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THE ATTENUATION OF THE NEUTRON DOSE EQUIVALENT IN A LABYRINTH THROUGH AN ACCELERATOR SHIELD

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The attenuation of neutron dose equivalent in concrete labyrinths with rectangular bends was studied by means of neutron sources and rem counters. The number of bends, the length of each section, and the width of the labyrinth could be varied. The results of these measurements were compared with the dose equivalent attenuation found in a labyrinth at the DESY 7-GeV electron synchrotron, with published data from a proton accelerator and from a nuclear reactor. An empirical formula describing the neutron dose equivalent is presented.

1. INTRODUCTION

Ten years ago Gollon and Awschalom published neutron attenuation calculations for penetrations in hadron shields. They introduced their article as follows: ''Among the various problems involved in the design of accelerator radiation shielding, the problem of personnel and vehicle penetrations has received the least attention in the shielding literature.''[1] This statement is still valid; the situation has not changed in the meantime. The reason for it is at least threefold: (i) At operating accelerators there is generally neither space nor time available for systematic experimental radiation studies; (ii) The diffusion of neutrons is a complicated process that can only be treated theoretically using approximations and by means of the most advanced computational techniques. These approximate theoretical results must be checked experimentally; (iii) At some large accelerator centers, rather crude estimates are available, sometimes published in internal papers, and these are thought to be adequate in view of the great uncertainty inherent in the estimate of the beam loss (source term) near the labyrinth. Nevertheless, in designing access ways for new accelerator installations where space for mazes is very limited, we have found it desirable to have simple and experimentally verified expressions describing the neutron dose equivalent attenuation in such labyrinths.

Simple formulae of this kind are not available at present. Much experimental and theoretical work has been done in this field for nuclear reactors, but the geometries are limited to ducts of small diameter; broad access ways are not common at reactor stations. Experimental studies of neutron attenuation in labyrinths at accelerators are described in Refs. 2–5. All measurements are done by means of threshold detectors. Only Stevenson and Squier combined the results of threshold detectors to determine the attenuation of the neutron dose equivalent, which is relevant for protection considerations. Alsmiller and Solomito[6] calculated the neutron production near the mouth of a labyrinth and the fluxes of thermal and low-energy neutrons at some points along the maze. In other calculations (Refs. 7, 1, and 8), the unphysical assumption of a constant neutron energy is made.

Detailed Monte Carlo calculations have been made by Vogt[9] for the very large access ways of the CERN SPS. Some of these calculations and experiments were combined to give an approximate ''universal'' attenuation curve suitable for proton accelerators.[10] For the short rudimental mazes common at small medical accelerators, McCall et al.[11] put together three ''cookbook'' approaches; they give similar results for the geometry for which they are tailored, but fail when applied to the labyrinths considered in this paper.

In order to collect more information, we first studied the attenuation of the neutron dose equivalent in concrete labyrinths by means of isotopic neutron sources. The similarity between the spectrum of accelerator-produced medium-energy neutrons and the spectrum of the well-known AmBe source or a fission spectrum had already been used to study attenuation parameters.[12] The number of bends of the labyrinth and the length and the cross section of each bend could be varied systematically. Then we compared the resulting attenuation curves with the attenuation in an existing labyrinth at the DESY electron synchrotron and with published data obtained at a proton accelerator and at a nuclear reactor.

2. MEASUREMENTS WITH NEUTRON SOURCES

The measurements with isotopic neutron sources were performed in labyrinths constructed of concrete blocks. A few examples are shown in the inserts of Figs. 1, 4, and 5. At critical points where neutrons could disturb the measurements by penetrating the concrete blocks, we used heavy concrete ($\rho = 3.7\ g\ \mathrm{cm}^{-3}$) instead of ordinary concrete. All mazes had a roof of 80 cm ordinary concrete; the height inside was 2.2 m.

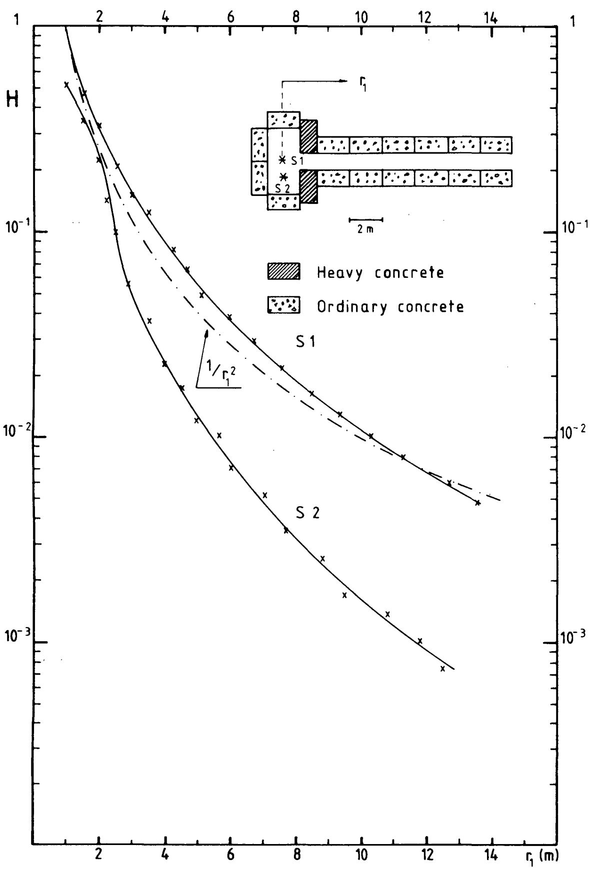

FIGURE 1 Dose equivalent attenuation in a straight access way. Two source positions *S* 1 and *S* 2 are indicated.

Two cross sections were used, $A = 2.2 \times 1\ \mathrm{m}^2$ and $A = 2.2 \times 2\ \mathrm{m}^2$. The neutron source was positioned at *S* as shown in the figures. The dimensions of the source housing were chosen to simulate a section of an accelerator tunnel. We used a 2-mCi Cf^{252} spontaneous-fission source and a 1-Ci Am^{241} -Be source. Because no difference in the attentuation of neutrons emitted by these sources was detectable, we used both sources simultaneously in order to increase the intensity.

The neutron dose equivalent was measured with moderated neutron counters. We used cylindrical counters after Andersson and Braun and spherical counters after Leake. For the most recent measurements of the dose response functions of these instruments, see Refs. 13 and 14. The instruments show an oversensitivity in the lower keV-region. Because the neutron spectrum is degraded in energy during the diffusion process, the instrumental oversensitivity leads to a systematic error in the measured attenuation factor, which is therefore an upper limit and a conservative estimate for shielding calculations. The absolute efficiencies of the detectors were determined by calibrated neutron sources in an essentially scattering-free geometry. After careful elimination of all electrical noise, the lowest detectable neutron dose was limited by the dose equivalent rate of cosmic neutrons, which was found to be roughly 1.8 mrem/*a* inside the labyrinth and 3.5 mrem/*a* outside.

2.1 *Dose Equivalent Attenuation in the First Section*

The dose equivalent distribution in the first section of a labyrinth (i.e., in a straight access way) was measured up to a length of 13 m and for both widths mentioned above. Examples are shown in Fig. 1, source position *S*1, and the left part of Fig. 4, where the dose equivalent is given as a function of the distance from the source, normalized at $r_1 = 1$ m (the mouth of the labyrinth). Small deviations from the $1/r^2$-law are seen. With increasing distance, this scattering contribution first increases and then decreases. Such a decrease in addition to the $1/r^2$-dependence has also been observed in Refs. 2 and 5; it has been explained by absorption in air, though the resulting cross section turned out to be unusually large. This behavior is more clearly shown in Fig. 2 where the ratio of scattering con-

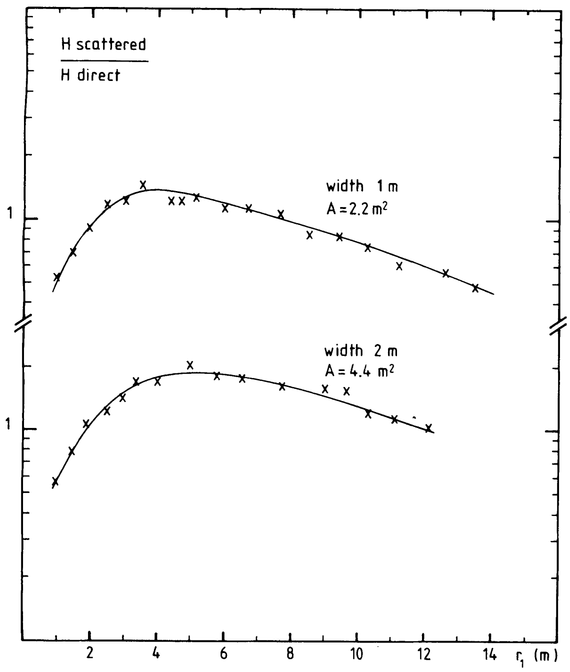

FIGURE 2 The ratio of scattered neutron dose equivalent to dose equivalent due to direct neutrons as a function of distance (from the source) inside the first section of a maze.

tribution to direct radiation (both unnormalized) is given for two maze cross sections.

The varying contribution of scattered neutrons cannot be explained by the presence of the labyrinth walls, because (i) the contribution is larger for a larger width of the labyrinth (which was already observed in Ref. 1 and (ii) the ratio of neutrons scattered from a surface to direct neutrons becomes constant for larger distances from the source.

The last-mentioned behavior has been studied recently by Jenkins.[15] For a neutron source and a detector placed at some heights above a concrete floor, he calculated the contribution of neutrons scattered from the floor. His expression for the total dose equivalent (due to direct and scattered neutrons) can be rewritten as

$$H_{\text{total}} = \frac{C}{4\pi r^2}\left(1 + \frac{1.5\left(\dfrac{h^2}{r^2} + \dfrac{1}{4}\right)^{1/2}}{1 + 8\left(\dfrac{h^2}{r^2} + \dfrac{1}{4}\right)^{3/2}}\right), \tag{1}$$

where h is the height of both the source and the detector and r the distance between them. For $r \gg h$,

$$H_{\text{total}} = \frac{C}{4\pi r^2}(1 + 0.37). \tag{2}$$

We checked these relations with our sources and detectors above a thick concrete floor. A comparison is shown in Fig. 3. The agreement is not good and may partly be due to the oversensitivity of the detector to multiply scattered neutrons, but both calculation and measurement give a constant contribution of scattered neutrons for larger distances ($r \geq 4$m).

The reason for the dose equivalent distribution shown in Fig. 2 is the neutrons multiply scattered inside the source housing ("the accelerator room") and then streaming down the access way. This contribution can be simulated with the source in, for example, position $S2$, Fig. 1, which gives a much stronger attenuation along the labyrinth. The deviations from the $1/r^2$-law depend mainly on the source building; they were found to be much smaller than those illustrated in Figs. 1 and 4 if, e.g., the concrete wall opposite to the mouth of the labyrinth is removed.

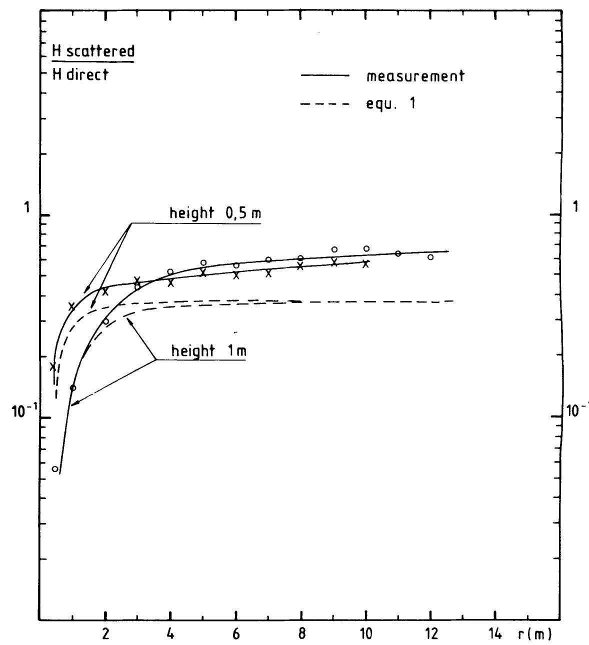

FIGURE 3 The ratio of scattered neutron dose equivalent to dose equivalent due to direct neutrons as a function of distance (from the source) above a concrete floor.

For typical labyrinths in actual use, the dose equivalent due to scattered neutrons roughly equals that of direct neutrons (see Fig. 2). Thus it is convenient to approximate the dose equivalent by increasing the direct contribution by a factor of two.

2.2. *Dose Equivalent Attenuation in the Second and Third Section*

Examples of measured dose equivalent distributions in the second and third section of a labyrinth are given in Figs. 4 and 5. If the dose in the second leg is normalized to unity at $r_2 = 0$, the attenuation curve is found to be independent of the length of the first section and independent of the position of the source in the source housing.

The curve is made up of 2 parts, both of which can be described by exponentials. The first part (at low r_2 values) is independent of the cross-sectional area, A, of the labyrinth; the second depends on A. The explanation is simple. The first exponential describes the "disappearance" of the source and of the scattering material near the source behind the corner, while the second and much smaller portion describes the attenuation of neutrons scattered near the mouth of the second section into this section. The latter part should be proportional to the cross sections of the first leg and of the second leg. If both are equal, a dependence on A^n is expected, where n takes a value between 1.0 and 2.0. A fit gives

$$f_2(r_2) = \mathrm{lp}\left[\exp\left(-\frac{r_2}{0.45}\right)\right.$$

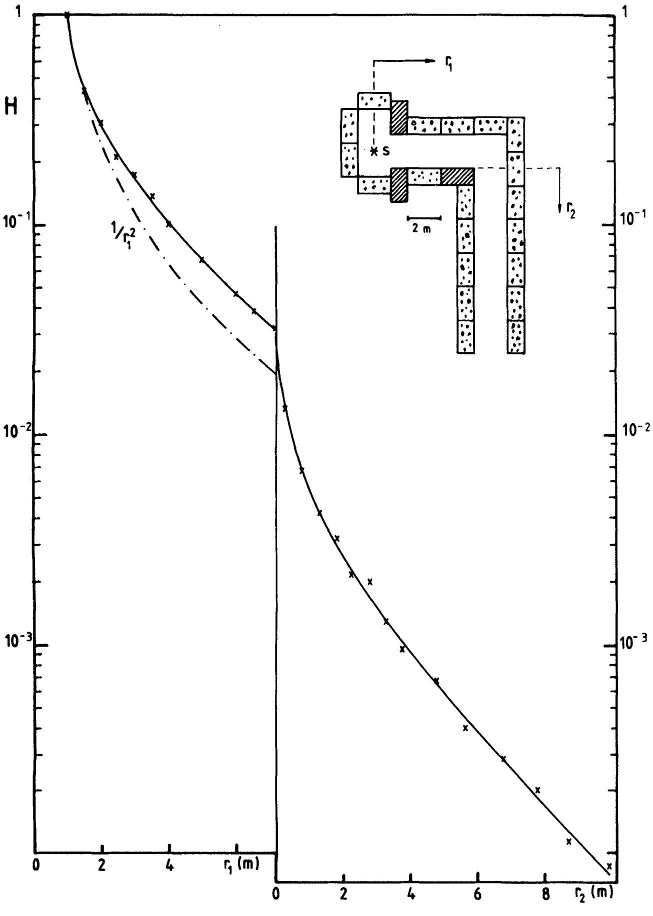

FIGURE 4 The attenuation of the neutron dose equivalent in a labyrinth with 2 sections. The width is 2 m.

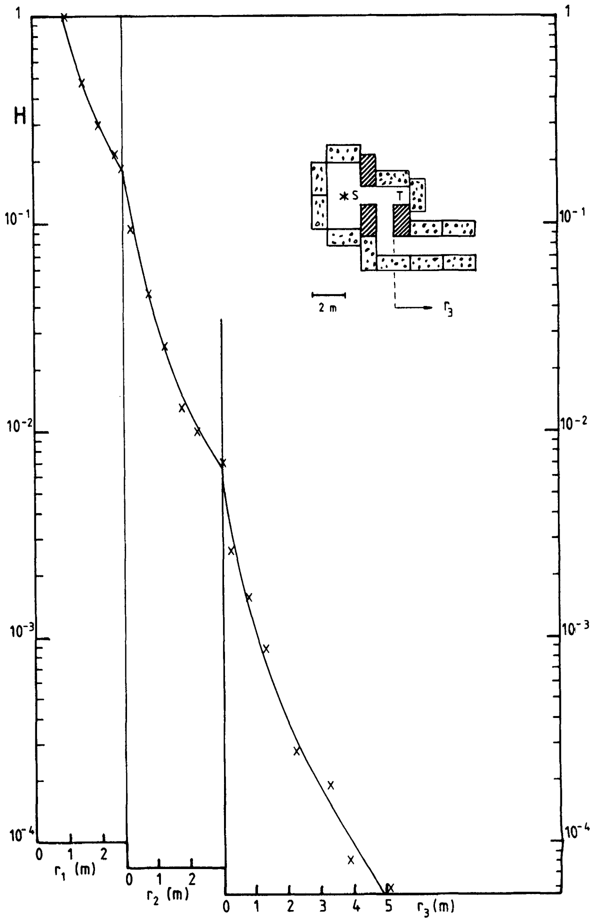

FIGURE 5 The attenuation of the neutron dose equivalent in a labyrinth with 3 sections. The width is 1 m.

$$+ 0.022A^{1.3}\exp\left(-\frac{r_2}{2.35}\right)\Bigg]\Bigg/\left[1 + 0.022A^{1.3}\right]$$

$$r_2 \text{ in m}; A \text{ in m}^2 \quad (3)$$

The scattered contribution from the walls of the second section is very small. The second exponential continues for several meters out of the labyrinth. When we removed the second half of these walls no change in the dose equivalent readings was observed.

A "neutron trap" (see T in Fig. 5) had no significant influence on the dose distribution in the second leg and is an unnecessary complication of the labyrinth.

For the dose equivalent distribution in the third section we found exactly the same curve if the dose is normalized to unity at $r_3 = 0$.

3. MEASUREMENTS AT ACCELERATORS, DISCUSSION

The secondary radiation to be considered in designing labyrinths at high-energy accelerators is produced at large angles, typically at 90°. Under these conditions, medium-energy neutrons, such as giant-resonance neutrons or evaporation neutrons, are the most important component. No large difference is expected between the attenuation of the dose equivalent of these particles and the neutrons investigated in the previous section. We checked this hypothesis in an existing three-legged labyrinth through the shielding of the DESY 7-GeV electron synchrontron. The height of the labyrinth was 2.2 m, the width was 1.4 m. The detectors in the first section were shielded with 5 cm of lead. First we checked the dose equivalent attenuation with the isotopic neutron sources and found agreement with our previous results. Then we measured the attenuation with the accelerator running in many different modes (electron or positron acceleration, one bunch or multibunch mode, etc.), the resulting attenuation curves were nearly identical. As expected, for the first section of the labyrinth we obtained good agreement between the two neutron fields. The dose equivalent due to neutrons scattered into the second section is roughly a factor of 2 higher for accelerator-produced neutrons than for isotopic-source neutrons because of spectral differences. This factor of two persists in the short third section, i.e., the effect of the second bend is the same for both spectra.

From these measurements and the results and simple phenomenological considerations of Section 2, we derive the following recipe for estimating the dose equivalent in a labyrinth. First the strength of the neutron source due to the estimated beam loss is calculated as an equivalent point source. With additional information of the spectrum, this gives the dose equivalent H at a certain distance. If a line source is a more appropriate model, an equivalent point source may be considered by assuming the length of the line source is twice the width of the labyrinth. Then the dose equivalent in the labyrinth is given by

$$H(r_1, r_2, r_3) = H(a)\frac{2a^2}{r_1^2} f_2(r_2) f_3(r_3) \quad (4)$$

$$f_2(r_2) = 2\left[\exp\left(-\frac{r_2}{0.45}\right) + 0.022A^{1.3}\exp\left(-\frac{r_2}{2.35}\right)\right]\Bigg/\left[1 + 0.022A^{1.3}\right]$$

$$f_3(r_3) = \left[\exp\left(-\frac{r_3}{0.45}\right) + 0.022A^{1.3}\exp\left(-\frac{r_3}{2.35}\right)\right]\Bigg/\left[1 + 0.022A^{1.3}\right],$$

where a is the distance from the source to the mouth of the first section, the r_i are the coordinates as defined in Figs. 4 and 5, r_2 and r_3 are given in m, A is the cross-sectional area of the maze in m^2. The r_i of the last section can be extended to values outside the last section.

In Fig. 6 the values from Eq. 3 are compared with results from a proton accelerator.[5] The function $f_2(r_2)$ describes well the attenuation of the dose equivalent measured inside the second leg of a labyrinth at a 7-GeV proton beam if normalized to unity at the beginning of the section. This function is also in agreement with an approximate curve which is in practical use at the CERN laboratory.[10] Also shown in Fig. 6 is the attenuation of the neutron fluence as measured by Stevenson and Squier by means of threshold detectors. The greater attenuation of the high-energy neutrons, especially for neutrons at a threshold of 20 MeV, supports the assumption that our equation can be applied to accelerators of much higher energies.

Recently a Monte-Carlo calculation has been

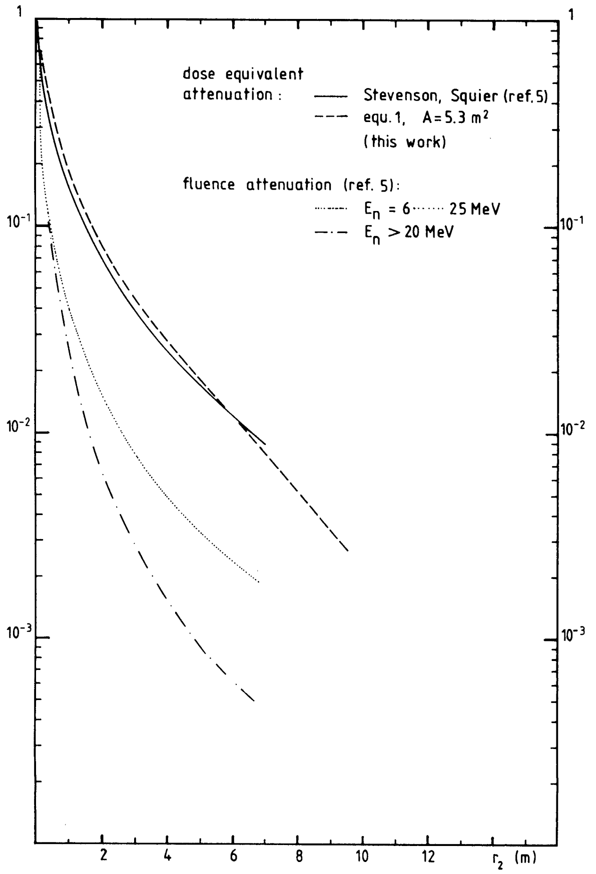

FIGURE 6 Comparison between the measurements of Stevenson and Squier (Ref. 5) and our results.

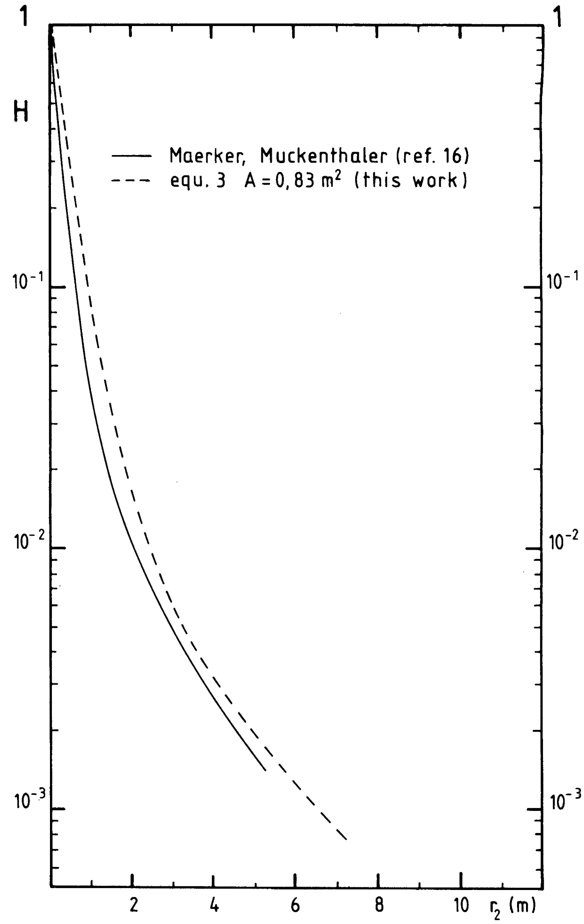

FIGURE 7 Comparison between the measurements at a nuclear reactor (Ref. 16) and our results.

performed by Y. Sizong[17] to study the attenuation of dose equivalent in the second section of the labyrinth of the above mentioned proton accelerator. For a primary neutron energy of 1.5 MeV, the results from the Monte-Carlo code MORSE are in agreement both with the experimental curve and with the results of Eq. (3) (Fig. 6).

In Fig. 7, a comparison is made with the fast neutron dose equivalent attenuation measured at a nuclear reactor.[16] The duct had a cross section A of only 0.91×0.91 m^2. The results are directly comparable with our measurements since we also used a neutron source with a fission spectrum. The approximate agreement indicates that the A-dependence seems to be reasonable though it was determined by only two A-values.

Therefore Eq. (4) is applicable at electron- and proton accelerators and for fast neutrons at nuclear reactors. The errors may be not much larger than those introduced by the imperfect response curve of the moderated neutron detectors (remmeters) used in this experiment and elsewhere for routine health physics purposes.

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