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SINQ BULK SHIELD ANALYSIS USING THE S_n -METHOD

by

V. Herrnberger, P. Stiller
Federal Institute for Reactor Research
5303 Wuerenlingen, Switzerland

SUMMARY

Two available high neutron energy cross section libraries for shield design were checked and corrected. Comments are given to the corrections and the errors found. Homogeneous iron and heterogeneous iron/concrete bulk shields were analysed by direct and adjoint S_n-method using these libraries. Some results were comparable to published data. Conclusions are drawn for the utility and accuracy achieved with these data libraries. This investigation was made for the project of a spallation source (SINQ) at the Swiss Institute for Nuclear Research (SIN).

1. INTRODUCTION

The design of a spallation source shield involves the same types of problems as for nuclear reactor shields - viz. designing the bulk shield, the beamholes and shutters, and the determination of sky- and groundshine. However, the energy range of the neutron and gamma radiation created by the spallation processes is much wider and the necessary cross-section data and models are less accurately known than for nuclear reactor shielding. An intercomparison of cross-sections (c.s.) and methods is useful in determining the effects of these uncertainties on the target quantities of interest, e.g. radiation damage, radiation heating and dose rates. For the bulk shield analysis of the SINQ we restricted ourselves to the established deterministic method of discrete ordinates using a version of ANISN in connection with two different high energy neutron c.s. libraries.
We proceeded in three steps:

a. Preparing the necessary group cross section libraries for the transport calculations.
b. Analysing a high energy neutron benchmark of a homogeneous iron shield with respect to equilibria spectra, relaxation length and build-up factors.
c. Analysing a heterogeneous bulk shield of iron and concrete and comparing the outer dose rates with rule of thumb results.

2. COMMENTS ON THE STATE OF THE HIGH ENERGY NEUTRON CROSS SECTION LIBRARIES

Two cross-section libraries which include the necessary neutron c.s. are available for use. The first, from the Oak Ridge National Laboratories, USA, will be refered to as HILO[1]. The other from the Los Alamos National Laboratory is termed LANL[2]. The main characteristics of the libraries are compared in Table 1. The LANL library is relatively old (1972) compared to HILO (1978) and it has been recommended, that it should be applied with caution[3]. It is neither adjusted to experiments nor based on the latest c.s. files. The energy resolution (number of groups) in the low-energy range is similar to that of HILO. In the high energy range HILO has a much better resolution. HILO may, therefore, be expected to be better suited for problems with strong spectrum variation in the high energy range, as is the case for an iron shield.

Table 1

Summary of the Characteristics of the HILO and LANL Libraries
(HE: high energy / LE: low energy range)

Characteristics	HILO	LANL
Coupled n & γ	yes	no γ
Number of n groups	HE: 31 LE: 35 } 66	HE: 11 LE: 30 } 41
n-energy range	HE: 14.9-400 MeV LE: 10^{-10}-14.9 "	HE: 17.-800 MeV LE: $1.39 \cdot 10^{-10}$-17.MeV
γ- energy range	10^{-2} - 14 MeV	-
Legendre expansion	HE: P_5 LE: P_3	P_3
Elastic scatter	Yes, except for Pb & W in HE	no in HE
Origin of data	HE: Intranuclear cascade/evaporation and optical model LE: VITAMIN-C from ENDF/B-IV	Intranuclear cascade/evaporation LE: ENDF/B-III
Adjusted to experiments	yes	no
References	(1) (5) (7)	(2) (5) (7)

Because of the obvious importance of the c.s. data in the calculations both libraries have been recently checked, corrected and compared directly to each other and to available measurements. The results were satisfactory with three exeptions:

LANL-library:

a. The c.s. of molybdenum in the energy range 17-20 MeV (group 11) seemed to be wrong, if compared to the neighbour groups. They were replaced by those generated by the NJOY-data-processing system[4] from ENDF/B-IV. To be consistent the corresponding values in the P_1-P_3 moments were generated and replaced too[5]. Table 2 compares the original LANL data with those from NJOY and ENDF/B-IV for the P_0-moment only.

b. The c.s. of lead is questionable above 100 MeV, if it is compared to measurements and HILO-c.s. data: This error was found by T. Armstrong too[6]. See Fig. 1.[7]. For lead the HILO c.s. is recommended for use instead of the LANL values.

HILO-library:

c. The HILO c.s. (except for Pb and W) are much too large above 100 MeV. This is due to an increase in the elastic c.s. obtained from optical model calculations, where global parameters were used[8]. Figure 2 shows the huge differences in comparison to the basic BNL-325 data for iron[5]. Therefore transport calculations for an iron bulk shield will generally give lower fluxes and dose rates with HILO c.s. than with LANL c.s., which don't contain elastic scattering in this energy range. (See table 1 and figure 2).

The influence of the c.s. differences on the calculated outer dose rates and the shield thickness is of major concern and can be examined by typical bulk shield benchmarks.

Table 2: Comparison of P_0-scattering transfer moments $\sigma_{11 \to g'}$ for molybdenum [barn]

g'	LANL	NJOY/ENDF/B-IV
11	0.	1.61990
12	1.65616-4	2.83250-1
13	-1.48324-3	1.29320-2
14	-1.11616-3	1.44870-2
15	-5.31374-4	2.54750-2
16	-5.49201-4	4.28840-2
17	-2.01767-4	6.70790-2
18	5.80335-5	2.73350-1
19	-1.17007-4	2.17190-1
20	1.72217-4	2.57970-1
21	2.82994-6	2.97200-1
22	7.15650-4	3.39110-1
23	-5.24013-4	7.39910-1
24	5.60998-4	6.97120-1
25	1.36244-3	5.02510-1
26	-7.13660-4	2.85860-1
27	7.63087-5	2.00580-1
28	-2.94215-4	3.47000-2
29	-2.02188-5	3.96010-3
30	-1.68503-5	0.
31	-3.24634-5	0.
32	-7.98184-6	0.
33	2.70260-5	0.
$\sigma_{T,11}$	-0.0025	5.91547
$\sigma_{tot,11}$	1.3513	3.65390
$\sigma_{abs,11}$	1.353	-2.26157

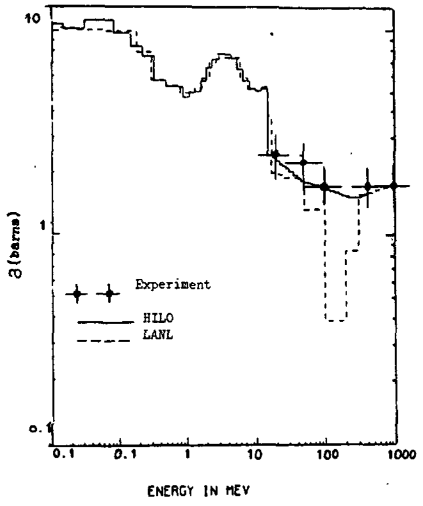

Fig. 1 Comparison of total/unelastic Pb c.s.

3. THE HIGH ENERGY NEUTRON BENCHMARK

A good tool for the analysis of the effect of cross section uncertainties on the dose rates is a so called "benchmark" configuration.

It has a simple definition of source material, composition and geometry to avoid unnecessary complexities of its analysis. Important characteristics of the real physical problem are, however, maintained so as to provide adequate physical insight. The benchmark, which was defined by EIR, SIN and KFA, has an isotropic spherical neutron source of 300 - 400 MeV of 10 cm diameter in an iron sphere of 10 m diameter. Spectra and dose rates were calculated by S_{16}/2.5 cm - mesh sizes. The source was normalized to 1 n/cm^3 sec.MeV. From the dose rates curves of Fig. 3 the relaxation lengths and the dose build-up factors were determined.

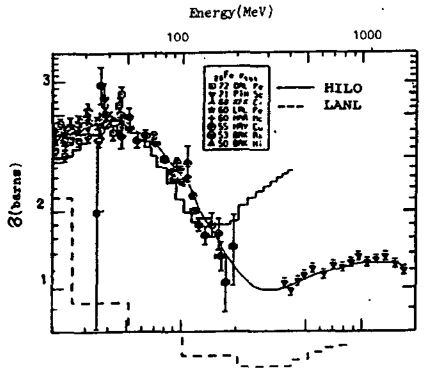

Fig. 2 Comparison of HILO-, LANL- and Barn Book data for total/nonelastic Fe c.s.

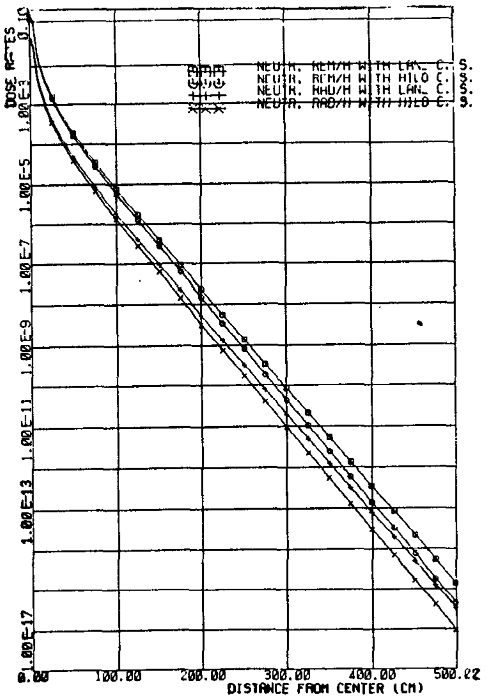

FIG.3 SPACE DEPENDENT DOSE RATES AND DIFFERENT C. S.

Equivalent and absorbed dose rates were limited to neutron energies above 15 MeV (Fig. 3), because they are the dominant contributions to the surface dose rate in a shield, which also includes concrete. From the spatial dose distribution relaxation lengths λ (Table 3) and dose build-up factors were derived (Fig. 4), which are useful for hand calculations.

The main conclusions are:

a. LANL c.s. show less attenuation than the HILO c.s., as it was concluded from the differences in their total c.s. (Fig. 1). The LANL c.s. give about a factor of 2 - 3 higher equivalent dose rates for penetration depths between 2 and 5 m.

b. Absorbed dose is a factor of 5 lower than the equivalent dose through the whole shield thickness. However the energy dependences of the dose conversion factors are different. Therefore the spectral changes are small and the absorbed dose can be easily estimated from the equivalent dose.

Table 3: Relaxation lengths λ for 300 - 400 MeV neutrons in iron

Reference	Penetration depth [cm]	λ [cm]
HILO	10 - 200	18.4
	200 - 300	17.8
	300 - 500	17.3
LANL	10 - 500	∿ 19.
(10)	100 -	17.

c. The relaxation length found with the HILO calculations is due to the space dependent build-up of scattered neutrons in the broad energy intervall of 100 MeV. No equilibrium above 60 MeV is reached after 2 m iron thickness. The LANL value of λ is constant and close to the value calculated in the HILO for the first 2 m. For greater penetration depth the HILO value gets smaller and approaches that of 17 cm[10].

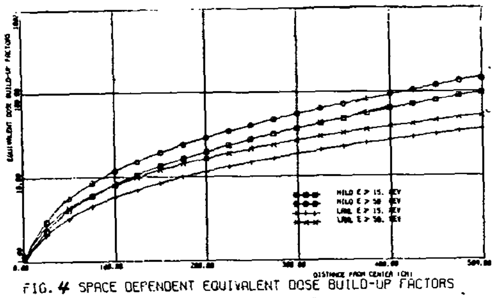

FIG. 4 SPACE DEPENDENT EQUIVALENT DOSE BUILD-UP FACTORS

Including the full spectrum above 15 MeV λ gets larger: 19.6 and 20.3 in the case of HILO and LANL respectively. The values are near to λ = 22 cm obtained by extrapolation back to 400 MeV the values quoted in reference 9.

d. The build-up factor increases with depth to a value of about 100. The build-up factor taken in conjunction with the relaxation length determines completely the dose rate greater penetrations depths. The HILO library gives 3 x higher values than LANL. The contribution of neutrons between 15 and 50 MeV to the dose rate is only about 30%.

The comparison of these results with Monte Carlo calculations performed by Atchison at SIN and with coupled Monte Carlo/S_n-calculations by Schaal et al. at KFA are underway. Finally the difference in the surface dose rates calculated by both libraries is relatively small, with respect to the deep penetration thickness of 5 m iron or 25 - 30 relaxtion lengths. The greater λ of LANL calculations is compensated to some extent by lower build up factor values. Relaxation lengths of the HILO calculation approaches published values. Therefore both libraries may be recommended for deep penetration problems in iron.

4. THE HETEROGENEOUS IRON/CONCRETE BULK SHIELD

Behind an iron shield thickness of 4 - 5 m the neutrons scattered below 15 MeV contribute more than 90% to the dose rate. This contribution may be eliminated by inclusion of concrete.

As a rule of thumb about 1/4 of the iron thickness is added from a rough balance between size and cost.

A first estimate for the bulk shield of the SINQ[12] indicated 3.9 m iron and 1 m of concrete would reduce the dose rate at the outer radius of 6 m to 0.25 mrem/h·mA (The inner radius of the iron shield is 1 m to contain the heavy water tank). Using the same method as in the benchmark analysis above this configurations has been examined for the importance of the source neutron energy with respect to the outer dose rate.

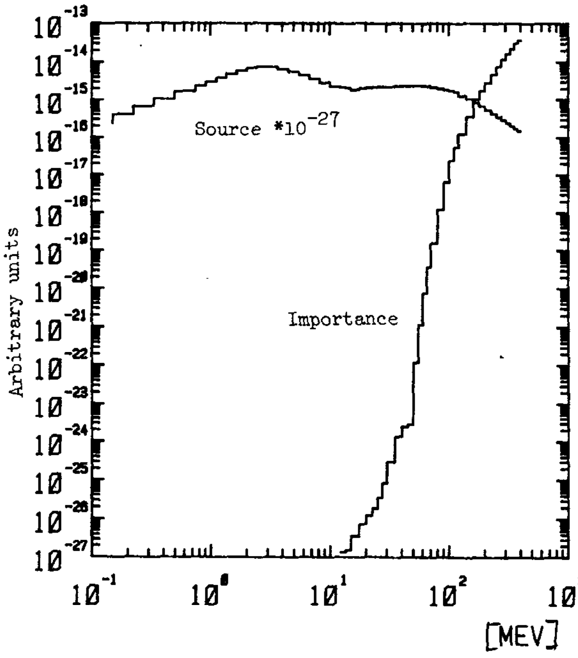

Fig. 5 Measured 90° source spectrum and its importance function for surface dose rate.

This can be done either by series of direct calculations with different monoenergetic sources or in a more economic way by one adjoint calculation with the dose rate response as source. The importance is defined as the dose rate per source neutron and unit lethargy. This together with the source spectrum is shown in Fig.5.

By folding both quantities, the outer dose rate can be calculated. The importance decreases with decreasing energy. Source neutrons below 50 MeV make only a very small contribution to the dose rate.

As the neutrons above 100 MeV are of primary importance direct calculations were performed with three different source energies to obtain more spectral information within the shield. The spectral shapes were all very similar below 100 MeV. Dose rates from the direct and the adjoint calculations are compared in Table 4. They agree within 25% or better, which shows the sufficient quality of the numerical approximation.

Table 4
Outer dose rate at a cast iron/normal concrete shield. Source diameter: 20 cm.

Calculation type	Source 1 n/cm^3·sec·MeV [MeV]	Dose rate [mrem/h]
adj. dir.	375 - 400	6.8 - 11*) 6.5 - 11
adj. dir.	250 - 275	1.8 - 11 1.8 - 11
adj. dir.	100 - 110	2.1 - 14 1.7 - 14

*)10^{-11} = - 11

To check the bulk shield estimates direct and adjoint transport calculations were repeated with 90° source spectrum measured by Cierjacks et al.[13] and a total source strength [14] of

$$8.6 \cdot 10^{16} \text{ n/sec mA}.$$

The dose rates at the surface of the shield were calculated to

(adjoint): 0.226) mrem/h·mA
(direct): 0.234)

which are in excellent agreement. The rule of thumb estimate gave 3.9 m or 30 tons/m^2 iron. Our calculation assumed 4 m or 29 tons/m^2 cast iron (ρ = 7.15 to/m^3). Hence the iron shield thickness is overestimated by 1 relaxation length (λ = 17 cm) with respect to the more sophisticated calculations. However we compared pure iron to cast iron, where the C and Si content may have implications for the attenuation characteristics. The spatial dose distriburion is shown in Fig. 6. The gamma dose contribution is neglegible.

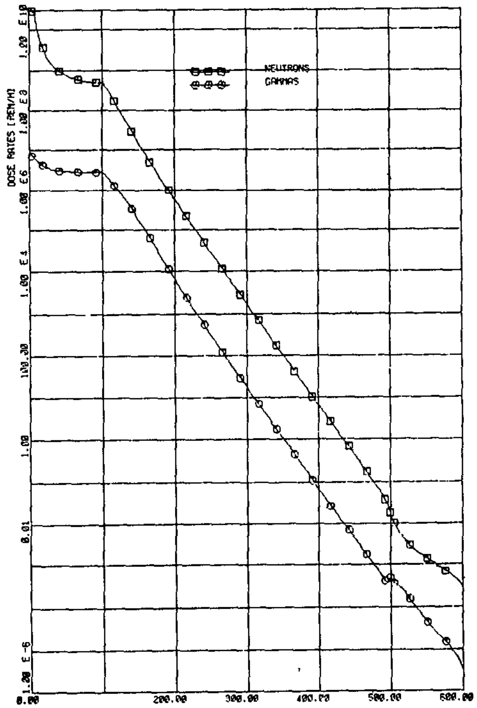

FIG. 6 SPACE DEPENDENT DOSE RATES

Fig. 7 illustrates the efficient elimination of neutrons below 10 MeV with increasing concrete depth. The spectrum shifts to higher energies. Therefore the gradient of the dose rate is the steepest in the first 20 cm of concrete (Fig. 6).

For more than 50 cm concrete depth the gradient gets much less steep than in the iron: Therefore the effective concrete thickness is at least about 30 cm. If the remaining 70% are replaced by an equivalent thickness of 20 cm iron, the overall shield thickness is reduced by 10% to 4.5 m.

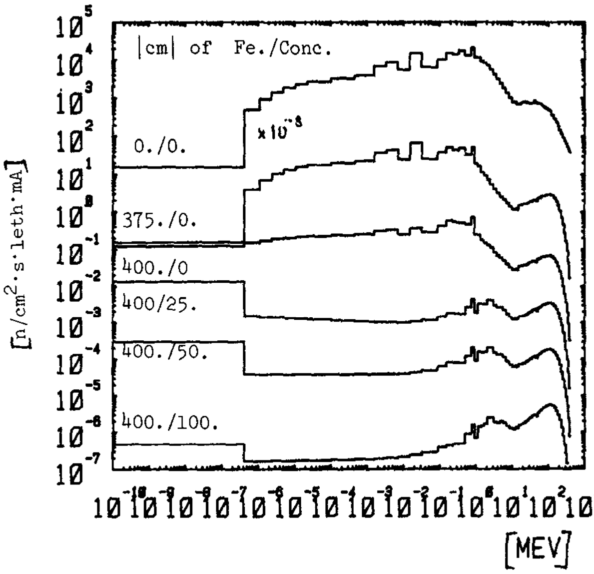

Fig. 7 Space dependent neutron spectra through the bulk shield

The main conclusions for the bulk shield design of the SINQ are:

a. Only neutrons above 100 MeV are important.

b. Adjoint calculation are economic and sufficiently precise.

c. The rule of thumb seems to overestimate the iron shield thickness by only one λ with respect to the more sophisticated transport calculations.

d. From the shielding point of view the thickness of an effective concrete layer at the surface of an bulk iron shield is 30 cm. The result should be relatively insensitive to the thickness of iron.

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