational configuration is that of an iron sphere of 5 m radius with a spherical volumetric isotropic neutron source at its center. The neutron source has a radius of 5 cm and the neutron energy spectrum is uniform over the energy interval 300 to 400 MeV. The density of iron was taken to be 7.84 g/cm\(^3\).
Fig. 1. Neutron energy spectra at 100 cm into pure iron slab for 2-MeV source calculated with the MCNP+ENDF/B-5 and ROZ6H+SADCO packages.

Fig. 2. The same as in Fig.1 but at 200 cm into slab.

Fig. 3. Neutron energy spectra at 100 cm into pure iron slab for 14-MeV source calculated with the MCNP+ENDF/B-5 and ROZ6H+SADCO packages.

Fig. 4. The same as in Fig.3 but at 200 cm into slab.
Comparisons of the neutron spectra at various radii calculated with the ANISN + HILO and ROZ6H + SADCO complexes are presented in Fig.7. As can be seen from this figure calculational results obtained with different codes agree at the small radii (20 and 100 cm), but the results disagree at the large radius (300 cm). The data obtained with ANISN + HILO are significantly underestimated against our data for the intermediate energy range.

A strong disagreement for the large radii is particularly striking in Fig.8, where the specific neutron and photon flux distributions are presented.

The character of neutron attenuation in the thick iron shielding is known to be determined by the big moderation length of neutron with the energy 10 keV ÷ 1 MeV. That is why the attenuation coefficient (\( \lambda \)) depends on the neutron source energy very slightly. This fact is vividly illustrated in Fig.5. The neutron flux attenuation is seen to be nearly equal for the 2-, 14-, 40- and 400-MeV neutron sources.

The attenuation coefficient for neutrons (calculated here, in [11], obtained using the data [16], from measurements [18], [19]) is presented in Table 1.

<table>
<thead>
<tr>
<th>Publication</th>
<th>Energy, MeV</th>
<th>( \lambda ), g/cm^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROZ6H + SADCO</td>
<td>2, 14, 40, 400</td>
<td>310 ± 10</td>
</tr>
<tr>
<td>MCNP + ENDF-B/5</td>
<td>2, 14</td>
<td>312</td>
</tr>
<tr>
<td>experiment [18]</td>
<td>&lt;1</td>
<td>289 ± 20</td>
</tr>
<tr>
<td>experiment [19]</td>
<td>&lt;1</td>
<td>296 ± 23</td>
</tr>
<tr>
<td>ANISN + HILO [16]</td>
<td>400</td>
<td>165</td>
</tr>
</tbody>
</table>

From this Table we see that the data of [16] are in a strong disagreement with other results. The character of disagreement, shown in Figs.7, 8 and in Table 1, seems to point to the fact that the angular distributions of neutron flux are incorrectly approximated by the complex ANISN + HILO. Probably, the distortion of the scattering cross section angular dependence in the HILO multigroup library is the reason of it. Another reason of disagreement is a small order (P_3) of the Legendre expansion in the angular flux decomposition used in [16]. It is not sufficient to describe an angular flux for the given energy range. Both the first and the second reason can lead to smoothed angular flux and to overstated attenuation for the big depth of iron.

4. Calculations and comparisons of space-energy characteristics of radiation fields for the high-energy 200-GeV hadron source

4.1. Boundary-value conditions, geometry, approximations

The geometry simulated by the Monte Carlo transport code FLUKA in [20] and its one-dimensional model accepted for our calculations are presented in Fig.9.
Fig. 5. Total neutron fluxes within iron slab at various primary energies.

Fig. 6. Neutron energy spectra at 100 and 200 cm into iron slab for 40-MeV source calculated with the ROZ6H+SADCO package.

Fig. 7. Neutron energy spectra at various radii into iron sphere for 400-MeV source calculated with the ANISN+HILO (symbols) and ROZ6H+SADCO (histograms) packages.

Fig. 8. Total neutron and photon fluxes as a function of radius for 400-MeV neutron source.
Fig. 9. Geometry of the calculations: a) – actual geometry; b) – one-dimensional model.

In the simulated experiment the shielded object was a thick copper target (length – 50 cm, diameter – 7 cm) irradiated by a high-energy (pulse – 205 GeV/c) proton ($\pi^+$-meson) beam. The layout of shield is shown in Fig.9.

Two cases were considered in calculations. In the first case the iron roof consisted of two 20-cm thick layers. The density of a lower iron layer was taken to be 7.65 g/cm$^3$, of an upper-layer – 7.2 g/cm$^3$. In the second case radiation fields behind concrete shields 80 and 160 cm thick were studied. The isotopical composition of concrete used for simulation is nearly the same as in Ref. [20]: oxygen (51.1%), silicon (35.8%), calcium (8.6%), aluminum (2.0%), iron (2.0%), hydrogen (0.5%). The density of concrete is 2.35 g/cm$^3$.

As is seen from Fig.9 our simplification of geometry is reduced to a neglect of some details, which do not disturb radiation fields and to the substitution of the angular distribution of particles emitted from a target to the monodirectional beam.

Calculations were carried out by two steps: the spectra of all particles generated on a target and fallen down on the shield were calculated at the first step; the hadrons and photons transport through the shielding was calculated at the second step.

The spectra of neutrons, protons, and pions emitted from the target were calculated by the MOSKIT Monte Carlo code [21] for the geometry of Fig.9(a). They are presented in Fig.10. These spectra were used as a boundary-condition for the problem of radiation transport through the one-dimensional iron or concrete shielding.

4.2. Neutron spectra behind iron shielding

The neutron spectra behind iron shielding calculated with the ROZ6H + SADCO package for the geometry of Fig.9b are presented in Fig.11. The spectra calculated with FLUKA using Monte Carlo (data taken from report [20]) are presented in the same figure.

From the presented data it can be seen that the spectra calculated with different methods are in a qualitative agreement: there is a high-energy peak in the 100 to 300 MeV region due to the pions generation, two peaks in the fast range (at 0.3 and 0.02 MeV) connected with a cross sections behavior, a sharp decrease in the intermediate range.
Fig. 10. Spectra of particles produced in a copper target by 205-GeV protons (histograms) and particle production spectra for 205-GeV p+Cu reactions (curves). The spectra are averaged over the target-to-detector angular interval (10–25°).

Fig. 11. Neutron and photon energy spectra behind the iron shielding 40 cm thick for a proton incident at 205 GeV calculated with the FLUKA (symbols) and ROZ6H+SADCO (histograms) packages. Solid histogram indicates the calculation for the pure iron shielding, dashed histogram represents the data calculated with taking into account the inner concrete floor, dotted histogram includes the radiation scattered behind the shielding (see text for more explanation).
At the same time strong discrepancies between our data and those calculated with FLUKA have engaged our attention. They are: different absolute values of peaks, a different behavior of spectra in the intermediate and low energy ranges.

The mentioned discrepancies cannot be explained by the simplification of geometry used in our calculations. As may be seen from Fig. 11 the data obtained for the iron shielding without taking into account the concrete floor and walls nearly coincide with the data calculated with account of them.

The inclusion of neutrons scattered by nuclei of air and concrete constructions behind the shielding considerably contribute to the results. The scattering radiation consideration brings our data closer to those calculated with FLUKA in the intermediate range and results in the appearance of a peak in the thermal range (in the data computed with FLUKA a thermal peak is absent).

To complete the pattern of radiation formation behind the shielding and to illustrate the potential of the developed complex ROZ6H + SADCO the spectrum of photons is presented on the same figure. One can see from figure that the photon spectrum occupies narrow enough energy range and has a typical shape for iron.

4.3. Neutron spectra behind concrete shielding

As is clear from Fig. 12 an agreement between spectra behind the concrete shielding 80 cm thick calculated by both methods is good.

Fig. 12. Neutron and photon energy spectra behind the concrete shielding 80 cm thick for 205-GeV incident proton calculated with the FLUKA (symbols) and ROZ6H (histograms) packages.

Fig. 13. Neutron energy spectra behind the concrete shielding 160 cm thick for 205-GeV proton incident.
Considering a wide scatter of calculated points, due to poor statistics of FLUKA calculation, the agreement of neutron spectra behind 160 cm concrete (Fig.13) may be evaluated as good. However, the high-energy part of spectrum calculated with FLUKA is just below than our data. Apparently, the mentioned discrepancy may be explained by a soft enough spectrum of cascade particles generated in FLUKA [3].

There is another difference between the presented spectra: the thermal neutron peak, well-known from calculated and experimental data in literature, is absent in spectra calculated with FLUKA [20].

Note that the influence of radiation scattered on nuclei of air and environmental concrete constructions on the spectrum behind the concrete shielding is far less than that behind iron.

As for iron shielding, the photon spectra behind concrete are also presented in Fig.12. The spectrum shape is determined by photon spectrum generated in inelastic interactions of neutrons with nuclei of isotopes contained in concrete and is typical for the given concrete composition.

4.4. Proton and π-meson spectra

The calculated proton and π-meson spectra behind iron and concrete shields are presented in Figs.14–19. One can see the strong disagreements between the proton spectra calculated with FLUKA and ROZ6H (Figs.14–16), which can be evaluated by a factor of 5÷10. It is impossible to explain the mentioned discrepancy by a poor statistics of FLUKA-calculated results only, even though statistics errors in it reach up to 100%.

Probably, the main discrepancy reason is a softer cascade particle spectrum generated in FLUKA than that in our code, as noticed above.

An agreement between pion spectra (Figs.17–19) is just better, although the difference is evaluated by a factor of 2÷3.

4.5. Relations between different radiation components

Relations between different radiation components are very important characteristics of radiation field behind the shielding. Here we have studied the specific distribution of the following components: neutrons with energy E>20 MeV (n_h), neutrons with energy 1 eV<E<20 MeV (n_f), protons (p) and pions (π), thermal neutrons (n_th) and photons (n_γ).

The thickness dependencies of the mentioned components in iron and concrete shielding calculated for the conditions described in section 4.1 are presented in Figs.20, 21. Note two important facts of radiation formation in the shielding:

-- as is indicated in [22] the relations among all the components depend very slightly on the primary hadron energy at energies E>1 GeV;

-- as can be seen from Figs.20, 21 all the components in the concrete shielding and high-energy components in the iron shielding are in an equilibrium for the shielding thickness more than 3÷5λ.
Fig. 14. Proton energy spectra behind the iron shielding 40 cm thick for 205-GeV proton incident.

Fig. 15. Proton energy spectra behind the concrete shielding 80 cm thick for 205-GeV proton incident.

Fig. 16. The same as in Fig. 15 but for the shielding 160 cm thick.

Fig. 17. Pion energy spectra behind the iron shielding 40 cm thick for 205-GeV proton incident.

Fig. 18. Pion energy spectra behind the concrete shielding 80 cm thick for 205-GeV proton incident.

Fig. 19. The same as in Fig. 18 but for the shielding 160 cm thick.
The mentioned regularities allow one to compare the calculated data with the experimental ones obtained for other energies and shielding thicknesses.

Calculated data characterizing the hardness of neutron spectra \((n_h/n_f)\) and the charged particle fraction from the total high-energy particle fluence behind the shielding \((p/n_h, (p + \pi)/n_h, \pi/n_h, \pi/p)\) are given in Tables 2–4.

**Table 2.** Relations between different radiation components behind the iron shielding 40 cm thick

<table>
<thead>
<tr>
<th></th>
<th>(n_h/n_f)</th>
<th>(p/n_h)</th>
<th>(\pi/n_h)</th>
<th>(\pi/p)</th>
<th>((p+\pi)/n_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from [20]</td>
<td>0.06</td>
<td>0.017</td>
<td>0.007</td>
<td>0.43</td>
<td>0.025</td>
</tr>
<tr>
<td>These data</td>
<td>0.03</td>
<td>0.1</td>
<td>0.03</td>
<td>0.27</td>
<td>0.13</td>
</tr>
</tbody>
</table>

**Table 3.** Relations between different radiation components behind the concrete shielding 80 cm thick

<table>
<thead>
<tr>
<th></th>
<th>(n_h/n_f)</th>
<th>(p/n_h)</th>
<th>(\pi/n_h)</th>
<th>(\pi/p)</th>
<th>((p+\pi)/n_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from [20]</td>
<td>0.74</td>
<td>0.018</td>
<td>0.015</td>
<td>0.81</td>
<td>0.032</td>
</tr>
<tr>
<td>These data</td>
<td>0.60</td>
<td>0.24</td>
<td>0.04</td>
<td>0.17</td>
<td>0.28</td>
</tr>
</tbody>
</table>

**Table 4.** Relations between different radiation components behind the concrete shielding 160 cm thick

<table>
<thead>
<tr>
<th></th>
<th>(n_h/n_f)</th>
<th>(p/n_h)</th>
<th>(\pi/n_h)</th>
<th>(\pi/p)</th>
<th>((p+\pi)/n_h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from [20]</td>
<td>0.40</td>
<td>0.005</td>
<td>0.0</td>
<td>0.01</td>
<td>0.005</td>
</tr>
<tr>
<td>These data</td>
<td>0.69</td>
<td>0.18</td>
<td>0.008</td>
<td>0.043</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The ratio of proton fluence to high-energy neutron one calculated with ROZ6H + SADCO is presented in Table 5. For comparison, the measured data [23], [24], calculated data [22] and calculated data [20] are given in the same Table as well.

The analysis of data presented in Table 5 shows a reasonable agreement of our results with the experimental data, a contribution of the charged component into a total flux obtained with FLUKA is underestimated by a factor of 10.
Table 5. Ratio $p/n_a$, %

<table>
<thead>
<tr>
<th>Publication</th>
<th>Top shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>iron</td>
</tr>
<tr>
<td>This paper</td>
<td>10.6</td>
</tr>
<tr>
<td>Calculation [22]</td>
<td>7±10$^1$</td>
</tr>
<tr>
<td>Experiment [23]</td>
<td>-</td>
</tr>
<tr>
<td>Experiment [24]</td>
<td>-</td>
</tr>
<tr>
<td>Calculation with FLUKA [20]</td>
<td>1÷2</td>
</tr>
</tbody>
</table>

$^1$Data for monodirectional proton beam with 1 GeV energy and 100- and 200-cm thick shielding.

$^1$This is the ratio of a dose equivalent from charged particles to a dose equivalent from neutrons ($H_{eq}^*/H_{tot}^*$). The thickness of the top concrete shielding is 220 cm. The energy of a proton beam is 70 GeV.

Fig. 20. Total particle fluxes within the iron shielding.

Fig. 21. Total particle fluxes within the concrete shielding.

Conclusion

To study a reliability of different radiation transport calculation methods and admissible areas of application, the results calculated with the complex ROZ6H + SADCO and those calculated with other well-known program packages were compared. Comparisons were performed for three energy ranges: $E<20$ MeV, $E<400$ MeV, $E<200$ GeV. Three program packages corresponding to the mentioned energy ranges were selected MCNP + ENDF/B, ANISN + HILO, FLUKA.

14
Comparisons of our data with the calculations performed with the program complex MCNP + ENDF/B-5 for low energy neutrons show:

- an agreement between our data and MCNP + ENDF/B-5 for the 2- and 14-MeV sources is impressive (within 10% error for spectra and 5% for spatial distributions), which confirms the adequacy, reliability and accuracy of both complexes;

- there is a strong discrepancy in neutron spatial distribution for the 40-MeV source calculated with MCNP + "extended library" and our data. The MCNP + "extended library" data are contradictory to an attenuation character of the 2- and 14-MeV sources calculated with MCNP + ENDF/B-5 as well and may be explained by uncertainties of the "extended library".

Neutron spectra and spatial distributions in the energy range E<400 MeV calculated with ANISN + HILO and complex ROZ6H + SADCO are in a reasonably good agreement at small iron thickness (up to 1.5 m). For the iron thickness more than 1.5 m, calculations with ANISN + HILO overstate the neutron attenuation and are in conflict both with our data and experimental ones.

Comparisons of radiation field characteristics behind the shielding of high-energy radiation (up to 200 GeV) for the experiment CERN-CEC, calculated with FLUKA and our results testify to the following:

- there is a good agreement of neutron spectra for the concrete shielding and for the iron shielding in the $10^{-6}$ to $10^3$ MeV region may be considered satisfactory;

- the agreement of charged particle ($p$, $\pi$) spectra is bad both for the iron and concrete shielding;

- the "hardness" coefficients for the neutron spectra calculated by both methods are in a reasonable agreement;

- the ratio of proton fluence to high-energy neutron fluence calculated with complex ROZ6H + SADCO vary from 15% for iron to 25% for concrete. Those values are in a good agreement with the experimental data, which are 12±18% for iron and 25±30% for concrete. The corresponding data calculated with FLUKA are 0.8±1.9% for iron and 1.3±2.3% for concrete, which is about 10 times lower both for our data and the experimental ones.

References


Received May 22, 1995
Д.В. Горбатков, В.П. Крючков
Сравнение результатов расчетов переноса излучений, полученных с использованием различных транспортных кодов (MCNP, ANISN, FLUKA, ROZ6H).

Оригинал-макет подготовлен с помощью системы \LaTeX.
Редактор Е.Н. Горина. Технический редактор Н.В. Орлова.

Подписано к печати 25.05.95. Формат 60 х 84/8. Офсетная печать.
Печ. л. 2,00. Уч.- изд. л. 1,5. Тираж 120. Заказ 328. Индекс 3649.
ЛР №020496 06.04.92.

ГНЦ РФ Институт физики высоких энергий
142284, Протвино Московской обл.
ПРЕПРИНТ 95-73, ИФВЭ, 1995