An MCNP-4C2 Determination of Gamma Source Shielding

The transmission of 0.511 MeV and 0.662 MeV photons through concrete, lead and iron

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ABSTRACT

The Monte Carlo simulation code MCNP-4C2 is employed to determine the transmission of 0.511 MeV gamma rays through concrete, lead or iron shields, with the transport calculations performed for a simple, cylindrically defined configuration. For the concrete, a series of cylinders, 50 cm in radius, with thicknesses between 0 cm (i.e. no shielding) and 50 cm, in 5 cm increments, are each exposed to a monoenergetic, plane parallel source, and the resulting kerma to a small volume of air behind the shield is recorded. The transmission factors are calculated by normalizing these results to the kerma similarly tallied in the shield's absence. For this material and this selection of thicknesses, it is found that the transmission factors for the shield span from 1 to less than 10^{-3}. Similar calculations for lead cylinders with thicknesses ranging from 0 cm to 10 cm in 1 cm increments provide transmission factors down to almost 10^{-7}. Thicknesses of iron up to 20 cm in 2 cm increments are also modelled, giving a transmission factor range down to the 10^{-5} order of magnitude.

The reliability of the transport method is assessed by performing the calculations for selected thicknesses of material (concrete, lead or iron) with a 0.662 MeV photon source, and comparing the results with measurement data available in the literature. In almost all cases, acceptable agreement is reported; the discrepancies existing in the remaining few are discussed. Justification for some of the assumptions and approximations inherent in this highly simplified geometry is also presented.

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Approval: August 2007
Publication: September 2007
£12.00
ISBN 978-0-85951-603-7

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1 INTRODUCTION

With the increasing use of radiation in medicine and elsewhere, the provision of adequate protection remains an important concern. One area of significance is the shielding of 0.511 MeV gamma rays, which can result from the annihilation of positrons with atomic electrons, and have energies effectively corresponding to the electron's or positron's rest mass. Such radiation is created, for example, during the handling of positron emitters (e.g. ^{18}F) for positron emission tomography (PET) scanning, where each annihilation event produces a pair of 0.511 MeV photons.

In principle, the range of electromagnetic radiation through a given shielding medium is infinite, though its intensity drops effectively to zero with a profile dependent on the shielding material and the energy of the radiation. In practice, therefore, the goal of a Radiation Protection Advisor (RPA) is to specify the quantity of material required to reduce the transmission through any potential shield to below a particular, agreed value. The task of actually deciding upon a shield thickness, however, is the outcome of two competing demands: ensuring that the shield is sufficiently thick to provide adequate reduction in dose equivalent rate; whilst at the same time prescribing the minimum amount of shielding that is required such that budget, practicality or construction demands may be accommodated. These principles may be summarized as being *as low as is reasonably practicable* (ALARP). Accurate data concerning the attenuation of photons in the materials of concern are therefore crucial, in order for the RPA to assess the probable effectiveness of proposed shielding. These data may be obtained experimentally, or, potentially more quickly and economically, by the use of Monte Carlo modelling techniques, such as those employed by the MCNP software package.

The aim of this document is to summarize recent MCNP calculations on the transmission of gamma rays through concrete, lead and iron. Firstly, the attenuation of 0.662 MeV photons by concrete is considered, and the results compared with the standard measurement data provided in the literature [Dunster *et al*, 1971; Kirn *et al*, 1954]. Good agreement is taken to indicate that the chosen Monte Carlo method may be employed to make additional calculations on the attenuation of sources with different energies, or through other materials, a capability particularly useful in cases where no analogous experimental data exist. To this end, the transmission of 0.511 MeV photons through: [i)] concrete, [ii)] lead, and [iii)] iron are considered, and the results presented and discussed, with half and tenth value thicknesses compared and contrasted with available literature data. Additional calculations with 0.662 MeV photons through lead and through iron are also performed and compared with literature data, in an attempt to provide further confidence in the results.

2 GEOMETRY

The geometry modelled was defined as shown in Figure 1. The shield was approximated as a cylinder, 50 cm in radius, with depth *d* to be varied as required; for the present purposes, this arrangement was consequently considered effectively infinite in width.

In fact for modelling purposes, the cylinder comprising the shield was actually sub-divided along its length into a series of shorter 'sub-cylinders'; these were relatively thin, co-axial, equal-radii, equal-length cylinders stacked end to end. For the preliminary validation calculations using concrete and a Cs-137 source, sub-cylinder thicknesses of 10 cm were employed. For the subsequent calculations, for which more data points with more precision were desired, 5 cm increments of thickness were instead used for the concrete, 0.5 cm thicknesses for the lead, and 1 cm thicknesses for the iron. Whatever the actual value of *d*, each configuration simulated (for a given source and material) had the same number of sub-cylinders, with the only change being which of these were defined as being air and which were defined as being the shielding material. For example, the configuration for which d = 30 cm of concrete was irradiated by a 0.511 MeV source was actually modelled by setting the material of the first six 5 cm thick sub-cylinders to concrete, and the material of the remaining four sub-cylinders to air. The advantage of this method was two-fold. Firstly, it meant that by performing only a few simple changes, the same basic input file could be used for each calculation, thereby saving time and reducing the likelihood of typing errors being introduced. Secondly, by setting appropriate MCNP cell 'importances' for the different sub-cylinders, variance reduction techniques could be applied to increase the computational efficiency of the simulation.

In accordance with data provided [Hubbell and Seltzer, 1995], and in the absence of a better alternative defined by any authoritative standards committee, the concrete was specified as having the atomic composition given in Table 1, and a density of 2.300 g cm^{-3}. This contrasts with a density of 2.36 g cm^{-3} quoted by Dunster *et al* [Dunster *et al*, 1971] (hereafter referred to as 'HRP'), and 2.35 g cm^{-3} quoted by Kirn *et al* [Kirn *et al*, 1954] (hereafter referred to as 'Kirn'). Curiously, HRP cites Kirn as the source of its data. Neither reference provides the composition of the concrete.

For the calculations with the metal shields, the lead was defined as the pure element with a density of 11.3 g cm^{-3}, whilst the iron had a density of 7.9 g cm^{-3} and was also pure. These agree with HRP.

The source was a monoenergetic beam of photons of energy E, emitted perpendicularly from a disk 50 cm in radius, orientated axially in-line with (and hence centred on) the long axis of the cylindrical shield. This axis is associated with the z-axis of the geometry, with the origin located at the centre of the front face of the shield. In the present investigation, only energies, E, of 0.662 MeV or 0.511 MeV are considered, with the former corresponding to the ^{137}Cs radionuclide reference field [ISO, 1996]. For practical purposes, vacuum is defined for all $z < 0$, and air for all $z > 0$, excluding the presence of the shielding material. The air is of density 0.001205 g cm^{-3} (1 atmosphere at standard temperature) and is chemically specified in accordance with the recommendations of ICRU Report 37 [ICRU, 1984]. The source disk is at z = -5 cm.

The calculations were performed in the photon-only transport mode of the general purpose Monte Carlo code *MCNP-4C2* [Briesmeister, 2000], which uses cross-section data taken from the ENDF library (originally derived by Hubbell *et al*). A typical input file for the configuration modelled is given in Appendix A.

TABLE 1 Composition of concrete used, by mass fraction per element. Data taken from [Hubbell and Seltzer, 1995].

Element atomic number (Z)	Mass Fraction
1	0.022100
6	0.002484
8	0.574930
11	0.015208
12	0.001266
13	0.019953
14	0.304627
19	0.010045
20	0.042951
26	0.006435

3 CALCULATIONS

The ‘transmission factor’, ${}^{E}T_{d}$, defined below for a gamma source of energy E through d cm of shielding material, was estimated indirectly by determining the dose imparted to a thin cylinder of air of length 0.1 cm, centred behind the shield on the z-axis. For the concrete shield configuration, this ‘tally’ cylinder spanned between $z = 50$ cm and $z = 50.1$ cm, and was of radius 1 cm. For the lead and iron calculations, for which considerably thinner shields were of interest due to the materials’ higher photon attenuations per unit length, the spans were from $z = 10$ cm to $z = 10.1$ cm, and from $z = 20$ cm to $z = 20.1$ cm respectively, and the cylinder radius was increased to 2 cm, as discussed later. The dose was calculated by employing the MCNP ‘*f6:p*’ track length tally and making the kerma approximation; the terms ‘dose’ and ‘kerma’ are thus used synonymously in this work.

The transmission factor for a given shield was evaluated by normalizing the tallied result to the dose recorded during an additional calculation for which $d = 0$ (i.e. the kerma ‘free in air’, with no shield present). That is, if ${}^{E}K_{d}$ is defined as the dose tallied behind a particular shield of thickness d cm, for a given source energy E, then the corresponding transmission factor, ${}^{E}T_{d}$, is given by:

$$ {}^{E}T_{d} = {({}^{E}K_{d})}\big/{({}^{E}K_{0})} $$

The standard relative error on each transmission result was calculated by evaluating the square root of the sum of the squares of the relative errors quoted by MCNP for ${}^{E}K_{d}$ and ${}^{E}K_{0}$.

4 RESULTS

The results corresponding to the 0.662 MeV and 0.511 MeV irradiations of concrete are given in sub-sections 4.1 and 4.2 respectively. Section 4.3 discusses the simplifications and approximations that were made when the geometry of the configuration was defined. The last two sub-sections give the results of the 0.511 MeV exposures of, in turn, lead and iron. All error bars in figures represent one standard deviation on the result.

4.1 ^{137}Cs irradiation of concrete

The ^{137}Cs source was a monoenergetic beam of 0.662 MeV photons. The aim of this part of the investigation was to generate a set of MCNP results that could be compared with known experimental data, in order to confirm the appropriateness of the geometry modelled and the reliability of the Monte Carlo calculations. For this initial comparison, four values of *d* were used, 10 cm, 20 cm, 30 cm and 40 cm, as well as a further $d = 0$ calculation to determine $^{0.662}K_0$ for this source energy.

The results of the calculations are given in Figure 2. Also provided is the transmission curve presented in HRP, and the individual measured results determined by Kirn upon which the HRP data are quoted as being based; Kirn's results were obtained entirely experimentally. The latter two plots were generated in their present forms by scanning the printed documents, and then employing the UnGraph™ software package [Biosoft, 2004] to extract the raw data; an unavoidable lack of reproduction accuracy is therefore introduced by the process, though this is expected to be small.

Recall the differences in the densities of the concrete shields used by MCNP, HRP and Kirn, and also the fact that there is generally no clear consensus, either in this study or elsewhere, as to what the exact composition of concrete should be. This, of course, reflects the reality that concrete varies considerably, but the absence of a standard concrete composition does make interpretation of the data more difficult. Moreover, note the discrepancies between the HRP values and Kirn's, especially for the thickest shielding. This is perhaps surprising, given that HRP cites Kirn as its source of data. These differences are not thought likely to be due to the UnGraphing process, but are instead conjectured to be a result of fitting inaccuracies in HRP. Uncertainty data are not provided in either HRP or Kirn. Additionally, note that Kirn reports that experimental data for thicknesses less than about 15 cm (i.e. four of the six data points) are not actually based on exposures of concrete, but instead on electron density equivalent thicknesses of polyethylene.

Nevertheless, despite the above comments, it is argued that the MCNP calculations agree acceptably with both sets of measurement data, especially (and, presumably, more importantly) the raw Kirn results. This paves the way for their use in subsequent analyses that incorporate sources of different photon energy.

4.2 0.511 MeV irradiation of concrete

The source was a monoenergetic beam of 0.511 MeV photons. As discussed earlier, the MCNP input file was a slightly revised version of that used for the Cs-137 irradiations, with changes made partly in order to provide a greater number of data points, each with improved precision. Thicknesses of shielding ranging from 0 cm to 50 cm in 5 cm increments were considered, with the d = 0 case used to determine a value of ${}^{0.511}K_0$ for this source.

The resulting transmission curve is shown in Figure 3, with the calculated data points provided in Table B1 of Appendix B.

4.3 Geometry approximations

The overall objective of the present work program has been to provide shield transmission data for 0.511 MeV photon sources that are analogous to those already available in the literature for ${}^{137}Cs$ and other energies. Such data of interest are quoted as being ‘broad beam’ in HRP, that is, corresponding to a source that is considered plane parallel and effectively infinite in extent. In accordance with this aim, a geometry was defined that incorporated a cylindrical shield with a radius (50 cm) very much larger than that of the tallying region (1 or 2 cm in radius); it was assumed that such an arrangement was approximately equivalent to determining the dose at a single point of test positioned immediately behind an infinite wall of shielding material. This assumption, however, requires justification. To this end, three scenarios were considered: an increase in the radius of the shield (and source); a decrease in the radius of the tally; and an increase in the radius of the tally. These scenarios will now be discussed in turn. In all cases, only the configuration with d = 50 cm of concrete was involved, since, if making the changes were to influence the results in any way, this is the arrangement for which their effects might be expected to be the most pronounced. The 0.511 MeV source was used throughout.

4.3.1 Source / shield radius

If a 50 cm radius shield is indeed effectively infinite in width, increasing the radius of the concrete cylinder should have no effect on the results. To examine this proposal, the radius of each sub-cylinder comprising the shield was changed from 50 cm to 100 cm; for obvious reasons, the radius of the source disk was also duly increased to 100 cm. After multiplying the tallied dose by four, in order to correct for the drop in fluence at the tallying cylinder caused by changing the area of the source[1], a transmission factor of $(6.91 \pm 0.18) \times 10^{-4}$ was found. This compares with $(6.45 \pm 0.18) \times 10^{-4}$ obtained previously for the 50 cm radius shield, as seen from Figure 3. The difference equates to roughly 7%, a figure sufficiently outside of the 1 sigma boundaries to not necessarily be considered purely statistical, but still arguably small enough to be considered negligible;

[1] MCNP normalizes the recorded dose to per-source-particle. Recall that the transmission factor is obtained by dividing this dose by ${}^{E}K_0$, which was determined using a 50 cm radius source.

it is noted that for smaller values of *d*, the differences between the two cases would likely be far less.

Overall, it is argued that a 50 cm radius cylinder model is, for the present purposes, practically equivalent to a shield that is infinite in lateral extent, especially when considering the obvious factor that no practical, work-place arrangement incorporates unbounded shielding anyhow.

4.3.2 Decreasing the tally size

In principle, the doses recorded, and hence the transmission factors quoted, should be defined at a point, and not over an extended region of space such as that enclosed within the tallying cylinder. In practice, of course, this is not done, so care must be taken to ensure that the size of the tallied region is such that it does not adversely affect the results obtained. Specifically, using a 0.1 cm thick cylinder that is 1 cm in radius should ideally tally the same result as would be given by a cylinder of some very small radius ∂r and length ∂L, with the optimum occurring as $\partial r, \partial L \rightarrow 0$. If the overall transmission data are to be trusted, this approximation requires examination.

In fact, the length of the tallying cylinder, 0.1 cm, is automatically assumed sufficiently thin without further investigation. This is justified partly because the field within the tallied region is barely expected to change over such small longitudinal distances due to the virtual 'transparency' of air to the transported photons, and partly because of the mechanism by which a track length estimator, such as MCNP's *f6* tally, actually works [Briesmeister, 2000].

Significantly reducing the tally's radius, however, is more troublesome, because as this is decreased, the number of particles encountering the tally also decreases (and hence the number of tracks scoring is reduced), and this results in higher statistical uncertainties, and hence an inherently more difficult modelling problem. So, in an attempt to compromise between the above ideal of $\partial r \rightarrow 0$ and the need for reasonable statistics, as a first trial to indicate whether a 1 cm radius cylinder is appropriate for the current program, the tally's radius was reduced to 0.5 cm. A transmission factor of $(6.64 \pm 0.17) \times 10^{-4}$ was found, which compares well with the result $(6.45 \pm 0.18) \times 10^{-4}$ obtained previously, as well as with the results of § 4.3.1 in which the same change in (shield):(tally) size ratio was performed. In the absence of any obvious reasons why the field should be expected to vary substantially over increasingly smaller spatial scales, it is difficult to imagine that subsequent reductions in the radius of the cylinder would begin to lead to drastic disagreements with the 1 cm radius result. Moreover, from a pragmatic perspective, if the transmitted field *were* highly non-uniform over spatial resolutions of less than 0.5 cm, such effects would be 'smeared out' anyhow in whichever extended body (such as a human 180 cm in length) the shield was actually protecting, just as they would be by an extended tally.

Overall, the suggestion is that doses recorded in the 1 cm radius tally may, for the present practical purposes, indeed be considered to be defined effectively at a point.

4.3.3 Increasing the tally size

The tally was centred on the *z*-axis, in line with the centre of the shield. In order for this to provide a true representation of the general level of transmission through the material, it is assumed that the field behind the shield is spatially homogenous, at least in the region immediately surrounding the tally in the lateral direction. However, this assumption needs validation, because serious problems could arise in practical applications of the resulting transmission data if, for instance, the chosen region of test happened instead to be located at a local minimum, for whatever reason.

To confirm whether this assumption is approximately correct, two potential methods might be suggested. Firstly, the position of the centre of the 1 cm radius cylinder could be moved arbitrarily away from the *z*-axis. This, however, would have the disadvantage that, for example, another hypothetical local minimum could be encountered; moreover, if this second tallied dose were actually smaller than the first, it is possible that the original might then even be falsely interpreted as a maximum. A better suggestion might therefore be to increase the radius of the tally cylinder from 1 cm to, say, 10 cm: if this change does not affect the results, it could be taken to indicate that the field is, on average, roughly constant over the 20 cm diameter central region directly behind the shield.

To this end, with the above change made, a transmission factor of $(6.57 \pm 0.04) \times 10^{-4}$ was found. This compares well with the result of $(6.45 \pm 0.18) \times 10^{-4}$ obtained previously, thereby demonstrating the desired homogeneity. In addition, the similarity suggests that the radius of the tally may, within reason, readily be increased without concern (for example, to 2 cm), which would have the advantage of improving the statistical uncertainties of the results without detriment to their accuracy.

4.4 0.511 MeV irradiation of lead

The source was a monoenergetic beam of 0.511 MeV photons. Thicknesses of shielding ranging from 1 cm to 10 cm in 1 cm increments were investigated. The value of ${}^{0.511}K_0$ was taken from that determined in the work of section 4.2. Because situations involving lead shields often require them to be employed in close proximity to the source, and hence potentially exposed to very high surface fluences, a greater order of magnitude range of transmission data was desired for the lead than for the concrete. This motivation, as well as the fact that per-unit-length lead is highly attenuating, required two noteworthy geometry changes to be made from the type of configuration that was defined for concrete: the number of sub-cylinders was increased from 10 to 20, such that more powerful variance reduction could be applied; and the radius of the tally was increased from 1 cm to 2 cm, in order to increase the frequency of tracks scoring. The acceptability of applying this last change was justified from the arguments of section 4.3. The transmission curve for lead is shown in Figure 4, with the calculated data points provided in Table B2 of Appendix B.

From Figure 4, it can be seen that the half value thickness (HVT) and tenth value thickness (TVT) for lead, as determined by MCNP, are approximately 5 mm and 17 mm respectively. These compare well with the corresponding values of 6 mm and 17 mm given by Delacroix *et al* [Delacroix *et al*, 2002] (hereafter referred to as 'RRPDH') for the shielding of gamma/X-rays from ^{11}C, ^{15}O and ^{18}F sources.

As a further quick check on the reliability of the modelled configuration and results, the calculations for d = 4cm and d = 10 cm thicknesses of lead were repeated for a ^{137}Cs source. With $^{0.662}K_0$ taken from the work described in section 4.1, transmission factors of $(1.81 \pm 0.02) \times 10^{-2}$ and $(2.24 \pm 0.03) \times 10^{-5}$ were found, respectively. These results agree acceptably with the analogous values of approximately 1.5×10^{-2} and 2.5×10^{-5} read from the graph provided in the literature [Dunster *et al*, 1971], though it is noted that actual measurements were only performed for thicknesses up to about 4.4 cm: the authors of the HRP performed an extrapolation in order to generate the data presented beyond this value. As a consequence, the apparent rough agreement of results is taken to indicate two aspects: that the MCNP method is, once again, shown to be reliable; and that the extrapolation featured in the literature appears self-consistent and permissible.

4.5 0.511 MeV irradiation of iron

4.5.1 Results

The source was a monoenergetic beam of 0.511 MeV photons. Thicknesses of shielding ranging from 2 cm to 20 cm in 2 cm increments were investigated. As with the lead configuration, the shield was divided into 20 sub-cylinders, a 2 cm radius air-cylinder tally was employed, and the value of $^{0.511}K_0$ was taken from that determined in the work of section 4.2. The resulting transmission curve for iron is shown in Figure 5, with the calculated data points provided in Table B3 of Appendix B.

As an additional, final quality assurance, a calculation was also performed for d = 0 cm for both 0.511 MeV and 0.662 MeV sources, in order to confirm the acceptability of having used $^{E}K_0$ data taken from the original 'concrete' configurations discussed in sections 4.1 and 4.2. As expected, and hoped for, both results agreed comfortably with their equal-energy counterparts, and certainly were well within statistical limits.

4.5.2 Comparison of results

In order to confirm the reliability of the above data for iron, the calculations for d = 2, 8, 14 and 20 cm were also performed using a Cs-137 source, and, with $^{0.662}K_0$ taken from § 4.1, the resulting transmission factors were compared with those published in HRP. These data are also shown in Figure 5, with the HRP curve extracted from the original printed document by again using the UnGraph™ software package. As can be seen, it was found that the MCNP result is about 50% lower than the HRP value for d = 20 cm, 25% lower for d = 14 cm, but within rough agreement for d = 8 cm and d = 2 cm (especially when the poor resolution due to the width of the printed curve in HRP is considered). The reasons for these discrepancies at high thicknesses remain unexplained, and it is unclear whether the fault lies with the MCNP calculations or in the original experimental data. However, in support of MCNP, it is recalled that the input files used for the iron calculations were only slightly modified versions of those used successfully in the previous concrete and lead investigations, and that the configuration involving d cm of iron was only a slightly modified version of that using d' cm of iron.

Thus, if the input files were incorrectly specified, it might be expected that, contrary to what was actually found, all of the MCNP results for the ^{137}Cs exposures of concrete, lead and iron would disagree with measured data (and possibly to a similar extent in each case), including those for d = 8 cm and d = 2 cm of iron. Moreover, it is remarked that, unlike for concrete and lead for which Kirn's paper is cited by HRP, the only reference provided by this for the iron data reads, rather unsatisfactorily: "Harrison, J. R., *Unpublished calculation*. (1963)". It is quite possible, then, that the HRP transmission curve could be an inappropriate fitting function of the data points, or was generated from too few data points, or that the curve at large values of d is the product of an inaccurate extrapolation of actual measured results, or that the original data themselves had large uncertainties or were the outcome of calculation error, incorrect measurement procedures, or even poor scientific practice. The precision, accuracy and energy dependence of the response of any instruments used by Harrison may also be factors. Without a proper reference in HRP, such suggestions will, of course, unfortunately have to remain unchecked.

The HVT and TVT of iron for 0.511 MeV photons, taken from the MCNP calculated attenuation curve shown in Figure 5, are approximately 21 mm and 55 mm respectively. The analogous data for steel provided in RRPDH for the shielding of gamma/X-rays from ^{11}C, ^{15}O and ^{18}F sources are 27 mm and 64 mm. RRPDH values for ^{137}Cs attenuation in steel also fail to agree with MCNP and HRP iron data[1]. Exactly what causes these discrepancies is unclear. Several points are made, however.

Firstly, the MCNP and HRP data correspond to iron of density 7.9 g cm^{-3}, whilst the RRPDH data are for steel of unspecified density and composition. The HVT and TVT given in RRPDH should therefore not necessarily be expected to exactly match those of pure iron. However, although many different types of steel are available, any variations in attenuation are actually likely to be small, and as such it is not thought likely that these factors alone could account for the overall differences in the results.

Secondly, it is noted that the above RRPDH data for 0.511 MeV photons are higher than the HRP values for 0.662 MeV photons; this is surprising and counterintuitive, if it is assumed that the HRP data are correct. The MCNP 0.511 MeV values, on the other hand, are lower than the HRP 0.662 MeV data, which is what might be expected.

Thirdly, the RRPDH data were obtained via the Microshield Version 4.10 package [Delacroix *et al*, 2002]. There may, however, be significant differences between MCNP and Microshield: Microshield may, for example, use cross section data that are either older or newer than those in the libraries available to MCNP-4C2, or it may not even be a Monte Carlo code. Moreover, Delacroix *et al* do not provide details regarding the technical specifications of this program[2], nor do they make it clear as to exactly how the calculations were performed. As a consequence, it is difficult to ascertain which of MCNP or Microshield is the more accurate, and hence whether one is a more 'correct' code to use in the calculations, or what approximations or assumptions might have been made during the determination of the RRPDH data.

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[1] It can additionally be shown that the RRPDH and HRP data for steel/iron also differ for ^{60}Co sources.

[2] Nor are these readily available from Grove Software Inc., the manufacturers of Microshield.

But, perhaps the most important point is that it is not clear whether the shielding data provided in RRPDH corresponds to the attenuation of monoenergetic 0.511 MeV photons, or to the entire gamma/X-ray spectrum generated by the radioisotope. In other words, it is not specified whether a 'pure' 0.511 MeV photon source has been used by Microshield, or a more realistic mixed source. This could make an appreciable difference to the results. The ^{15}O source, for example, also emits a 1.732 MeV beta; if secondary photons subsequently generated by this are also included in the calculations, the field could be hardened significantly, and the overall HVT and TVT results are therefore likely to be increased. Hence, the fact that the data from MCNP and RRPDH differ may not necessarily be an indicator of error or inaccuracy on either part, but simply a consequence of disparate conditions; in this case, it could be argued that MCNP and RRPDH were in fact complementing one another, instead of contradicting. As has been remarked above, however, RRPDH seems neither to reference nor give any details about the calculation of its HVT or TVT data, so this issue cannot easily be pursued further. Moreover, it also leaves open the remaining question as to why MCNP and RRPDH seem broadly to agree on the HVT and TVT for lead, but not for iron.

5 SUMMARY

In order to evaluate their performances as potential shields, MCNP-4C2 has been employed to calculate the transmission of gamma rays through three materials of interest: concrete, lead and iron. A basic configuration was used consisting of a large cylindrical block of shielding material located in front of a small cylindrical region of air that acted as a simple dose monitor, with the front face of the shield exposed to a plane parallel photon source. A 0.511 MeV source was of prime interest, though calculations were also performed for 0.662 MeV photons (corresponding to ^{137}Cs) in order to check the MCNP results against available measurement data [Dunster *et al*, 1971; Kirn *et al*, 1954]. For a given source energy E and thickness d of material, the transmission factor, ${}^{E}T_{d}$, through the shield was determined by dividing the kerma tallied in the air cylinder, ${}^{E}K_{d}$, by the kerma tallied in the air cylinder in the alternative case when no shield was present, ${}^{E}K_{0}$.

Initial calculations for concrete using the 0.662 MeV source showed acceptable agreement with data provided in the literature, as seen in Figure 2; this apparent similarity is despite the lack of any clear consensus as to what the exact composition or density of concrete should be. The agreement was taken to indicate evidence supporting the use of the MCNP code in subsequent analyses. Furthermore, by varying some of the parameters of the configuration, some of the assumptions and simplifications made in the definition of the geometry could themselves be justified, as discussed in section 4.3. With this encouragement, the transmission factors calculated using the 0.511 MeV source are approached with confidence: the results for concrete are shown in Figure 3, for lead in Figure 4, and for iron in Figure 5. The half and tenth value thicknesses for the lead agreed well with data provided by RRPDH, but less well for iron, as discussed in Section 4.5.2. For selected thicknesses of shield, Cs-137 calculations were also undertaken for both lead and iron; the results of these agreed with literature data for lead, but only at the thin end of the thickness range for iron. No explanation of this latter discrepancy has been forthcoming, though it was speculated that the problem might lie with the HRP data themselves.

Perhaps more than the generation of the actual transmission curves featured in Figures 3 to 5, a central success of this work has been to demonstrate that MCNP may be used to accurately determine photon shielding data, at least in situations involving gamma rays with energies in the few tenths of an MeV range passing through media such as concrete, lead or iron. This capability may prove particularly useful in the future to similarly evaluate the performances of other materials, and/or for different source energies, for which experimental data are either simply unavailable or prohibitively expensive to obtain.

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7 FIGURES

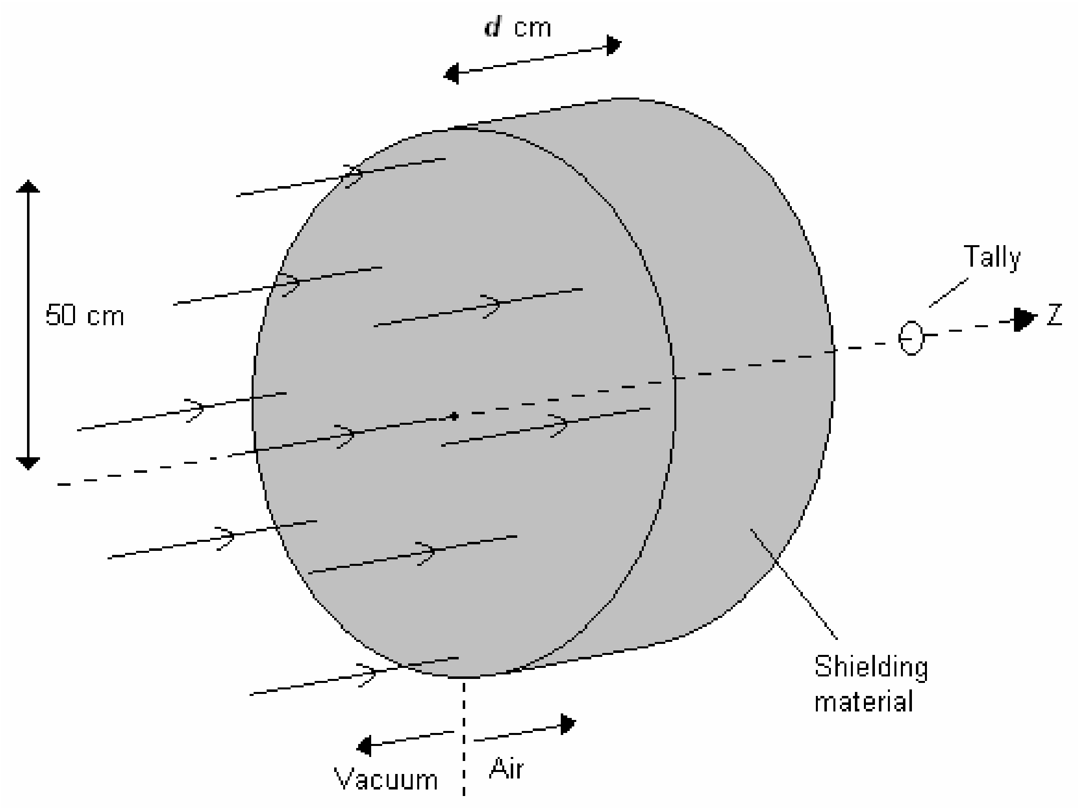

Figure 1: Geometry of the modelled configuration, with the source impinging from the left.

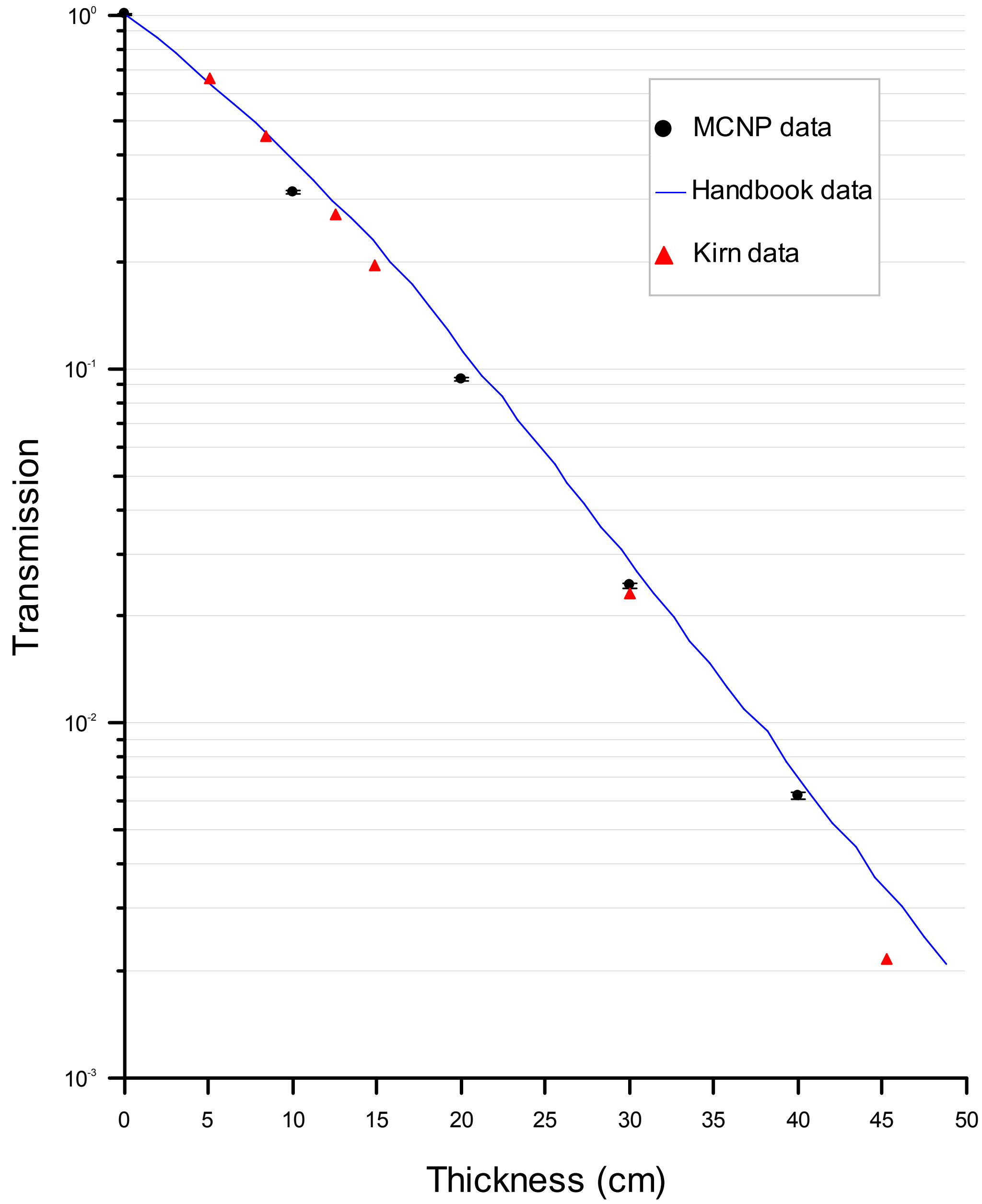

Figure 2: Transmission of 0.662 MeV gamma rays through concrete. Both MCNP and experimental results are presented.

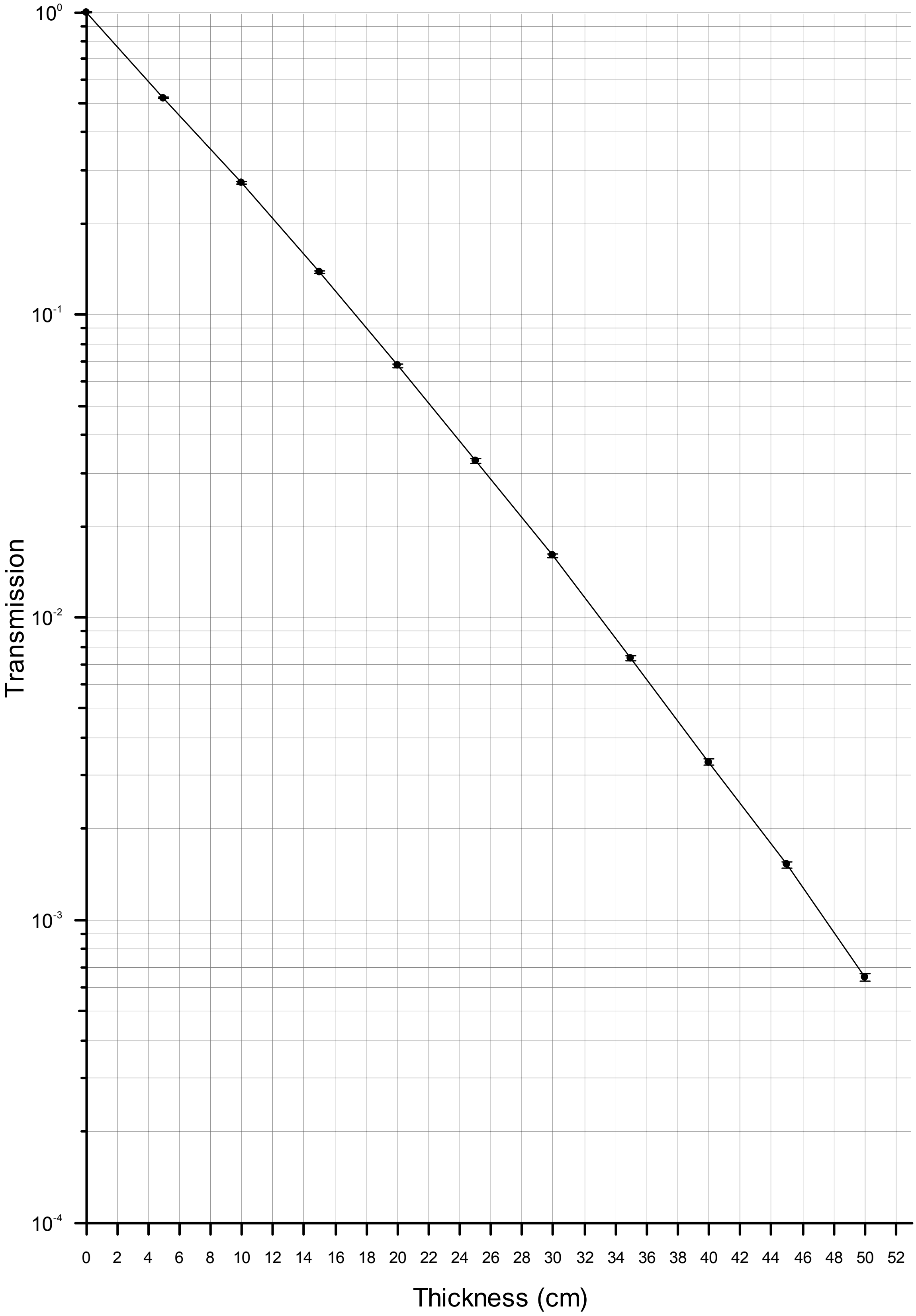

Figure 3: Transmission of 0.511 MeV gamma rays through concrete.

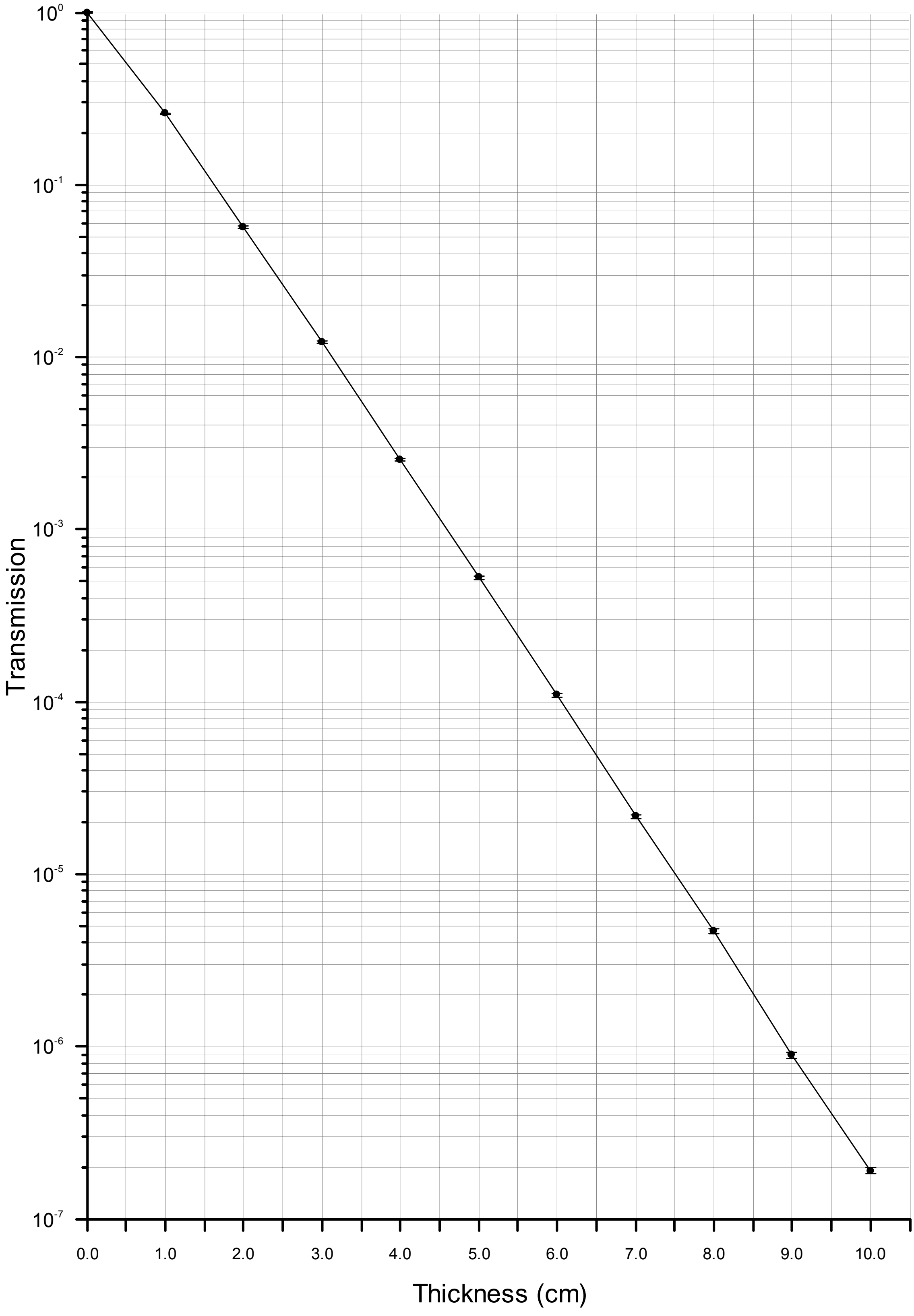

Figure 4: Transmission of 0.511 MeV gamma rays through lead.

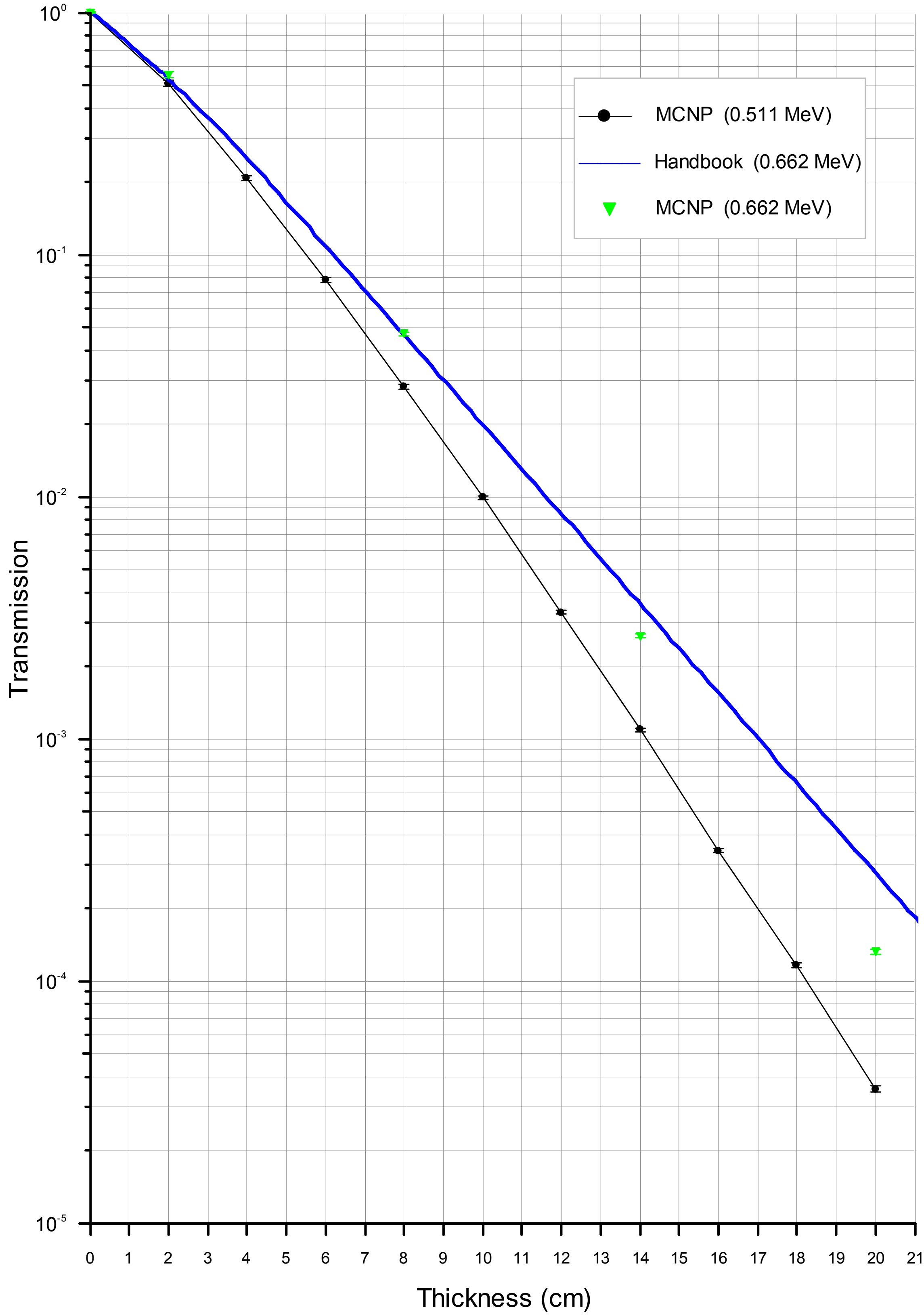

Figure 5: Transmission of 0.511 MeV gamma rays through iron. Also presented are the HRP and MCNP data for the Cs-137 gamma ray transmission through iron.

APPENDIX A Example MCNP input file

The following is a copy of the MCNP input file used to calculate the transmission of 0.511 MeV gamma rays through 50 cm of concrete. The file should be taken as a typical example of the type of configuration used in the current program of work, and, with a few fairly simple changes, may be modified to calculate any of the other results presented in this report.

```
MCNP input for Concrete Attenuation calculation
c
c Cell Cards:
c Concrete...
1     1  -2.3       -1
5     1  -2.3       -5
10    1  -2.3       -10
15    1  -2.3       -15
20    1  -2.3       -20
25    1  -2.3       -25
30    1  -2.3       -30
35    1  -2.3       -35
40    1  -2.3       -40
45    1  -2.3       -45
c Tally...
60    2  -0.001205     -60   $ Tally
70    2  -0.001205  60 -70   $ Air surroundings
c Environment...
80    0  -80   $ Source region
90    0   1 5 10 15 20 25 30 35 40 45 70 80 -90   $ Surroundings
99    0   90   $ Void

c Surface Cards:
c Concrete:
1       rcc   0   0   0   0   0   5   50
5       rcc   0   0   5   0   0   5   50
10      rcc   0   0   10   0   0   5   50
15      rcc   0   0   15   0   0   5   50
20      rcc   0   0   20   0   0   5   50
25      rcc   0   0   25   0   0   5   50
30      rcc   0   0   30   0   0   5   50
35      rcc   0   0   35   0   0   5   50
40      rcc   0   0   40   0   0   5   50
45      rcc   0   0   45   0   0   5   50
c Tally:
60      rcc   0   0   50   0   0   0.1   1 $ Tally
70      rcc   0   0   50   0   0   5   59  $ Air surrounding Tally
c Environment:
80      rcc   0   0  -10   0   0   10   9  $ Source Vacuum
85      pz   -5      $ Source
```

```
90      rcc   0   0  -10   0   0   80  60     $ Surrounds

mode  p
c Materials:
m1    1001.      -0.0221     $  CONCRETE
      6000.      -0.002484
      8000.      -0.574930
      11000.     -0.015208
      12000.     -0.001266
      13000.     -0.019953
      14000.     -0.304627
      19000.     -0.010045
      20000.     -0.042951
      26000.     -0.006435
m2    7000.      -0.755267   $  AIR
      8000.      -0.231781
      18000.     -0.012827
      6000.      -0.000124
c
c Importances:
imp:p  1    1r   2    1r   4    $ 1, 20
       8    8    16   32   64   $ 25, 70
       2r   1    1r   0         $ 80, 99
c
c Source:
sdef  POS=0 0 -5  SUR=85  RAD=d1 VEC=0 0 1  DIR=1  PAR=2  ERG=0.511
si1   50
c
c Tally cards:
f4:p  60
f6:p  60
c
c Output:
print 110 120 130 160 162
c
c Cutoffs:
phys:p  1 0 0
nps  100000000
```

APPENDIX B Calculated data points

The following three tables contain the individual transmission factor results calculated by MCNP, which were plotted as discrete data points in Figures 3 – 5 and interpolated to generate the transmission curves shown. Table B1 corresponds to the 0.511 MeV irradiation of concrete (cf. Figure 3), Table B2 to the 0.511 MeV irradiation of lead (cf. Figure 4), and Table B3 to the 0.511 MeV irradiation of iron (cf. Figure 5). Values in brackets indicate one standard deviation error on the results.

TABLE B1 Transmission of 0.511 MeV gamma rays through concrete

Shield Thickness, *d* (cm)	Transmission factor
0	1
5	0.521 (0.004)
10	0.273 (0.003)
15	0.138 (0.002)
20	0.0680 (0.0009)
25	0.0329 (0.0005)
30	0.0160 (0.0002)
35	0.00732 (0.00015)
40	0.00332 (0.00007)
45	0.00152 (0.00004)
50	0.000645 (0.000018)

TABLE B2 Transmission of 0.511 MeV gamma rays through lead

Shield Thickness, *d* (cm)	Transmission factor
0	1
1	0.259 (0.003)
2	0.0568 (0.0007)
3	0.0122 (0.0002)
4	0.00254 (0.00004)
5	0.000524 (0.000010)
6	0.000109 (0.000002)
7	0.0000216 (0.0000006)
8	0.00000468 (0.00000014)
9	0.000000888 (0.000000032)
10	0.000000190 (0.000000008)

TABLE B3 Transmission of 0.511 MeV gamma rays through iron

Shield Thickness, *d* (cm)	Transmission factor
0	1
2	0.508 (0.015)
4	0.207 (0.005)
6	0.0781 (0.0019)
8	0.0285 (0.0006)
10	0.0099 (0.0002)
12	0.00333 (0.00006)
14	0.00109 (0.00002)
16	0.000345 (0.000006)
18	0.000116 (0.000002)
20	0.0000357 (0.0000010)