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WHY NOT TO TRUST A NEUTRON REMMETER

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Abstract—The shortcomings of neutron remmeters have been well documented by various research laboratories and discussed by the ICRU. Nonetheless, due to a forced reliance on them at the operational level there is frequently an undue confidence in them. This paper reviews the concept of dose equivalent index and how accurately neutron remmeters measure this quantity. It is shown that both instrumental and conceptual shortcomings mean remmeters can overestimate the dose equibalent index by up to a factor of 15 in the worst case, and up to a factor of 3 or 4 in situations which are not unusual.

1. INTRODUCTION

MOST PEOPLE concerned with neutron radiation protection know it is very difficult to accurately assess dose equivalent which is a measure of the radiobiological hazard associated with a given neutron field. This is because the conversion from neutron fluence to dose equivalent is very strongly dependent on neutron energy and because it is very difficult to measure neutron energy spectra, especially over the wide range of energies experienced in radiation protection situations. Fortunately, by placing moderating material around various thermal neutron detectors one obtains a class of instruments called neutron remmeters whose response to a neutron fluence as a function of neutron energy is said to correspond to the maximum dose equivalent that would be created in a human body exposed to that fluence (it is in fact this maximum dose equivalent in the body, called the dose equivalent index, which is of interest in radiation protection). It was believed that this instrumental development meant the radiobiological hazard of a neutron field could be obtained without direct knowledge of either the neutron energy spectrum or the neutron fluence. As a result, neutron remmeters now represent the primary source of neutron radiation protection information around reactors and low energy accelerators. They are even used to help calibrate personnel dosimeters by measuring the field's dose equivalent index.

However neutron remmeters are not as accurate as often assumed. For example, as will be shown below, a remmeter calibrated with a radioactive neutron source overresponds by a factor of about 15 if placed in an isotropic field of 10–50-keV neutrons. This occurs as a result of two factors: (i) the relationship between dose equivalent index and neutron fluence depends on the directional characteristics of the neutron fluence and in an isotropic field this problem causes an error of more than a factor of three in the remmeter measurement; and (ii) calibration data from this and other laboratories have shown that these instruments overrespond by a factor of five when irradiated by 20-keV neutrons. Two further factors which complicate the situation are that: (i) the NCRP and ICRP have recommended neutron fluence to dose equivalent index conversion factors which differ by a factor of two at certain energies; and (ii) the dose equivalent indices for neutrons of differing energies are not additive whereas remmeters are.

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From the radiation protection point of view it is fortunate that these effects lead to the dose equivalent index being overestimated as long as the remmeter is calibrated using a small neutron source with an average neutron energy of 1–6 MeV (e.g. an Am–Be or Pu–Be source). However, in view of the fact that there is a serious proposal which would effectively reduce the maximum permissible neutron dose equivalent index by a factor of about 10 (Ros77; Ros78) these remmeter overestimates could pose serious operational limitations unless they are recognized and dealt with.

The characteristics and shortcomings of neutron remmeters have been studied in detail at many laboratories [see e.g. (An63; Na72; Han75a; Han75b; Har75; Har76)] and mentioned by the ICRU in their Report 25. Nonetheless there appears to be an undue confidence in them at the operational level caused by the lack of a better alternative. This paper will review the shortcomings of remmeters in order to prevent a blind reliance on their accuracy and to stimulate proposals for more meaningful measurements of the dose equivalent index. In the next section the quantities dose equivalent and dose equivalent index will be defined since these are what a remmeter is meant to measure. In Section 3 the paper deals with two conceptual problems which mean that even an instrumentally perfect remmeter does not give an accurate measurement of dose equivalent index. Section 4 deals with a discrepancy in the recommended fluence to dose equivalent index conversion factors which causes problems but which in principle can be solved by more detailed calculations. Lastly, Section 5 deals with the instrumental shortcomings of an Andersson–Braun remmeter, a commonly used device which exhibits the problems found in many remmeters.

2. DEFINITIONS

For a formal definition of dose equivalent the reader is referred to the Supplement to ICRU Report 19 entitled "Dose Equivalent". In essence dose equivalent is a quantity which is related to the presumed radiation risk incurred by exposure to a radiation field. It is defined at a point in a body and is given in practice by the product of the absorbed dose at that point and a quality factor Q related to the biological effectiveness of the radiation at that point. For protection purposes the factor Q is defined in terms of the average LET of the particles delivering the dose. The dimensions of dose equivalent are J/kg, the same as for absorbed dose. The special unit of dose equivalent is the rem (1 rem = 0.01 J/kg). The proposed unit in the SI system is the Sievert (= 1 J/kg).

Thus, for example NCRP Report 38 contains graphs of dose equivalent per unit fluence vs depth for neutrons with various energies incident on a phantom. The values have been calculated using Monte Carlo simulations of the interactions of neutrons in a human body.

However for radiation protection purposes we don't really deal with dose equivalent but with a slightly different quantity, the dose equivalent index. This has been formally defined in ICRU Report 25 entitled "Conceptual Basis for the Determination of Dose Equivalent". In essence the dose equivalent index is the maximum value of dose equivalent within the human body when exposed to a radiation field (it is actually defined for a tissue equivalent sphere which is 30 cm in diameter). The special unit of dose equivalent index is also the rem.

So for example, Table 2 of NCRP Report 38 presents values which can be used to convert neutron fluence to dose equivalent index for different neutron energies (although dose equivalent index is not explicitly mentioned and the calculation is for a cylinder rather than a sphere). These values are obtained by taking the maximum dose equivalent per unit fluence from the calculated dose equivalent vs depth curves mentioned above. It is this dose equivalent index vs neutron energy curve that the response of a remmeter is said to represent.

3. CONCEPTUAL PROBLEMS

3.1 *Angular dependence*

The most significant shortcoming of all current remmeters is not due to an imperfect implementation of the concept, but rather it is a fundamental problem. It concerns the response of a remmeter (even one with an ideal isotropic response) to neutron fields with different directional characteristics. To demonstrate this problem consider two situations which both involve parallel beams of 1 MeV neutrons incident on a tissue equivalent phantom 30 cm in diameter.

Case A: The entire fluence, $F\,n/cm^2$, falls on one side.

Case B: Half the fluence, $\frac{1}{2}F\,n/cm^2$ falls on each of two opposite sides.

What is the dose equivalent index in each case?

The maxinum dose equivalent for a fluence of $F\,n/cm^2$ of 1 MeV neutrons is (say) 7 rem and it occurs less than 2 cm below the surface of the phantom (see Fig. 1). Less than 0.1% of this maximum value is delivered to the 2 cm volume behind the opposite surface (NCRP 38, p. 65) and thus in case B there is essentially no increase in the maximum value at one surface due to the beam incident on the far surface. Thus in case A the dose equivalent index is 7 rem but in case B, with an incident fluence of only $\frac{1}{2}F\,n/cm^2$ on each

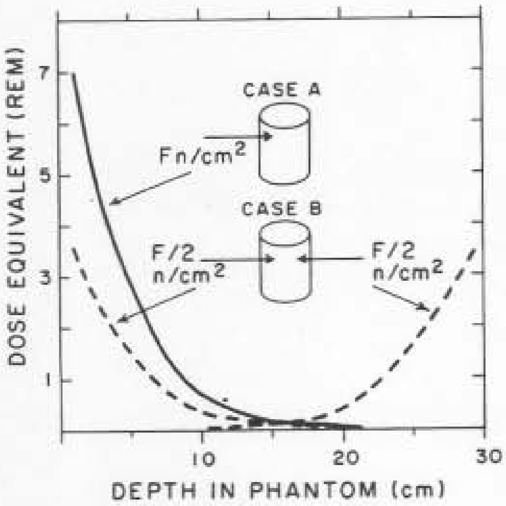

FIG. 1. Dose equivalent vs depth in a tissue equivalent phantom subjected to a total fluence of F neutrons/cm². In case A all neutrons are incident from the same direction whereas in case B half the neutrons are incident from each side. The dose equivalent index in case A is twice that in case B although a remmeter would give the same response in each case.

surface, the dose equivalent index is 3.5 rem. This is because the dose equivalent index refers to the maximum value of dose equivalent in the phantom and, although the integrated dose equivalent in the phantom is the same in both cases, there are two maxima in case B, both of which are only one half the size of the maximum in case A. Hence the dose equivalent index in case B is half that in case A.

Now consider the output of a remmeter with an isotropic response which is placed in each radiation field. It would give the same reading in both cases. Rather than being sensitive to the maximum point on the dose equivalent vs depth curve it is sensitive to the total neutron fluence which is proportional to the integrated dose equivalent in a phantom placed at the same location. The neutron remmeter therefore overestimates the dose equivalent index in case B by a factor of two.

Without a fairly detailed knowledge of the directional attributes of the radiation field, an isotropic remmeter is subject to severe overestimates if calibrated for a monodirectional beam. Based on these kinds of considerations Harvey (Har75) has shown that if placed in an isotropic field instead of a parallel beam, remmeters with an isotropic response will overrespond by factors of 4.0, 3.4 and 3.1 in monoenergetic fields of thermal, 10 keV and 1 MeV neutrons respectively.

This directional dependence, which has nothing to do with the variations in the angular response of the instrument (discussed in Section 5.2), will continue to constitute a major uncertainty associated with the use of remmeters until some method is devised which takes into account the direction of the incident neutrons.

3.2 *Mixed field problems*

Harvey (Har75) has pointed out a second problem which is also fundamental in nature but which is less important in practice. It concerns the additivity of the dose equivalent indices found for radiation fields consisting of different reutron energies. Consider three further cases, this time involving parallel beams of neutrons of the same fluence Fn/cm^2, incident on a tissue equivalent phantom 30 cm in diameter.

Case C: Neutron energy = 1 keV, Fn/cm^2.
Case D: Neutron energy = 500 keV, Fn/cm^2.
Case E: Fn/cm^2 of 1 keV neutrons plus Fn/cm^2 of 500 keV neutrons.

What is the dose equivalent index if these irradiations are done separately or together?

The essential point here is that the maximum in the dose equivalent vs depth curve is at different locations for these two radiations. For 1 keV neutrons the maximum dose equivalent is (say) 10 rem and it occurs at a depth of 4 cm. In case D the maximum dose equivalent is also (say) 10 rem but occurs at a depth of 0.5 cm (see Fig. 2). Thus in both case C and case D the dose equivalent index is 10 rem because that is the maximum dose equivalent in each case. The dose equivalent curve in case E is determined by simply adding the two separate curves. Thus, for example the dose equivalent at 0.5 cm is 13 rem made up of 10 rem from the 500 keV neutrons plus 3 rem from the 1 keV neutrons. The maximum dose equivalent on this summed curve is nearly 14 rem at about 2 cm depth. Thus the dose equivalent index is 14 cm in case E rather than the 20 rem expecetd if the dose equivalent index were additive.

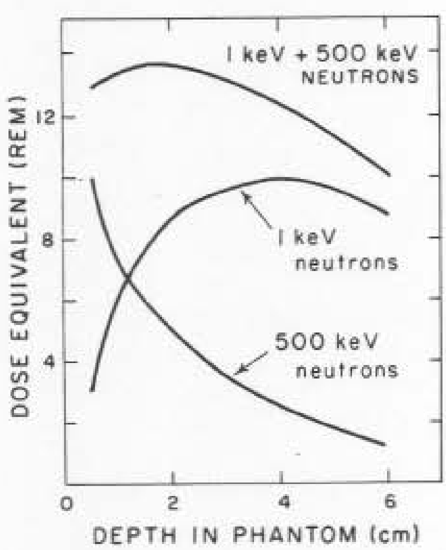

FIG. 2. Dose equivalent vs depth in a tissue equivalent phantom subjected to neutrons with energies of 1 keV, 500 keV and a mixture of both. In the individual cases the fluences are Fn/cm^2 and in the combined case it is $2Fn/cm^2$. Since the maxima occur at different depths the dose equivalent index for the combined case is only 40% larger than for the individual cases. A neutron remmeter would register a dose equivalent index equal to the sum of the two individual cases.

Consider now the output of a remmeter in these fields. To the extent that its energy response as a function of energy is correct, it would correctly measure the dose equivalent index for each irradiation separately, but since it is an additive device it would measure 20 rem for the combined fields. Once again, even an instrumentally ideal remmeter would overestimate the proper dose equivalent index. In case E the overestimate would be by 43% but in general its magnitude would depend on the degree of overlap of the dose equivalent curves and the relative intensities of the various energy neutron groups.

The fact that the dose equivalent index is not additive for different radiations means remmeters could overestimate the dose equivalent index by up to 100% in the case in which there is no overlap in the dose equivalent distributions. However in practice this seldom occurs and the error will be much less since neutrons at many energies produce their maximum dose equivalent at roughly the same depth, viz within a few cm of the body's surface. The problem is potentially more significant if the neutron dose equivalent index is to be combined with that from another form of radiation.

4. RESEARCH PROBLEMS

Another problem involving the use of remmeters and neutron radiation protection in general is the fact that there is no generally "accepted" curve of dose equivalent index vs neutron energy. The problem is essentially caused by the need to estimate the peak value on the dose equivalent vs depth curve from Monte Carlo calculations which give average values of dose equivalent for fairly large volume elements. I have dealt with this previously (Ro78) but the problem is summarized in Fig. 3 which shows the percentage

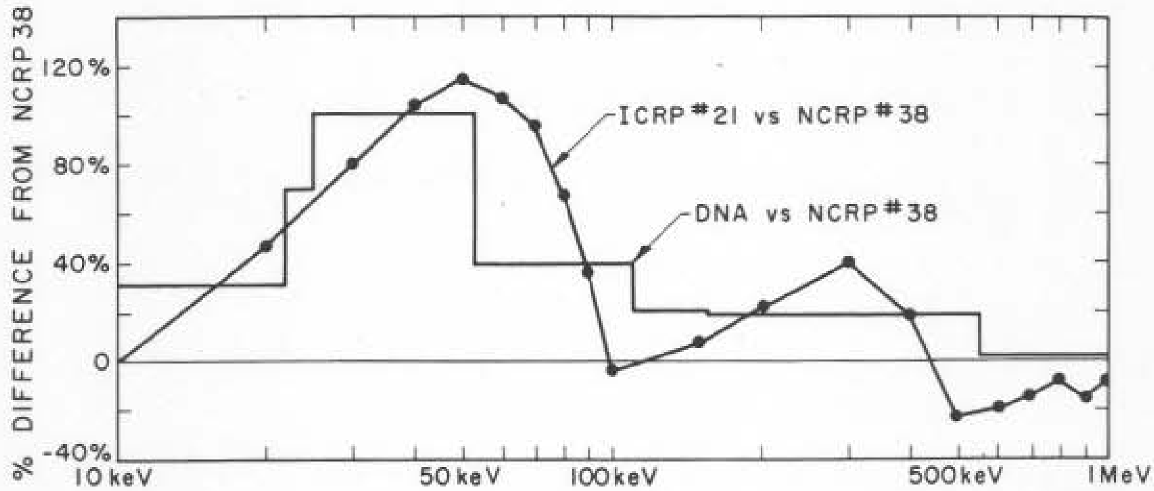

FIG. 3. The percentage difference between NCRP recommendations for the dose equivalent index vs neutron energy curve [using a linear interpolation between values of (n/cm^2/rem)] and those of ICRP Report 21 and the DNA Cross Section Library (Ba77).

difference between the conversion factor values recommended by NCRP 38, ICRP 21 and the Defence Nuclear Agency cross section library (Ba77) for neutron energies between 10 keV and 1 MeV (agreement is good outside this range). Two points are worth noting: (i) all three recommendations were based on the same set of Monte Carlo calculations (done by W. S. Snyder for the NCRP)! and (ii) the NCRP values were obtained using a linear interpolation between values of (n/cm^2)/rem [this method is stated explicitly by the NCRP but is frequently overlooked (see (Han77; Ro77a)]. These discrepancies can hopefully be removed by more detailed Monte Carlo calculations. In the meantime one may choose to use the NCRP prescription on the basis that one of its authors did the Monte Carlo calculations in question and because the NCRP at least attempts to take into account the difference between the average dose equivalent in a volume element and the maxinum value. Intuitively however the ICRP recommendations are more satisfying because they give a smooth curve whereas the NCRPs values have cusps in a plot of rem/(n/cm^2) vs neutron energy. The ICRP values have been formally adopted in many countries.

As we shall see in the next section these variations can play a significant role in this energy region, particularily if the instrument is calibrated at a single energy (say 500 keV) for use with filtered photoneutrons from medical linacs [see e.g. (Ro79)]. In view of these problems it is essential that the source of conversion factors be explicitly included in any reported measurements of low energy spectra.

5. INSTRUMENTAL PROBLEMS

5.1 *Energy dependence*

It is sometimes believed that the energy response of neutron remmeters matches the dose equivalent index curve to within 20%. This just isn't so, especially in view of the fact that there is no agreement on what the curve should be (Section 4). But it goes beyond the problem of specifying the dose equivalent index curve. Figure 4 shows the response of a commercial Andersson–Braun remmeter vs neutron energy using both the NCRP and ICRP conversion factors. These results were obtained using the various accelerator-produced mono-energetic neutron beams available at this laboratory (Ro77b). Relative to a calibration based on an Am–Be source, at 20 keV there is a dramatic overresponse by a factor of five using the NCRPs conversion from fluence to dose equivalent index or by a factor of 3 using the ICRPs conversion factor. At 500 keV there is a 25% underresponse if we adopt the NCRP conversion factors whereas with the ICRPs

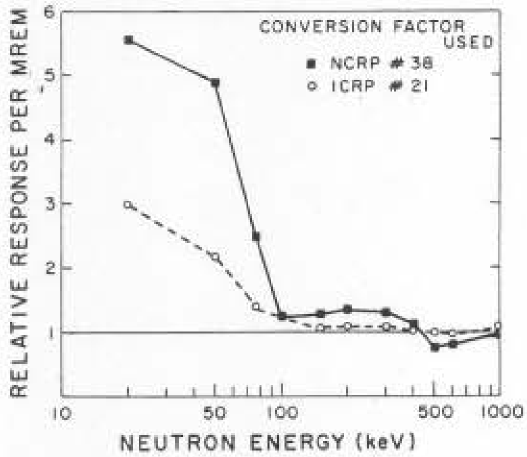

FIG. 4. The response of an Andersson–Braun neutron remmeter normalized to unity for an Am–Be calibration [using 3.73×10^{-8} rem/(n/cm^2) (K172)]. The response to mono-energetic neutrons falling on the side of the cylinder is shown for both the NCRP and ICRP conversion factors. The neutrons were provided by the ^{45}Sc(p, n) [for 20 and 50 keV (see Ro77b)], ^{7}Li(p, n) and ^{11}B(p, n) (for 1 MeV) reactions.

values the response is quite accurate. Other studies have shown that these results are typical of those for other types of moderating remmeters and that at neutron energies above 7 MeV the response of remmeters drops off quickly and is low by a factor of about 3 at 14 MeV (Han75a). There is both calculated and experimental evidence that below 20 keV the relative response of the remmeters would fall and they underrespond to neutrons with energies below 100 eV (Har76; Te75). Hankins has pointed out there can also be a severe overresponse by this remmeter and possibly other remmeters when exposed to thermal neutrons which can get through the cable channels to the internal thermal neutron detectors without going through the moderator (Han75b). Hankins has suggested this should be corrected by placing a cadmium sheet over the cable channel if the remmeter is to be used in an environment with thermal neutrons.

In short, remmeters give adequate indications of the dose equivalent index only in the range 100 keV–6 MeV. Above and below that range they are inadequate. In typical CANDU reactor environments the majority of the dose equivalent is in this 100 keV–6 MeV range and thus in practice this problem is not as important as the directional response limitations discussed in Section 3.1. Nonetheless there have been neutron spectra measured around the Ontario Hydro's Pickering reactor in which most of the neutron fluence was at energies below 50 keV (Fa78). In fields such as these a remmeter would overrespond by a factor of three to five on account of the energy dependent response.

5.2 *Angular response*

Many remmeters have spherical moderators and as a result they exhibit a nearly iostropic reponse except for their instrument packets. As was recognized right from the beginning, this is not the case with Andersson–Braun type remmeters because they have cylindrical moderators (An63). Figure 5 presents the measured angular response over a range of neutron energies from 20 keV to 1 MeV. Note that for neutron energies below about 100 keV the shape of the angular response changes as the instrument packet begins to represent a window rather than a shield. The lines only join the points and the

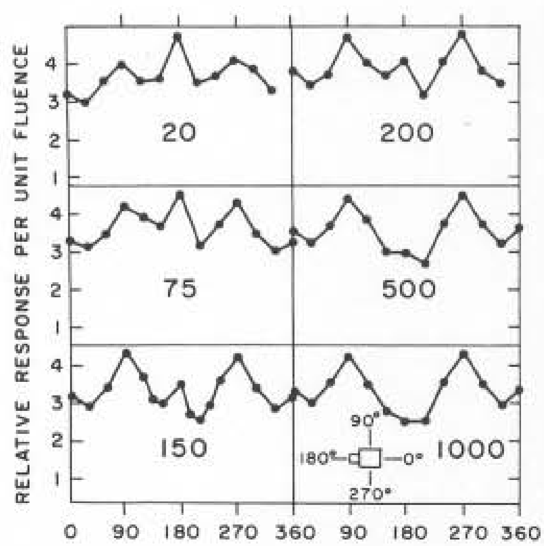

FIG. 5. The relative response as a function of angle of a commercially available Andersson–Braun neutron remmeter for the neutron energies shown in keV. The lines merely join the experimental points as a visual guide.

work by Hankins at energies above 150 keV suggests there is even more structure in the response with angle (Han75b). The important point is that there is nearly a factor of two variation in response with angle. Operationally this implies that an Andersson–Braun remmeter must always be rotated to find the maximum value before taking a reading since its calibration likely was done from the side position, representing its most efficient orientation. Hankins has recently suggested modifications for the Andersson–Braun remmeter which would reduce this angular variation (Han78). However, one might argue that this variation in angular response is useful since it provides indication of whether the neutron field is isotropic (in which case there will be no variation in reading when the remmeter is rotated) or mono-directional (in which case there will be a variation by a factor of nearly two).

6. CONCLUSIONS

The neutron remmeter is not nearly as accurate as often assumed. In particular, even if the response of the detector is isotropic, its response is highly sensitive to the directional characteristics of the neutron field. If the remmeter is calibrated in a monodirectional field (e.g. with a source) then there can be an overresponse by a factor of 3 or 4 if the remmeter is used in an isotropic field such as occurs around many reactors. Problems with additivity in a mixed field, specification of the dose equivalent index curve and the instrumental energy response also make the use of remmeters inaccurate. In practice however, these latter three problems are not as critical in the sense that they represent errors which taken together are likely to cause less than a 50% overresponse. The non-isotropic response of cylindrical Andersson–Braun remmeters means that they could be subject to the most serious problem in the sense that they could underestimate the dose equivalent index of a mono-directional neutron field by a factor of two if they were not roatated in order to find the maximum reading. This problem could be reduced by modifying the remmeter but this removes the possibility of learning about the radiation field's directional characteristics by rotating the remmeter. An alternative solution is to calibrate the remmeter at an angle corresponding to its minimum sensitivity. This has the advantage of making the instrument always overestimate the dose equivalent index and is therefore suitably conservative for protection purposes. On the other hand it means the instrument will usually read high by a factor of two.

For all of the above reasons great care must be taken interpreting the readings from neutron remmeters. In particular it is at best questionable to use remmeters as calibration devices when testing or verifying other types of dosimeters under field conditions. Nonetheless, as long as they are rotated to obtain the maximum reading, neutron remmeters do provide an adequate radiation protection instrument in the limited sense that they err on the conservative side and provide an overestimate of the dose equivalent index.

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REFERENCES

An63 Andersson I. O. and Braun J., 1963, "A Neutron Rem Counter with Uniform Sensitivity From 0.025 eV to 10 MeV", in: *Neutron Dosimetry*, Vol. II, p. 87 (Vienna: IAEA).

Ba77 Bartine D. E., Knight J. R., Pace J. V. and Roussin R., 1977, "Production and Testing of the Defence Nuclear Agency Few-Group Coupled Neutron-Gamma Cross Section Library", Oak Ridge National Laboratory Rep. ORNL/TM-4840.

Fa78 Facey R. A. and Walsh M. L., 1978, "Calibration of an Albedo Dosimetry System in a Reactor Environment", paper presented at the June 1978 Health Physics Society Meeting.

Han75a Hankins D. E., 1975, "Energy Dependence of Four Neutron Remmeter Instruments", *Health Phys.* **28**, 305.

Han75b Hankins D. E., 1975, Lawrence Livermore Laboratory unpublished notes.

Har75 Harvey J. R., 1975, "An Approach to the Surveying of Radiation Environments for Radiation Protection Purposes", *Phys. Med. Biol.* **20**, 1003.

Har76 Harvey J. R., Lavender A. and Thompson I. M. G., 1976, "The Calibration of a Number of Neutron Sensitive Instruments with a Novel Source Emitting Neutrons around 0.5 keV", *Health Phys.* **31**, 363.

Han77 Hankins D. E., 1977, "Neutron Dosimetry Studies at LLL", in: *6th ERDA Workshop on Personnel Neutron Dosimetry*, July 1977, Battelle Rep. PNL-2449/UC-48.

Han78 Hankins D. E., 1978, "A Modified A-B Remmeter with Improved Directional Dependence and Thermal Neutron Sensitivity", *Health Phys.* **34**, 249.

ICRU73 International Commision on Radiation Units and measurements, 1973, Supplement to *ICRU Report* 19, "Dose Equivalent" (Washington, D.C.: ICRU).

ICRU76 International Commision on Radiation Units and measurements, 1976, "The Conceptual Basis for the Determination of Dose Equivalent", *ICRU Report* 25 (Washington, D.C.: ICRU).

ICRP73 International Commision on Radiological Protection, 1973, "Data for Protection Against Ionizing Radiation from External Sources", *ICRP Publication* 21 (Oxford: Pergamon Press).

Kl72 Kluge H., Weise K. and Zill H. W., 1972, "Measurement of Spectral Distributions of Neutrons from Radioactive Sources and the Resulting Fluence-Dose Conversion Factors", in: *Neutron Monitoring for Radiation Protection Purposes*, Vol I, p. 13 (Vienna: IAEA).

Na72 Nachtigall D. and Burger G., 1972, "Dose Equivalent Determinations in Neutron Fields by Means of Moderator Techniques", in: *Topics in Radiation Dosimetry* (Edited by Attix F. H.) (New York: Academic Press).

NCRP71 National Council on Radiation Protection, 1971, "Protection Against Neutron Radiation", *NCRP Publication* 38 (Washington, D.C.: NCRP).

Ro77a Rogers D. W. O., 1977, "On the Definition of Dose Equivalent Received from a Neutron Flux", NRC Rep. PXNR-2432.

Ro77b Rogers D. W. O., 1977, "The ^{45}Sc(p, n) reaction as a source of monoenergetic 10–50 keV neutrons", *Nucl. Inst. & Meth.* **142**, 475.

Ro78 Rogers D. W. O., 1978, "Conversion of Neutrons/cm^2 to Rem", *Health Phys.* **34**, 395.

Ro79 Rogers D. W. O. and van Dyke G., 1979, "Remmeter Measurements of Neutrons from Medical Linacs", in preparation.

Ros77 Rossi H. H., 1977, "The Effects of Small Doses of Ionizing Radiation", *Rad. Res.* **71**, 1.

Ros78 Rossi H. H. and Mays C. W., 1978, "Leukemia Risk from Neutrons", *Health Phys.* **34**, 353.

Te75 Tessler G. and Glickstein S. S., 1975, "Monte Carlo Calculation of the Response of the Portable Neutron Monitor SNOOPY", *Health Phys.* **28**, 197.