NBS MEASUREMENT SERVICES: NEUTRON PERSONNEL DOSIMETRY

Robert B. Schwartz

Center for Radiation Research
National Measurement Laboratory
National Bureau of Standards
Gaithersburg, MD 20899

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PREFACE

The calibration and related measurement services of the National Bureau of Standards are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NBS offers over 300 different calibration, special test, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NBS. These services are offered to the public and private organizations alike. They are described in NBS Special Publication (SP) 250, NBS Calibration Services Users Guide.

The Users Guide is being supplemented by a number of special publications (designated as the "SP 250 Series") that provide a detailed description of the important features of specific NBS calibration services. These documents provide a description of the: (1) specifications for the service; (2) design philosophy and theory; (3) NBS measurement system; (4) NBS operational procedures; (5) assessment of measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NBS. These documents will present more detail than can be given in an NBS calibration report, or than is generally allowed in articles in scientific journals. In the past NBS has published such information in a variety of ways. This series will help make this type of information more readily available to the user.

This document (SP 250-12), NBS Measurements Services: Neutron Personnel Dosimetry, by R. B. Schwartz, is the twelfth to be published in this new series of special publications. It describes the preparation and calibration of neutron dosimeters and remmeters with californium neutron sources, both "bare" and moderated (see test number 44060C in the SP 250 Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the author or one of the technical contacts cited in SP 250.

The Center for Radiation Research (CRR) is in the process of publishing 21 documents in this SP 250 series, covering all of the calibration services offered by CRR. A complete listing of these documents can be found inside the back cover.

NBS would welcome suggestions on how publications such as these might be made more useful. Suggestions are also welcome concerning the need for new calibration services, special tests, and measurement assurance programs.

George A. Uriano Director Measurement Services	Chris E. Kuyatt Director Center for Radiation Research

Detailed procedures are given for calibration of neutron dosimeters and remmeters with californium neutron sources, both "bare" and moderated. Corrections for air scatter, room-return, anisotropic neutron emission, and deviation from the inverse square law are discussed, and specific examples given. The uncertainties in arriving at the final value for the calibration factor are also discussed.

Key words: calibration; californium; dose equivalent; dosimeter; neutron; remmeter.

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1. Description of Service

The National Bureau of Standards (NBS) supplies essentially "free-field" neutron irradiations for calibrating neutron detection instrumentation. This is done under SP 250 Number 44060C (formerly 8.1J)[1]. By "free-field" is meant that the irradiations are performed in a relatively large, open room (specifically, the lower level of the Van de Graaff low-scatter room) with a minimum of scattering material, so that the neutron field is close to that which would exist in the vicinity of an isolated source. Explicit corrections are made for residual scattering effects, and, in fact, these corrections form an important part of our work.

The neutron fields available are those produced by californium-252 sources, either free in air, or in the center of a 15 cm radius heavy-water sphere covered with cadmium[2]. These are referred to as the "bare" and the "moderated" sources, respectively. Whether to use the bare or the moderated source is determined by the type of device to be calibrated and the neutron spectrum to which it (and the radiation worker) are expected to be exposed. For calibrating albedo dosimeters, particularly if they are to be used in the relatively soft spectra found in reactor environments, moderated californium, with its spectrum rich in low and intermediate energy neutrons, is clearly preferred[3,4] (compare Figures 4 and 5, Appendix D). We have shown[4] that for other common dosimeter types (NTA film, CR-39, polycarbonate) there are not very great differences (less than a factor of 2) in calibration factors between bare and moderated ^{252}Cf. For common types of remmeters, the difference in calibration factors is a factor of ~ 1.4. Thus, moderated ^{252}Cf is the more versatile of the two types, since it is appropriate for all of the commonly used personnel protection instrumentation. It is also the only neutron source given in ANSI N13.11[5]. On the other hand, the spontaneous fission neutron spectrum from bare californium, similar to that from ^{235}U fission, has been very carefully evaluated and is better known than that from moderated californium, and higher dose equivalent rates are obtained from bare californium. In the end, however, the customer usually has his own ideas about which source to use (sometimes asking that the same device be calibrated with both sources), and we, of course, abide by his wishes.

The differential energy spectra, taken from a recent ISO Draft Standard[6], are given in Appendix D.

Most of our work involves calibrating neutron personnel protection instrumentation, both passive (e.g., dosimeters) and active (e.g., remmeters). For dosimeters, we irradiate to a known dose equivalent (see Appendix E for definitions), and return the dosimeters to the customer. The customer then reads out the dosimeters in his usual manner, and thus obtains a calibration for his system in terms of our delivered dose equivalent. Remmeters, on the other hand, are placed in a field of known dose equivalent rate. We read the remmeter and report the reading, the true dose equivalent rate, and the calibration factor which we define as the ratio of the actual dose equivalent rate to the remmeter reading. The rest of the discussion will concentrate on these types of calibrations, but the facility can be used for calibrating any other type of neutron detector, and at times is used for calibrating Bonner Spheres, tissue equivalent proportional counters, etc.

The basic physical principles are straightforward. We start with a californium neutron source of known emission rate, Q, measured at NBS[7] with an uncertainty of ~ ±1.3%. (Note that this uncertainty, and all other uncertainties given in this document, are understood to be one standard deviation (1σ)). At any point a distance r from the source, the free field fluence rate is just $Q/4\pi r^2$. Using conventional fluence-to-dose equivalent conversion factors[8], we calculate the free field dose equivalent rate at that point. We then put the instrument at the distance r and either read its output (for a real-time instrument), or expose it for a measured length of time in the case of an integrating device such as a "film badge".

The conversion factors for the two different spectra are obtained by taking the energy-dependent conversion factors as given by the International Commission on Radiation Protection (ICRP)[8] and weighting these factors with the neutron energy spectra. This is done via a 620 energy group calculation which approximates a continuous integral of the product of the ICRP factors and the neutron energy spectra, using log-log interpolation on the given ICRP values. The calculation is done by C. M. Eisenhauer, using the code DETAN. The numerical values are given in equations 5 and 6, below.

Note that in this system, the closest thing to a "standard" is the calibrated neutron source. There are no "standard" instruments in this field. Note also that once the source is calibrated (they are re-calibrated about every six years), the principal "measurement" made during the calibration is just the source-to-detector distance. This is generally done with an ordinary tape measure, calibrated in meters.

There is, however, more to calibrating than simply putting a source and a detector in the middle of a room and reading the detector output. The neutron field at the detector differs from that due to the source itself due to nuclear reactions with the walls and floor of the calibration room, with the air in the room, and with the source encapsulation. These reactions generally result in scattered neutrons with lower energy, different angular distribution, and different variation with distance than the direct source neutrons. Further, since none of the instruments have an energy-independent response on either a fluence or dose equivalent basis, interpretation of the instrument reading is not as straightforward as it might at first appear. All of these effects may be dealt with by appropriate (Monte Carlo) computer codes, but this seems a somewhat cumbersome procedure, requiring a new calculation for each change in source-to-detector distance, source encapsulation, and so on. Instead, we treat all of these effects as corrections, and have developed a semi-empirical approach to making the corrections. While this approach itself makes use of computer calculations, it offers physical insight into the problem without requiring further significant calculations. The corrections are discussed in section 3 of this report.

In order to get a wide range of dose equivalent rates, we use three different sources (differing in intensity by approximately factors of 10) for the moderated irradiations, and two sources, differing in emission rate by a factor of 50, for the bare irradiations. By using the different sources at different distances, we generally cover the range from a few millirem per hour to a few rem per hour for bare irradiations, and from a few millirem per hour to ~ 700 mrem per hour for the moderated irradiations. We are limited in the maximum dose equivalent rate for moderated irradiations by the present californium source strength and by the fact that there are spectral changes at close distances (< 30 cm)[9,10] which limit the minimum distance which can be used. We plan, however, to get a new californium source with more than three times the emission rate of our present strongest source, so that we will be able to do moderated irradiations up to ~ 2 rem/hour. We are also getting a third source for bare irradiations, to give more flexibility.

The calibration uncertainty is generally in the range of ~ ±5% (1σ). The limitations on accuracy include a ±4%[6] uncertainty in the fluence to dose equivalent conversion factor for the moderated source, and ~ 1.3% uncertainty in the knowledge of the neutron source emission rate. At low dose equivalent rates the statistical fluctuations in the instrument readings usually provide the dominant uncertainty, and at close distances the uncertainty in the location of the effective center of the instrument is significant. These uncertainties are discussed in more detail in Section 5.

In addition, the readings of many instruments drift in an uncertain manner which may amount to several per cent per hour[11]. While we do not understand in detail the physical mechanism for this drift, it appears to be primarily due to an actual change in the count rate of the BF_3 proportional counter, rather than, say, a drift in some part of the electronics. It is not known *a priori* which instruments will drift and which won't. Since it is much too time consuming to measure the drift for each instrument, we consider the calibration to be a sort of "snap-shot" at some stage of the drift cycle. Since a calibration usually takes somewhat less than an hour, there is thus the possibility that an instrument reading taken at, say, the end of the calibration is a few percent higher than it would have been at the beginning. Since we don't *know* whether an instrument is drifting or not, it is not possible to assign a realistic uncertainty for drift. On the other hand, any drift will manifest itself as a variation in the readings, and hence will automatically contribute to the overall uncertainty in the calibration factor. Since the instruments are all portable and battery operated, in actual use they are usually left on for a time period no longer than the time it takes us to do a calibration. Hence, we feel that our "snap-shot" is a realistic one. It is not an ideal situation, but we feel that our approach is a reasonable compromise, given that these are field instruments.

2. Facility Description

Our facility is located in the lower level of the NBS Van de Graaff accelerator low-scatter room. (See Figure 1.) This area has an 11 m x 12 m concrete floor, and concrete walls which extend to a "ceiling" height of 4.6 m. This "ceiling" is actually an aluminum grating which serves as the floor of the low-scatter room above. The sources are stored in a 25 cm diameter, 1.6 m deep, hole in the center of the concrete floor. This hole is sub-divided into 8 smaller holes, with each source in one of the separate smaller holes. When not in use, each hole is shielded by a lucite and steel plug, and the whole arrangement is covered with a polyethylene cap which is kept locked in place to prevent unauthorized access to the californium sources. A length of beaded chain is attached to each source; the other end of the chain is attached to a dacron string which passes through a series of teflon-lined eyelets and then to a fishing reel mounted behind a shield wall near the entrance to the low-scatter room. The operator uses the fishing reel to raise and lower the sources into position. The position of the source is monitored by closed-circuit television cameras.

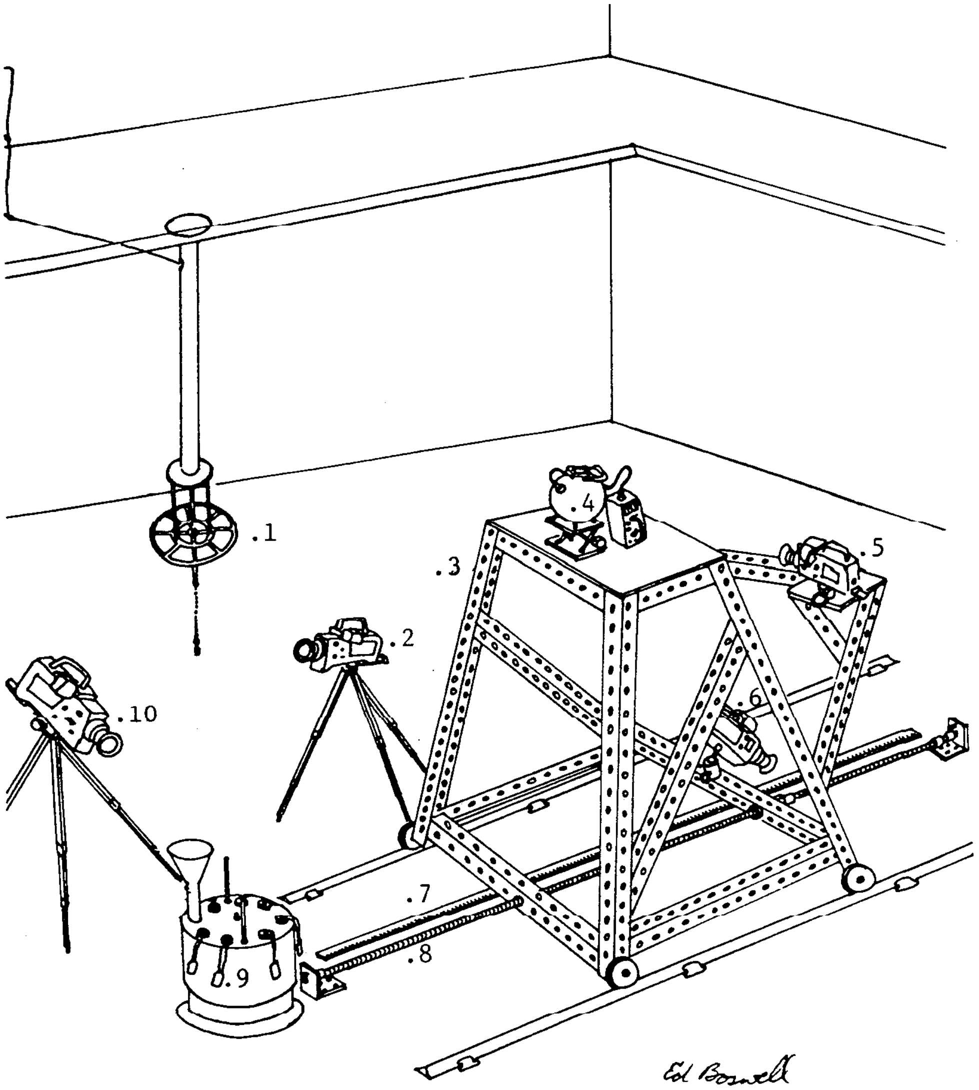

FIG. 1 Simplified view of Low Scatter Neutron Calibration Facility (sections of overhead grating floor shown removed.). Perspective variation allows compressed view of what is virtually a large, nearly empty room.

.1 Neutron source being raised into position
.2 T.V. camera for monitoring of source in exposed position.
.3 Remote mobile platform.
.4 PRS-2 neutron meter in position for calibration.
.5 T.V. camera for monitoring of neutron meter read-out.
.6 T.V. camera for monitoring of platform position.
.7 Platform position indicator.
.8 Ball screw and nut assembly.
.9 Source storage facility.
10. T.V. camera for monitoring source movement in and out of storage facility.

The rest of the facility consists of a low mass stand approximately 2.1 m high. The top of the stand is an aluminum platform, approximately 60 cm x 60 cm x 6 mm thick, to support the instruments to be irradiated. The stand is on casters which ride on angle irons set in the floor to serve as tracks. Another closed-circuit television camera mounted on an arm attached to the stand enables the instrument being calibrated to be read remotely.

3. Corrections

Although, as indicated above, our facility is designed to come as close as possible to providing "free-field" irradiations, there are still important corrections which must be made. We have identified four separate corrections: correction for anisotropic source emission, for neutron scattering off the walls, floor, and ceiling ("room return"), for air scattering, and for the deviation from the $1/r^2$ law due to the finite size of the source or detector. (It should be noted that our approach does not give consistent results in very large calibration halls (linear dimensions ~ 20 m or more) which use grating floors. We think that this is probably due to scattering off the grating which our model does not take into account, but this has not been conclusively demonstrated. In any case, the method which we describe below must be used with caution in these kinds of rooms.)

3.a. Anisotropic Emission

Neutron source emission rates are determined by a manganese bath calibration[7], which measures the total emission rate into 4π. Dividing the emission rate, Q, by $4\pi r^2$ would give the fluence rate at a distance r if the neutron emission were isotropic. Neutron scattering within the source encapsulation, however, usually results in anisotropic emission. Spherical encapsulation does not give any asymmetry; a right circular cylinder with diameter equal to the height minimizes the asymmetry, and a long circular cylinder maximizes the asymmetry. Our bare sources are right circular cylinders, viewed in the direction perpendicular to the cylindrical axis. For this case, the effect of the internal scattering is always to increase the fluence rate over that which would be calculated from $Q/4\pi r^2$. Since the scattered neutrons have a different energy spectrum from the source neutrons, the effect on any instrument depends upon that instrument's energy response. We use anisotropy correction factors to correct for the increase in instrument response, and thus there are different corrections for each instrument-source combination. The corrections are based on to-be-published calculations and measurements by C. M. Eisenhauer and J. B. Hunt, and estimation in cases where there are no data.

For the bare sources and devices such as remmeters and NTA film which respond primarily to higher energy neutrons, the correction is essentially zero for the lightly encapsulated NS-series sources, and 3% for the heavier, SR-Cf, sources. For devices more sensitive to lower energy neutrons, such as the 3" sphere or albedo dosimeters, the correction is taken to be 1% and 3.7% for the NS and the SR-Cf sources, respectively. The correction is independent of the source-detector distance.

Scattering within the moderator makes the field produced by the moderated source more nearly isotropic, and therefore no anisotropy correction is made for those irradiations.

3.b. Room Return

It has been shown[12,13] that room scattered neutrons are essentially uniformly distributed throughout the room, and since the fluence of source neutrons varies as $1/r^2$, if we first correct for air scattering (see 3.c.), we can, in general, write for the total response, D, at a distance, r:

$$D = R_o + R_s = D_o/r^2 + R_s, \qquad (1)$$

where R_o is the response of the detector to the source neutrons,
R_s is the response to the room scattered neutrons, and
D_o is the response at unit distance to the source neutrons alone.

The quantity D_o is the quantity which we are trying to determine. If we define the quantity S as

$$S = R_s/D_o, \qquad (2)$$

we can re-write eq. 1 as

$$Dr^2 = D_o(1 + Sr^2). \qquad (3)$$

The quantity S is, physically, the fractional room-return correction at unit source-detector distance. By making measurements of D as a function of r and fitting to equation 3, we have determined the quantity S for bare and for moderated californium for the usual devices which we calibrate. The results are listed in Table 1, in units of percent scatter correction, per meter-squared.

Table 1 - Room Return Corrections, S, percent per meter-squared

Device	Bare	Moderated
3" Sphere	33%	13%
Albedo Dosimeter	20	5.4
9" Spherical Remmeter	6	7.9
Andersson-Braun Remmeter	2.4	

3.c. Air Scatter

The results of transport calculations show that neutron air in-scattering is approximately twice the out-scattering, so that the net effect is always to increase the fluence at the detector. The effect varies linearly with the source-detector distance. The in-scattered spectrum is, however, shifted to lower energies due to the kinematics of the elastic scattering from nitrogen and oxygen. The effect of the in-scattered neutrons is represented by an integral over the energy and angular response of the detector. The calculated corrections, in percent per meter, are listed in Table 2, taken from references 14 and 15. They are based on unpublished Morse Monte Carlo air transport calculations by R. C. McCall and energy response measurements by D. Hankins[16].

Table 2 - Air Scatter Correction, percent per meter

Device	Bare	Moderated
3" Sphere	1.7%	4.5%
Albedo Dosimeter	1.1	3.0
Remmeter	1.0	2.3
NTA Film, Track Etch Dosimeter	0.5	0.9

3.d. Deviation from Inverse Square Law

For a spherical detector and a point isotropic neutron source, Axton[17] showed that the response of the device is increased by a factor of approximately

$$[1 + \delta(a/2r)^2]$$

above that expected by the inverse square law, where a is the radius of the sphere, r is the distance from the source to the geometric center of the sphere, and δ is a numerical constant less than unity, whose value was estimated to be ~ 2/3. J. B. Hunt[18] has shown that δ depends upon the sphere size. Following Hunt, we use $\delta = 0.4$ for a 3" diameter sphere, 0.5 for a 9" or 10" diameter sphere, and 0.55 for an Andersson-Braun remmeter. Ing and Cross[19] have shown that the case of a spherical source irradiating a small detector is formally similar, and we therefore use the same form of correction, with δ taken to be 0.5. For a spherical source irradiating a spherical detector, we modify the above factor to

$$\{1 + \delta[(a^2 + b^2)/(2r)^2]\}$$

where b = 15 cm, the radius of the moderated source.

4. Procedures

The first step is to decide on the dose equivalent rates, and hence the distances and sources, to be used for the calibrations. This is done with the help of spreadsheets. The operator enters the source emission rate and the distance into the spreadsheets; the software then calculates the free field dose equivalent rate, the scattering correction, and the other quantities necessary for the calibration. Several of the equations used may also be conveniently programmed on a Hewlett-Packard Series 10 calculator; these programs are listed in Appendix A. The procedures for calibrating passive devices, such as dosimeters, are different from those for calibrating active devices (remmeters). Hence, we shall consider them separately. The best way to do this is to consider the entries in the spreadsheets, item by item.

4.a. Spreadsheet for Dosimeter Irradiation

Figure 2 is the spreadsheet used for albedo dosimeter irradiations. (Digital Equipment Corporation (DEC) Professional 350 computer; C-Calc spreadsheet software.) This irradiation was done on January 30, 1985 and actually consisted of a series of irradiations: 300, 500, and 1000 mrem total dose equivalents with both bare and moderated californium. (After this calibration was completed, the spreadsheet was copied onto a diskette for a permanent record. This spreadsheet is then used as a template for the next dosimeter irradiation. One does not lay out a new spreadsheet for each new calibration.)

DOSIMETER IRRADIATIONS January 30, 1985

Source	Q(n/s)	D(cm)	FFDE	CORRECTION	EFF.FFDE	hrs/mrem
NS-86	5.477e+08	50.8	488.1	4.01 %	507.7	0.001970
NS-39						
Cf-136						
NS-79	2.554e+08	50.8	944.2	6.72 %	1007.7	0.000992
Cf-132						

Source	Dose(mrem)	Time(hr)	Dose	Time(hr)	Dose	Time(hr)
NS-86	300	0.5909	500	0.9849	1000	1.9698
NS-39						
Cf-136						
NS-79	300	0.2977	500	0.4962	1000	0.9924
Cf-132						

Figure 2. Spreadsheet for Dosimeter Irradiations

On this worksheet, the first column gives the identification numbers of the five sources which we are currently using. These identifications are not used in any calculations, but are for the convenience of the operator. The second column in the upper part of the spreadsheet is the source emission rate, in neutrons/second. Since the sources decay at the rate of 0.5% per week, the appropriate emission rate must be entered.

For dosimeter irradiations we usually have little choice in the source-detector distance, D. According to ANSI N13.11[5] , all dosimeters are to be mounted on the front face of a 40 cm x 40 cm x 15 cm thick rectangular lucite phantom, the distance between the center of the front face of the phantom and the center of the source is to be 50 cm, and the distance D is to be measured between the source center and the point on the front face of the phantom directly behind the sensitive element of the dosimeter. For a single dosimeter centered on the phantom, clearly D = 50 cm. In general, however, one irradiates more than one dosimeter at a time (up to ~ six); the dosimeters are then arranged in a circle centered on the phantom face. In this case the circle was 9 cm in radius, hence:

$$D = \mathrm{SQRT}(50^2 + 9^2) = 50.80 \text{ cm.} \qquad (4)$$

The free field dose equivalent rate (FFDE) for NS-86 (a moderated source) is calculated from

$$\mathrm{FFDE}_{\mathrm{mod}} = .0023{*}Q/D^2, \qquad (5)$$

and for NS-79, a bare source,

$$FFDE_{bare} = .00954*Q/D^2, \tag{6}$$

where the numerical factors are the fluence-to-dose equivalent conversion factors discussed in Section 1.

The correction (percent) for the moderated source (NS-86) is

$$CORRECTION(\%)_{mod} = 5.4*(D/100)^2 + 3*D/100 + 2813/D^2, \tag{7}$$

where the first term accounts for room scattering (5.4% per meter-squared), the second term is air scattering (3% per meter), and the third term corrects for the non-$1/r^2$ behavior of the field. D is in cm. The corrections would be of the same form for the other two moderated sources. For the bare source (NS-79),

$$CORRECTION(\%)_{bare} = 1 + 20*(D/100)^2 + 1.1*D/100, \tag{8}$$

where the first term is a 1% correction for non-isotropic emission, the second term is a 20% per meter-squared room scattering correction, and the third term is a 1.1% per meter air scatter correction. The correction for the other bare source (Cf-132) is of the same form except that the non-isotropic emission correction is 3.7%, rather than 1%.

Now, each of the terms in the scattering corrections result in extra neutrons reaching the dosimeter, and therefore they increase its reading over a free field by the amount indicated. But note that this is <u>not</u> the increase in the dose equivalent; the dose equivalent is actually increased only slightly. As explained in Section 3, the correction actually represents the increase in the reading of the dosimeter, whether or not the dosimeter is accurately measuring the dose equivalent. We then calculate an "effective" dose equivalent rate as

$$EFF.FFDE = FFDE*(1 + CORRECTION), \tag{9}$$

and the irradiation time per millirem as

$$hrs/mrem = 1/EFF.FFDE. \tag{10}$$

The desired irradiation dose equivalents are then entered in the "Dose" columns in the lower half of the spreadsheet, and the irradiation times are calculated, simply, as

$$Time(hr) = Dose*hrs/mrem. \tag{11}$$

It was not necessary, in this case, to do the calculations for the other sources, since for the sources selected (the strongest sources) the irradiation times turned out to be convenient. One would only consider using the weaker sources if the desired dose equivalents were so low that the irradiation times became so short that there was a possibility of significant timing errors. As a rule-of-thumb, the minimum desirable irradiation time is taken to be ~ 5 minutes.

4.b. Spreadsheet for Remmeter Irradiation

Remmeter calibrations are quite different from dosimeter calibrations. For one thing, in the latter case one never sees the results. The dosimeters are irradiated and sent back to the owner who takes care of the processing and reading. In addition, the distance is generally fixed (as explained above), and, of course, each dosimeter only gets irradiated once.

For remmeters, we read the remmeter, apply the corrections, and derive a calibration factor. (Ratio of free-field dose equivalent rate to corrected reading) It is necessary to calibrate the remmeter over a wide range of dose equivalent rates, and therefore generally all the sources will be used, at two or three different distances. We use two computers for remmeter calibrations: the Pro 350 for initially setting up the calibrations and for permanent storage of the results, and a portable computer to actually take to the calibration room and calculate the results as the calibration progresses. In that way, one has all the calibration factors and uncertainties calculated a few minutes after the calibration is done. We use the spreadsheet "Lucid" on the Tandy 200 computer. If several instruments are to be calibrated, a separate spreadsheet should be prepared for each instrument by copying the original worksheet, but giving it a name which will identify the particular instrument being calibrated. (If there is not much else stored in the Tandy 200 memory, there is room for about 17 spreadsheets.)

The use of two computers is primarily a matter of convenience: the Pro 350 is physically awkward to move back and forth, and the bulk storage available for the Tandy 200 (magnetic tape cassettes) is not appropriate for archival storage. As an incidental benefit, the use of two independent computers furnishes a valuable safeguard against "computer error".

Figure 3 shows a spreadsheet for the calibration of a 9-inch spherical remmeter with moderated californium on April 23, 1986. This calibration was done in six separate "runs"; the first column just identifies the runs. The second and third columns are the source identification numbers and emission rates, as described above. The fourth column is the distances used, and the fifth column is the calculation of the free field dose equivalent rates, also as described above. To start out, one chooses distances D, either on the basis of guesses or by choosing the ones which were used last time. The spreadsheet then calculates the FFDE rates, and then one iterates on the values of D to get an appropriate range of FFDE rates. In general we do not go below 3 or 4 mrem/hr for the lowest rate, nor choose a D value smaller than 25 or 30 cm to get the highest rate. (Since the instrument is ~ 23 cm in diameter, the deviations from the $1/r^2$ law become large and uncertain at closer distances.) It is not coincidental that each distance is used three times, once for each source. This makes the work a little simpler: by doing the calibrations in the order in which they are listed on the worksheet, we only have two distances to measure. More important, however, is the fact that this furnishes an important internal check. If one gets two different values for the calibration factor for two measurements with different sources at the same distance, one can be quite certain that it's a fault in the instrument rather than a possible error in distance measurement. On the other hand, if one distance triad gives a set of calibration factors significantly different from those obtained at the other distance, than the possibility of an error in the distance measurement should be considered.

PRS-2 S/N 348 Calvert Cliffs Test 237140

run	Source	Q(n/s)	D(cm)	FFDE	D′(cm)	Corr	Read	CRead	CalF
1	136-z	4.959e+06	60	3.17	33.3	4.8	4.38	4.18	0.76
2	NS-39	5.007e+07	60	31.99	33.3	4.8	44.4	42.3	0.76
3	NS-86	3.977e+08	60	254.1	33.3	4.8	344.7	328.8	0.77
4	NS-86	3.977e+08	38	633.5	11.3	4.5	849.6	813	0.78
5	NS-39	5.007e+07	38	79.7	11.3	4.5	110.1	105.4	0.76
6	136-z	4.959e+06	38	7.90	11.3	4.5	10.85	10.4	0.76

ratio = 80.2 Apr. 23, 1986

Stat	cal	Corr	Dist	Sum	Sum+4	FFDE	Cal F
11	1.3	1.0	1.7	11.2	11.9	3.17	0.758
2.2	1.3	1.0	1.7	3.2	5.1	31.99	0.755
0.5	1.3	1.0	1.7	2.4	4.7	254.1	0.773
0.5	1.3	0.9	2.6	3.1	5.1	633.5	0.779
1.5	1.3	0.9	2.6	3.4	5.3	79.7	0.757
6.2	1.3	0.9	2.6	6.9	8.0	7.90	0.761

Figure 3. Spreadsheet for Remmeter Caibration

The quantity D is defined as the source-to-detector center-to-center distance. The quantity D' (= D - 26.7) is the source surface to instrument surface distance, where D and D' are in centimeters, and is the distance which is actually measured.

The correction, Corr, is of the same general form as for the dosimeter calibrations:

$$\mathrm{Corr}(\%) = 7.9*(D/100)^2 + 2.3*D'/100 + 4446/D^2, \qquad (12)$$

where the first term is a 7.9% per meter-squared room scatter correction and the second term is a 2.3% per meter air scatter correction. The last term is the correction for deviation from the $1/r^2$ law. The quantities D and D' are in centimeters. The numerical values for δ (=0.5), a (=11.4 cm), and b (15 cm) discussed in section 3.d. are incorporated in the numerical coefficient of the last term.

The instrument reading is entered into the "Read" column by the operator. If the instrument has an analog readout, the operator mentally averages any fluctuations in the reading to get the value to be entered. He then notes the magnitude of the fluctuations, and estimates the 1σ value of these fluctuations (see p. 14), which is then taken to be the statistical uncertainty. With a digital readout, several readings (typically, 5 to 8) are averaged, using the program "AVERAG" (Appendix B). For the most common digital instrument (Eberline PRS-2) one switch-selects the number of counts to be accumulated, and thus the statistical precision, for the individual readings. AVERAG then computes the weighted mean, and compares the sample-based weighted standard deviation with the standard deviation calculated assuming that the weights approximate the true (reciprocal) variances of the individual readings. See p. B-1 for a more complete discussion of this point.

The corrected reading, CRead, is just

$$\text{CRead} = \text{Read}/(1 + .01*\text{Corr}), \qquad (13)$$

and the calibration factor, CalF, as defined above, is

$$\text{CalF} = \text{FFDE}/\text{CRead}. \qquad (14)$$

The entry marked "ratio = " is the "Q" for NS-86 divided by that for 136-z. The division is performed by the spreadsheet when new values are entered for these quantities. Since this ratio is almost independent of the decay of the sources, the constancy of the ratio from one calibration to the next serves as a check that the correct emission rates have been entered.

The lower half of the worksheet is used solely to calculate the uncertainty in the calibration factor. As indicated earlier, all uncertainties are given as one standard deviation (1σ). The first column, "Stat", is the statistical uncertainty in the instrument reading, as discussed above. The second column, "cal", is the estimated uncertainty in the source calibration. As indicated, this is 1.3%. The next column, "Corr", is the uncertainty in the correction, equal to 20% of the correction itself which is listed on the top half of the worksheet (Section 5.b.). The "Dist" column is the uncertainty in the effective distance due to uncertainty in the location of the effective center of the instrument. This is taken to be 0.5 cm, and the correction is then numerically equal to 100/D, with D in cm (Section 5.c.). "Sum" is the sum in quadrature of the preceding four columns, and is taken to be the total random uncertainty in the calibration factor. The next column, "Sum+4" adds (in quadrature) the 4% systematic uncertainty in the fluence to dose equivalent conversion factor[10] to arrive at the total uncertainty. The last two columns, "FFDE" and "Cal F" are the same as the fifth and tenth columns in the upper part of the worksheet, and are listed for convenience. The uncertainties are discussed in more detail in Section 5.

To sum up the use of this spreadsheet:

Before beginning the actual calibration, one enters the run number, source identification, source emission rate, and uncertainty in the emission rate in the appropriate cells in the spreadsheet. One then determines the distance, D, to be used. At this point the spreadsheet calculates FFDE, D'(cm), and Corr in the upper part of the worksheet, and the uncertainties in the correction and distance in the lower part. As the calibration itself proceeds, one enters the reading ("Read") and the statistical uncertainty ("Stat") in the appropriate cells, and the spreadsheet will calculate the corrected reading ("CRead"), the calibration factor ("CalF"), and the over-all uncertainty in the calibration factor ("Sum" and "Sum+4").

Similar spreadsheets have been prepared for the other types of remmeters which we encounter, for both the bare and moderated sources. The spreadsheets are all of the same general form, but with different numerical values for some of the quantities.

4.c. Performing the Calibration

Again, the procedure for calibrating dosimeters is quite different from that for calibrating remmeters, and so we shall discuss them separately.

4.c.1. Dosimeter Irradiations

In general, dosimeters are mounted on a phantom. While a variety of phantoms are available, the ANSI phantom[5] mentioned in section 3.a. is to be used unless there is a specific reason not to do so. Since it weighs ~ 28 kg, carrying the phantom up a ladder and positioning it on the stand is not a trivial procedure. This, however, is not considered an adequate reason for not using it. Two lab jacks are placed on top of the calibration stand, the phantom is placed on the jacks, and the jacks are used to adjust the height of the phantom so that its center is on a horizontal line with the center of the source.

To simplify the mounting of the dosimeters, 40 cm x 40 cm x 1/4" thick lucite sheets are available. The dosimeters are mounted on a lucite sheet, and the sheet then taped to the front face of the phantom. This is much easier than standing on the ladder and trying to mount the dosimeters directly on the phantom. The dosimeters are generally held in place with double-backed foam tape. To avoid possible neutron scattering from one dosimeter to another, one should not irradiate too many dosimeters at once; the rule-of-thumb limit is ~ 6. The sensitive element of the dosimeter should not be closer than 10 cm from the edge of the phantom[20], and the dosimeters should be arranged on the periphery of a circle of some convenient radius so that they are all at the same distance from the center of the source. The stand is then moved so that the front surface of the lucite sheet (which is now considered to be the front face of the phantom) is 50 cm from the source center.

It is now just a matter of removing the shield plug from the hole containing the proper source, attaching the beaded chain to the source, pulling the source up out of the hole, and starting the stopwatch. At the end of the irradiation time, the source is lowered back into the hole, the hole covered with the shield, and the dosimeters taken down.

4.c.2. Remmeter Calibrations

The remmeter is placed on a lab jack on the calibration stand and adjusted so that the remmeter and source centers are at the same height. The instrument package is positioned so that it can be read by the television camera attached to the stand.

Any necessary range switching is done at this time. The Eberline PNR-4, the most common type of remmeter, effectively has automatic range switching, so this step is not necessary. The Eberline PRS-2, the next most common instrument, is digital and does not require range switching. It does, however, have a switch to select the number of counts it will accumulate, and hence the statistical accuracy, for each update of the reading. The count range switch has four positions, corresponding to 10, 100, 1000, and 10000 counts. The lowest (10 counts) position is too few counts to be of any use. Since the instrument's intrinsic count rate is approximately 50 counts/minute per millirem/hr, when reading 4 mrem/hr the instrument will require 30 seconds to reach 100 counts, and that is the position which is used at the lowest dose equivalent rates. On the other hand, at 2 rem/hr it only takes 6 seconds to accumulate 10,000 counts, so, clearly, that is the position to use at the highest dose equivalent rates. Somewhat arbitrarily, we use the 100 range for the two lowest dose equivalent rates, the 1000 scale for the two intermediate rates, and the 10,000 scale for the two highest rates. No attempt is made to maintain a constant statistical precision at all dose equivalent rates, but a minimum of 4 readings is taken at each point.

Most of the other instruments (e.g., "Snoopy", Ludlum Remmeter) do require conventional range switching.

Once the instrument is set up, the television camera is focused and adjusted. Then the plug is removed from the hole, the desired source attached to the chain, the source raised into position, and the instrument reading observed on the television monitor and written down in the notebook. The rest of the calibration data are taken by lowering the source, changing either the source or the distance or both, making any necessary changes in the instrument range switch, and continuing.

At convenient intervals during the course of the calibration (or perhaps at the end) the readings and statistical uncertainties are entered in to the spreadsheet and the results noted. If there are significant differences in the calibration factors at different dose equivalent rates, the operator should carefully examine the data to see whether the instrument is faulty (an all too common occurrence)[11] or whether there is a possibility that an error was made in the calibration itself. It may be necessary to repeat one or two points. In any case, the operator should satisfy himself that the calibration was done properly before taking the instrument down.

The final report for the instrument calibrated using the spreadsheet in Figure 3 is given in Appendix C. There were actually three instruments calibrated at this time, as is clear from the report. The spreadsheet in Figure 3 is for just one of them.

5. Uncertainties

It must be emphasized that our systematic approach to the corrections for neutron scattering and "geometry" effects is a relatively new development, and is still a subject for research, both here and at our sister laboratories in the U.K. (NPL) and in Germany (PTB). Thus, while some of the components of the overall uncertainty are well established and easily defended, other uncertainty components are (at least for the time being) estimates based on a few specific measurements, and our general experience. With this in mind, we can discuss the error components illustrated on the bottom portion of the spreadsheet in Figure 3. The numerical values given in the columns marked

"Stat", "cal", "Corr", "Dist", "Sum", and "Sum+4" in the bottom part of Figure **3** are the uncertainties expressed as percentages. Again, all uncertainties are given as one standard deviation (1σ).

5.a. Statistical Uncertainty ("Stat")

This is discussed in section 4.b., "Spreadsheet for Remmeter Irradiation", and in Appendix B. To summarize, for an instrument with digital output, several readings are taken, and using the code "AVERAG", the weighted mean, the standard deviation of the mean computed from the weights (i.e., the counting statistics), and the sample-based standard deviation of the mean are calculated. Whichever of the two standard deviations thus calculated is the larger is taken as the statistical uncertainty. For instruments with an analog output, the fluctuations in the meter reading are noted and an estimate is then made of the standard deviation. This is done by estimating the magnitude of the "swing" of the needle which encompasses most (i.e., 95%) of the readings, and assigning that a value of 2σ. This value is then just divided by 2, and converted to a percent of the average reading. The uncertainty is thus objectively correct for digital instruments, and, necessarily, rather subjective in the case of instruments with only an analog reading. The statistical uncertainty is usually the dominant uncertainty at the lowest dose equivalent rates, and negligible at higher rates.

There is considered to be nothing analogous to a statistical uncertainty when irradiating dosimeters.

5.b. Uncertainty Due to Source Calibration ("cal")

The calibration of neutron sources has a long and well documented history at NBS[7], and the uncertainty in the source calibration has been carefully investigated and is well understood. It is usually ~ 1.3%, as it is in this case.

5.c. Uncertainty Due to Corrections ("Corr")

The general form of the correction factor is the same for all instruments, but the numerical coefficients will differ from one instrument type to another, and between the bare and moderated sources. We assume that the numerical values will be the same for all instruments of the same type, for the same source. An uncertainty of 20% of the value of the correction itself is assumed. Note that the column marked "Corr" in the upper part of the spreadsheet is the value of the correction factor in percent. In an unfortunate choice of notation, the uncertainty in the correction is also labelled "Corr", in the lower part of the spreadsheet. The latter is 20% of the former. This is based on the estimated uncertainty in our determinations of the room return correction (Section 3), and to allow for the fact that the manufacturer sometimes makes changes in the construction of the instrument without telling anyone (and, at times, without being aware of it himself). Thus, supposedly identical instruments are not necessarily identical, and hence the corrections may not always be exactly right. The 20% is an estimate, based on our general experience. It is probably somewhat conservative.

5.d. Uncertainty in Distance Determination ("Dist")

This is not an uncertainty in the measurement of the distance; it is rather an uncertainty due to our lack of knowledge of the location of the effective center of the instrument. It has been shown by J. B. Hunt[18] that for a spherically symmetric instrument, the effective point of measurement can be taken as the instrument's geometric center. Unfortunately, none of the instruments in common use in the United States is spherically symmetric. While the most common types do have spherical moderators, the detector itself is a cylindrical proportional counter 1.3 cm in diameter by 2.5 cm long. Based on our general experience, we assume that this introduces a 0.5 cm uncertainty in the effective source-detector distance. This means a percentage uncertainty in D of 0.5/D, where D is expressed in meters. Since the fluence varies as $1/D^2$, the percent uncertainty in the fluence, and hence the dose equivalent, is twice the percent uncertainty in the distance, or just 1/D, with D in meters. This is quite important at the smallest distances.

As indicated above, when irradiating dosimeters, by convention the effective point of measurement is taken to be the point on the phantom face directly behind the dosimeter, and, by convention, there is then no uncertainty in D.

5.e. Uncertainty in Fluence-to-Dose Equivalent Conversion

The energy-dependent fluence-to-dose equivalent conversion factors given in ICRP Publication 21[8] are taken as "given", in that these are internationally agreed-upon factors with no uncertainties in any utilizable form being cited. Therefore uncertainties in the conversion factors are assumed to be solely due to uncertainties in the energy spectra of the neutron fields. For bare ^{252}Cf, the uncertainty is negligibly small since the spectrum is well known in the energy region responsible for most of the dose equivalent[21].

There is only one published calculation of the moderated californium spectrum[9] and we use a conversion factor derived from weighting the Ing and Cross spectrum with the ICRP 21 data. The conversion factor thus obtained was verified experimentally at NBS[10]; the measured value agreed with the calculated value within 2%, with an estimated uncertainty of ±4%. We therefore assume a value of 4% for the estimated uncertainty in the conversion factor for moderated californium.

For each run, the uncertainties listed in the first four columns of the lower part of the spreadsheet are added in quadrature to obtain the total random uncertainty, and given in the column marked "Sum". To this is added (again in quadrature) the estimated 4% uncertainty in the conversion factor, to obtain the total uncertainty ("Sum+4").

6. Internal Quality Control

As indicated above, there are no "standard" instruments in this field. In fact, there are no instruments other than the field instruments of the type which we calibrate. We have therefore purchased one of these instruments and carefully calibrated it with both the bare and moderated sources. Since this instrument has an adjustable, digital, calibration multiplier, we can easily set the instrument so that its calibration factor is unity for whichever source we are using. We then "calibrate" this instrument along with other remmeters. If the calibration factor stays at unity, we can be confident that we have not made any mistakes.

It must be said, however, that the most important form of internal quality control is just watching the results carefully as they come in. This is particularly true in the case of instruments with a digital readout. As indicated in the "Procedures" section, at a given calibration point several readings are taken, and averaged using the program "AVERAG". This program computes the weighted mean, the sample-based weighted standard deviation of the mean, and the standard deviation of the mean computed from the assigned weights. (See Appendix B). If the former uncertainty is significantly greater than the latter, it is a signal that something may be wrong; e. g., a number read incorrectly or entered into the computer incorrectly, an initial transient when the instrument was turned on, a warm-up problem, etc. In any case, some judgment is required.

Our experience indicates that for most instrument types, calibration factors are usually reasonably constant for a given instrument, within the uncertainties, over the range of dose equivalent rates which we use. (The calibration factor is, however, by no means necessarily equal to unity, nor is it necessarily the same from instrument to instrument.)[11] As indicated in the "Procedures" section, an outlier should be looked at carefully; two outliers, if associated with a particular distance or a particular source, should be looked at very carefully.

Finally, we generally calibrate several instruments of the same type during a calibration session, using the same set-up for each. We then carefully compare results among the instruments to look for correlations among any outliers which might suggest a systematic error in some part of the calibration.

Unfortunately, none of these quality control measures are applicable to a passive device such as a dosimeter. It should be clear that these calibrations are much easier to do than remmeter calibrations, and one just has to be careful to get it right the first time.

7. Safety

We are concerned with the safety of the operator and of other personnel who may be in the vicinity of the calibration facility. The safety of the latter group is assured by simply keeping them out of the calibration area. There is only one entrance to the calibration area (there are two exits, but one can only be opened from the inside) and the operator does the calibrations from a position just inside the doorway. The operator thus acts as a guard to keep people out. For long irradiations, if the operator is not present, the door is locked and only the operator and Health Physics have keys. As additional warnings, the door to the Van de Graaff control room is closed (but not locked), and has a sign posted noting that a calibration is in progress. Additionally, an illuminated warning sign (controlled by a Geiger counter) at the entrance to the facility is automatically turned on whenever a californium source is taken out of its hole.

The operator himself must wear a neutron dosimeter issued by Health Physics, and should have a remmeter with him at all times.

8. Acknowledgement

I should like to thank Charles Eisenhauer for his close collaboration and expert guidance in making this calibration service a reality.

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Appendix A. Pocket Calculator Programs

The listings on the following page are programs for Hewlett-Packard Series 10 calculators.

The first listing, "DOSE EQUIVALENT RATE", is used for solving equations (5) and (6), knowing the source emission rate, Q, and either the free field dose equivalent rate, FFDE, or the distance, D. To use this program, the californium source emission rate, in neutrons/sec, is keyed in and stored in register 1 (STO 1). If the distance is known, it is keyed in and LBL B (f B) will calculate the dose equivalent rate for the bare source; LBL D (f D) will calculate it for the D_2O-Moderated source. If the desired dose equivalent rate is known, it may be keyed in and LBL A will give the required distance from the bare source; LBL C will give the distance from the moderated source. All distances are in cm and dose equivalent rates are in millirem/hour.

The second listing, "CORRECTION (%)", calculates the distance-dependent correction for nine-inch (or ten-inch) spherical remmeters, for either the bare or moderated sources. Steps 37-42 compute the room scatter, 43-49 compute the air scatter, and 51-59 compute the non-$1/r^2$ effect. To use, first either set flag 0 (g SF 0) if it is the moderated source, or clear flag 0 (g CF 0) if it is the bare source. Then key in the distance in <u>meters</u>, and LBL E (f E) will compute the correction in per cent. For bare irradiations using sources with "Cf" identification numbers, 3% must be added as a correction for anisotropic neutron emission (compare equation (12)). The anisotropy correction is ~ 0 for other remmeter irradiations. The total correction will be the same (except for rounding errors) as the quantity "Corr" discussed on p. 9, and as used in equation (13).

The labels and subroutine identifications are chosen so that the programs do not interfere with each other, and hence may be in the calculator at the same time. These two programs occupy 13 program registers.

DOSE EQUIVALENT RATE

Keystrokes	Display
f LBL A	001- 42,21,11
4	002- 4
.	003- 48
1	004- 1
4	005- 4
4	006- 4
-	007- 10
f LBL C	008- 42,21,13
GSB 1	009- 32 1
x	010- 11
g RTN	011- 43 32
f LBL B	012- 42,21,12
2	013- 2
.	014- 48
0	015- 0
3	016- 3
6	017- 6
-	018- 10
f LBL D	019- 42,21,14
g x	020- 43 11
GSB 1	021- 32 1
g RTN	022- 43 32
f LBL 1	023- 42,21,1
1/x	024- 15
2	025- 2
.	026- 48
3	027- 3
EEX	028- 26
CHS	029- 16
3	030- 3
X	031- 20
RCL 1	032- 45 1
X	033- 20
g RTN	034- 43 32

CORRECTION (%)

Keystrokes	Display
f LBL E	035- 42,21,15
STO 0	036- 44 0
g x	037- 43 11
g F? 0	038- 43,6,0
GSB 7	039- 32 7
6	040- 6
X	041- 20
STO 2	042- 44 2
RCL 0	043- 45 0
g F? 0	044- 43,6,0
GSB 6	045- 32 6
.	046- 48
1	047- 1
1	048- 1
-	049- 30
STO + 2	050- 44,40,2
RCL 0	051- 45 0
g x	052- 43 11
1/x	053- 15
g F? 0	054- 43,6,0
GSB 5	055- 32 5
.	056- 48
1	057- 1
6	058- 6
X	059- 20
STO + 2	060- 44,40,2
RCL 2	061- 45 2
g RTN	062- 43 32
f LBL 5	063- 42,21,5
2	064- 2
.	065- 48
8	066- 8
X	067- 20
g RTN	068- 43 32
f LBL 7	069- 42,21,7
1	070- 1
.	071- 48
3	072- 3
X	073- 20
g RTN	074- 43 32
f LBL 6	075- 42,21,6
.	076- 48
2	077- 2
2	078- 2
-	079- 30
2	080- 2
.	081- 48
3	082- 3
X	083- 20
g RTN	084- 43 32

Appendix B. Averaging Program

The listing on the next page is for the program "AVERAG" on the Tandy 200. The user is first prompted for the number of input data points (line 20) and then for the manner in which the uncertainties are expressed (lines 30-70). The program then goes to the appropriate subroutine, prompts for the input data, and, after the last datum is entered, calculates the weighted mean, the standard deviation of the mean computed from the weights, and the sample-based standard deviation. These three quantities are listed on the computer display screen, and whichever of the two uncertainties is the larger is converted to a percent uncertainty, and also listed. (The peculiar symbols in lines 162-240 put a frame around the output listing on the Tandy 200 display.) The quantities are calculated from the following formulas:

$$\text{Weighted Mean} = \Sigma(x_i \cdot w_i)/\Sigma w_i,$$

$$\text{stdev of the mean computed from weights} = 1/\sqrt{(\Sigma w_i)}, \qquad \text{(B-1)}$$

$$\text{sample-based weighted stdev of the mean} = \sqrt{\Sigma w_i(x_i-\bar{x})^2/(N-1)\Sigma w_i}, \qquad \text{(B-2)}$$

where x_i are the individual input data,

w_i are the weights corresponding to each x_i,

$w_i = 1/(E_i)^2$, where the E_i are the uncertainties in the input data,

$\bar{x}$ is the weighted mean, and

N is the number of data points.

B-1 and B-2 are both correct formulae for computing the standard deviation (stdev) of the mean, independent of any assumed statistical distribution. In the application discussed in the text, we make the usual assumption of the Poisonness of the counting data in order to assign the uncertainties; i. e., the E_i's are assumed to be the square root of the number of counts, but this is the only assumption which is made regarding the statistical distribution of the data.

Formula B-2 is the more "robust" of the two formulae, in that it will give a reasonable estimate of the stdev even if the weights are not quite correctly chosen. If the weights are properly chosen, B-1 is mathematically equivalent to B-2 and will give the same answer. By "properly chosen" we mean that the w_i are actually equal to the (reciprocal of the) true data point variances. In our case, if the counting statistics are the only source of uncertainty within a given data set, then the weights will be properly chosen and B-1 and B-2 will give the same answer. This is observed to be the case for most of our data. If B-2 and B-1 give different results, this is taken to be a "flag", signalling that something else may be causing fluctuations in the data, as discussed in the text.

```
1 REM - "AVERAG.BA"
10 CLEAR:CLS
20 INPUT "How many data points are there";N
25 DIM G(N-1,1)
30 PRINT "Are the uncertainties given as:"
35 PRINT
40 PRINT TAB(2);"1. Absolute standard deviations?"
50 PRINT TAB(2);"2. % S.D.; same value for all points?"
60 PRINT TAB(2);"3. % S.D., and not all the same?"
65 PRINT
70 PRINT TAB(5);"ENTER 1,2 or 3";TAB(20)
75 INPUT C
77 PRINT
80 ON C GOSUB 300, 500, 700
90 WA!=WTDT/SUMW
100 U!=SUMW^-.5
110 FOR A=0 TO N-1
120   SCATR=SCATR+G(A,1)*(G(A,0)-WA!)^2
130 NEXT A
140 SPRD!=SQR(SCATR/((N-1)*SUMW))
150 PCT!=U!*100/WA!
160 IF SPRD!>U! THEN PCT!=SPRD!*100/WA!
162 CLS:PRINT "▛";
163 FOR N=1 TO 38
164   PRINT TAB(N);"▀";
165 NEXT N
166 PRINT TAB(39);"▜";
170 PRINT "▌";TAB(2);"Weighted Mean =";WA!;"±
";PCT!;"%";TAB(39);" ▌";
175 PRINT "▌";TAB(39)" ▌";
180 PRINT "▌";"Stat. Std. Dev. of Mean=±
";U!;TAB(39);" ▌";
190 PRINT "▌";"S.D. from Data Spread =±
";SPRD!;TAB(39);" ▌";
200 PRINT "▙";
210 FOR A=1 TO 38
220   PRINT TAB(A);"▄";
230 NEXT A
240 PRINT TAB(39);"▟";
250 END
300 FOR A=0 TO N-1
310   PRINT "No.";A+1;TAB(6)
320   INPUT "Datum,uncert.";D,E
330   G(A,0)=D:G(A,1)=E^-2
350   WTDT=WTDT+ D*G(A,1)
360   SUMW=SUMW+G(A,1)
370 NEXT A
380 RETURN
500 INPUT"ENTER per-cent uncertainty";P
510 FOR A=0 TO N-1
520   PRINT "No.";A+1;TAB(6)
530   INPUT "Datum";D
540   G(A,0)=D:G(A,1)=(.01*P*D)^-2
560   WTDT=WTDT + D*G(A,1)
570   SUMW = SUMW + G(A,1)
580 NEXT A
```

```
590 RETURN
700 FOR A=0 TO N-1
710   PRINT "NO.";A+1;TAB(6)
720   INPUT "Datum,% Uncertainty";D,P
730   G(A,0)=D: G(A,1)=(.01*P*D)^-2
750   WTDT=WTDT + D*G(A,1)
760   SUMW=SUMW + G(A,1)
770 NEXT A
780 RETURN
```

Appendix C. Sample Test Reports

Pages C-2 - C-4 are a typical remmeter test report, generated from the data shown in the spreadsheet of Figure 3. This is followed on pages C-5 and C-6 by a test report for dosimeter irradiations. The reports should be self-explanatory.

FORM NBS—259
(REV. 6-68)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND 20899

REPORT OF TEST

NBS Test No.

Instruments Submitted by: Nuclear Power Station

Dates of Irradiation: April 24, 1986

Neutron Sources:

Californium-252 spontaneous fission source NS-79 (neutron emission rate of 1.86×10^8 n/s ± 1.6%) and SR-Cf-132 (emission rate of 3.91×10^6 n/s ± 1.3%.

Type of Instruments: Eberline PRS-2 Remmeters

Quantity: 3

Serial Numbers: 348, 355, 377

The instruments were alternately mounted on a stand and measurements were made at various distances from one or the other of the two sources to obtain different dose equivalent rates. Table I lists the source and distance combinations used, together with the instrument readings for each source-distance combination.

The second column in Tables II lists the "Free Field Dose Equivalent" (FFDE) Rates corresponding to the source-distance combinations of Table I. The FFDE Rate is the dose equivalent rate due to neutrons from the source alone, in the absence of background caused by neutrons scattered into the instrument from the walls, the air in the room, and the source support. The FFDE rate, in mrem/hr, is calculated using the formula:

$$\text{FFDE Rate} = 9.54 \times 10^{-3}\, Q/r^2$$

where Q is the source emission rate (n/s), and r(cm) is the distance listed in Table I (R.B. Schwartz and C. M. Eisenhauer, NBS Special Publication 633 (May 1982)).

The next columns in Table II, "Corrected Instrument Readings" are the remmeter readings from Table I, corrected for the neutron background mentioned above. (At the smallest distance, there is also a small correction for the deviation from the inverse square law due to the finite size of the source and detector.) For most of the data the corrections are small (~5%), as can be seen by comparing the observed readings from Table I with the corrected readings in Table II. At the largest distance, however, the relatively large background of room scattered neutrons leads to ~10% corrections.

The FFDE, divided by the corrected reading, gives the calibration factor listed in Table III. The calibration factor is thus the factor by which the instrument reading should be multiplied to get the true dose equivalent.

All three instruments showed a random, fluctuating, reading in the absence of any neutrons. This "background" reading varied between 0 and 0.6 mrem/hr. For the purpose of analyzing the data, a "background" of 0.3 ± 0.25 mrem/hr was substracted from all readings. These extraneous counts do not have any appreciable effect on the calibrations at the higher dose equivalent rates, but they do increase the uncertainty in the calibration factor at the lowest rates.

The estimated uncertainties (1σ) in the calibration factors also include the uncertainty in the source calibration, statistical fluctuations in the instrument reading, and the uncertainty of the location of the effective center of the detector and uncertainty in the scatter and source anisotropy corrections. Uncertainty in the flux density to dose equivalent rate conversion is not included.

It should be understood that the uncertainty figures are current estimates based on the judgement of the NBS staff and are not necessarily supported by a long term data base.

Measurements associated with this calibration were performed by:

R. B. Schwartz, Physicist

For the Director,

R. S. Caswell

R. S. Caswell, Chief
Ionizing Radiation Division

Test No.:
SP250 No. 8.1J

Date: May 7, 1986

NBS Test No.

TABLE I - Experimental Data

Source No.	Distance (r) (center-to-center), cm	Instrument Readings, mrem/h Ser. #348	Ser. #355	Ser. #377
SR-Cf-132	99	4.18	3.67	4.6
SR-Cf-132	50	14.9	14.35	16.7
SR-Cf-132	25.4	56.3	56.7	65.8
NS-79	99	175.5	184	201
NS-79	50	636	686	733
NS-79	25.4	2428	2558	2869

TABLE II - Results

Free-Field Dose Equivalent Rate, mrem/h	Corrected Instrument Readings, mrem/h Ser. #348	Ser. #355	Ser. #377
3.80	3.80	3.34	4.18
14.9	14.1	13.6	15.8
57.7	53.1	53.5	62.1
180.7	164.1	172.1	187.5
708	621	669	715
2745	2357	2483	2785

TABLE III - Calibration Factor and Estimated Uncertainty

Free-Field Dose Equivalent Rate, mrem/h	Instrument Calibration Factor Ser. #348	Ser. #355	Ser. #377	Estimate Uncertai %
3.80	1.00	1.14	0.91	13
14.9	1.06	1.10	0.94	7
57.7	1.09	1.08	0.93	5
180.7	1.10	1.05	.96	3
708	1.14	1.06	.99	3
2745	1.17	1.11	.99	4
Mean	1.11	1.07	0.97	2

Instrument High Voltage: #348-2052 v
#355-2041 v
#377-1953 v

Temperature of Calibration Room: 19°C

Relative Humidity: 43%

FORM NBS-259
(REV. 6-85)

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
GAITHERSBURG, MARYLAND 20899

REPORT OF TEST

NBS Test No.

Dosimeters Submitted by:

Date of Irradiation: January 2, 1985

Dose Equivalent Delivered: 750 mrem

Certified Source Strength:
Californium-252 spontaneous fission source NS-86
Emission Rate 5.62×10^8 n/s ± 1.3%

The californium source was moderated in the NBS 30-cm diameter heavy water sphere.

Type of Dosimeters: Eberline Albedo Dosmeters

Quantity: 15, plus 4 controls

The dosimeters were irradiated in three groups of five each, as follows:

Group 1: 0002 0301, 0302, 0303, 0305, 0306.
Group 2: 0002 0307, 0308, 0309, 0310, 0311.
Group 3: 0002 0312, 0313, 0314, 0315, 0316.
Controls: 0002 0300, 0304, 0317.

For each group, the dosimeters were mounted equally spaced on a 14 cm diam circle centered on the front face of a 40 cm x 40 cm x 15 cm thick lucite phantom. The distance from the center of the source to the center of the front face of the phantom was set at 50 cm. All the dosimeters were mounted with the typed identification numbers facing the source.

The free field dose equivalent rate is given by the formula

$$\text{D.E. Rate} = 2.30 \times 10^{-3}\, xQ/r^2,$$

where the dose equivalent rate is in millirem/hr, Q is the source emission rate in neutrons/sec, and r is the source-to-phantom distance (50 cm). In this case, the free field dose equivalent rate at the center of the phantom is 517 mrem/hr. Since, however, the dosimeters are 7 cm away from the center, the dose equivalent rate at the dosimeter position is 2% lower. On the other hand, we estimate that the air and room scattered neutrons will increase the dosimeter response by approximately 4%. Thus, the "effective" dose equivalent rate is 530 mrem/hr, giving an irradiation time of 1 hr 25 min for the 750 mrem irradiation.

The estimated uncertainty in the delivered dose equivalent is ±5% (one standard deviation), due largely to the uncertainty in the fluence to dose equivalent conversion factor.

Note that dosimeter 0002 0304 fell open during handling, and its reading may therefore be suspect.

This irradiation was performed by

R. B. Schwartz, physicist

For the Director,

R. S. Caswell, Chief
Nuclear Radiation Division

Test No.:

January 3, 1985

Appendix D. Graphic and Tabular Representation of the Neutron Spectra

The spectra are represented as plots of $\Delta B_0/\Delta \ln(E/E_0)$ (linear scale) versus neutron energy E (logarithmic scale) with ΔB_0 (group source strength) normalized to a total source strength Q = 1 neutron/sec and E_0 taken as 1 MeV.

In the tabulations, the energy associated with a value of $\Delta B_0/\ln(E/E_0)$ corresponds to the upper limit of the particular interval. This energy also serves as the lower boundary of the next higher energy interval, and so on.

The data are taken from reference 6.

Table 3 – Values of group source strength per logarithmic energy interval for a ^{252}Cf spontaneous fission source

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}
$4,14 \times 10^{-7}$	
0,01	$4,40 \times 10^{-5}$
0,05	$2,74 \times 10^{-3}$
0,10	$1,24 \times 10^{-2}$
0,20	$3,33 \times 10^{-2}$
0,25	$6,04 \times 10^{-2}$
0,30	$7,90 \times 10^{-2}$
0,40	$1,07 \times 10^{-1}$
0,50	$1,46 \times 10^{-1}$
0,60	$1,84 \times 10^{-1}$
0,70	$2,21 \times 10^{-1}$
0,80	$2,55 \times 10^{-1}$
1,00	$3,01 \times 10^{-1}$
1,20	$3,53 \times 10^{-1}$
1,40	$3,95 \times 10^{-1}$
1,50	$4,19 \times 10^{-1}$
1,60	$4,32 \times 10^{-1}$
1,80	$4,46 \times 10^{-1}$
2,00	$4,58 \times 10^{-1}$
2,20	$4,62 \times 10^{-1}$
2,30	$4,61 \times 10^{-1}$
2,40	$4,59 \times 10^{-1}$
2,60	$4,53 \times 10^{-1}$
2,80	$4,42 \times 10^{-1}$
3,00	$4,27 \times 10^{-1}$
3,40	$4,01 \times 10^{-1}$
3,70	$3,66 \times 10^{-1}$
4,20	$3,25 \times 10^{-1}$
4,60	$2,78 \times 10^{-1}$
5,00	$2,39 \times 10^{-1}$
5,50	$1,99 \times 10^{-1}$
6,00	$1,61 \times 10^{-1}$
6,50	$1,28 \times 10^{-1}$
7,00	$1,01 \times 10^{-1}$
7,50	$7,92 \times 10^{-2}$
8,00	$6,16 \times 10^{-2}$
8,50	$4,76 \times 10^{-2}$
9,00	$3,65 \times 10^{-2}$
9,50	$2,79 \times 10^{-2}$
10,00	$2,13 \times 10^{-2}$
11,00	$1,42 \times 10^{-2}$
12,00	$8,04 \times 10^{-3}$
13,00	$4,51 \times 10^{-3}$
14,00	$2,50 \times 10^{-3}$
16,00	$1,08 \times 10^{-3}$
18,00	$3,20 \times 10^{-4}$

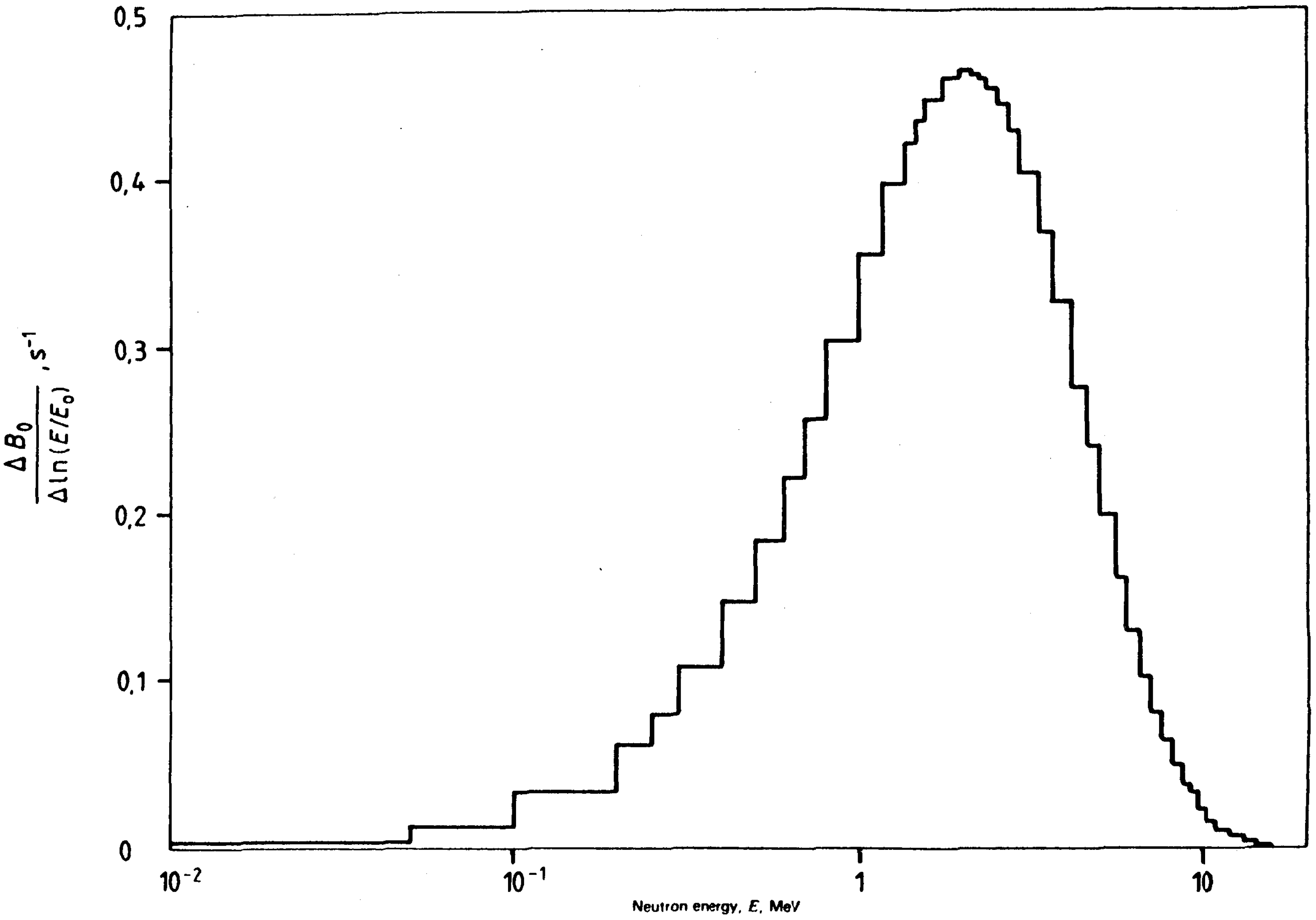

Figure 4 - Neutron spectrum from a ^{252}Cf spontaneous fission source

Table 4 - Values of a group source strength per logarithmic energy interval for a ^{252}Cf spontaneous fission source in the centre of a D_2O sphere with a radius of 150 mm

Neutron energy, E	$\frac{\Delta B_0}{\Delta \ln(E/E_0)}$
MeV	s^{-1}
$4{,}14 \times 10^{-7}$	
$1{,}0 \times 10^{-6}$	$2{,}15 \times 10^{-2}$
$1{,}0 \times 10^{-5}$	$2{,}74 \times 10^{-2}$
$5{,}0 \times 10^{-5}$	$3{,}75 \times 10^{-2}$
$1{,}0 \times 10^{-4}$	$4{,}57 \times 10^{-2}$
$2{,}0 \times 10^{-4}$	$4{,}92 \times 10^{-2}$
$4{,}0 \times 10^{-4}$	$5{,}51 \times 10^{-2}$
$7{,}0 \times 10^{-4}$	$5{,}86 \times 10^{-2}$
$1{,}0 \times 10^{-3}$	$6{,}29 \times 10^{-2}$
$3{,}0 \times 10^{-3}$	$6{,}88 \times 10^{-2}$
$6{,}0 \times 10^{-3}$	$7{,}34 \times 10^{-2}$
$1{,}0 \times 10^{-2}$	$7{,}42 \times 10^{-2}$
$2{,}0 \times 10^{-2}$	$7{,}89 \times 10^{-2}$
$4{,}0 \times 10^{-2}$	$7{,}38 \times 10^{-2}$
$6{,}0 \times 10^{-2}$	$7{,}30 \times 10^{-2}$
$8{,}0 \times 10^{-2}$	$6{,}95 \times 10^{-2}$
$1{,}0 \times 10^{-1}$	$6{,}52 \times 10^{-2}$
$1{,}5 \times 10^{-1}$	$6{,}10 \times 10^{-2}$
$2{,}0 \times 10^{-1}$	$5{,}54 \times 10^{-2}$
$2{,}5 \times 10^{-1}$	$5{,}12 \times 10^{-2}$
$3{,}0 \times 10^{-1}$	$4{,}88 \times 10^{-2}$
$3{,}5 \times 10^{-1}$	$4{,}26 \times 10^{-2}$
$4{,}0 \times 10^{-1}$	$3{,}66 \times 10^{-2}$
$4{,}5 \times 10^{-1}$	$2{,}25 \times 10^{-2}$
$5{,}0 \times 10^{-1}$	$2{,}98 \times 10^{-2}$
$5{,}5 \times 10^{-1}$	$4{,}41 \times 10^{-2}$
$6{,}0 \times 10^{-1}$	$4{,}73 \times 10^{-2}$
$7{,}0 \times 10^{-1}$	$5{,}08 \times 10^{-2}$
$8{,}0 \times 10^{-1}$	$5{,}08 \times 10^{-2}$
$9{,}0 \times 10^{-1}$	$4{,}88 \times 10^{-2}$
1,0	$3{,}39 \times 10^{-2}$
1,2	$4{,}10 \times 10^{-2}$
1,4	$5{,}47 \times 10^{-2}$
1,6	$6{,}84 \times 10^{-2}$
1,8	$7{,}26 \times 10^{-2}$
2,0	$7{,}66 \times 10^{-2}$
2,3	$9{,}57 \times 10^{-2}$
2,6	$1{,}18 \times 10^{-1}$
3,0	$1{,}04 \times 10^{-1}$
3,5	$8{,}01 \times 10^{-2}$
4,0	$6{,}13 \times 10^{-2}$
4,5	$6{,}88 \times 10^{-2}$
5,0	$6{,}21 \times 10^{-2}$
6,0	$4{,}77 \times 10^{-2}$
7,0	$3{,}20 \times 10^{-2}$
8,0	$1{,}81 \times 10^{-2}$
9,0	$1{,}10 \times 10^{-2}$
10,0	$7{,}27 \times 10^{-3}$
11,0	$4{,}65 \times 10^{-3}$
12,0	$1{,}86 \times 10^{-3}$
13,0	$1{,}55 \times 10^{-3}$
14,0	$8{,}00 \times 10^{-4}$
15,0	$4{,}10 \times 10^{-4}$

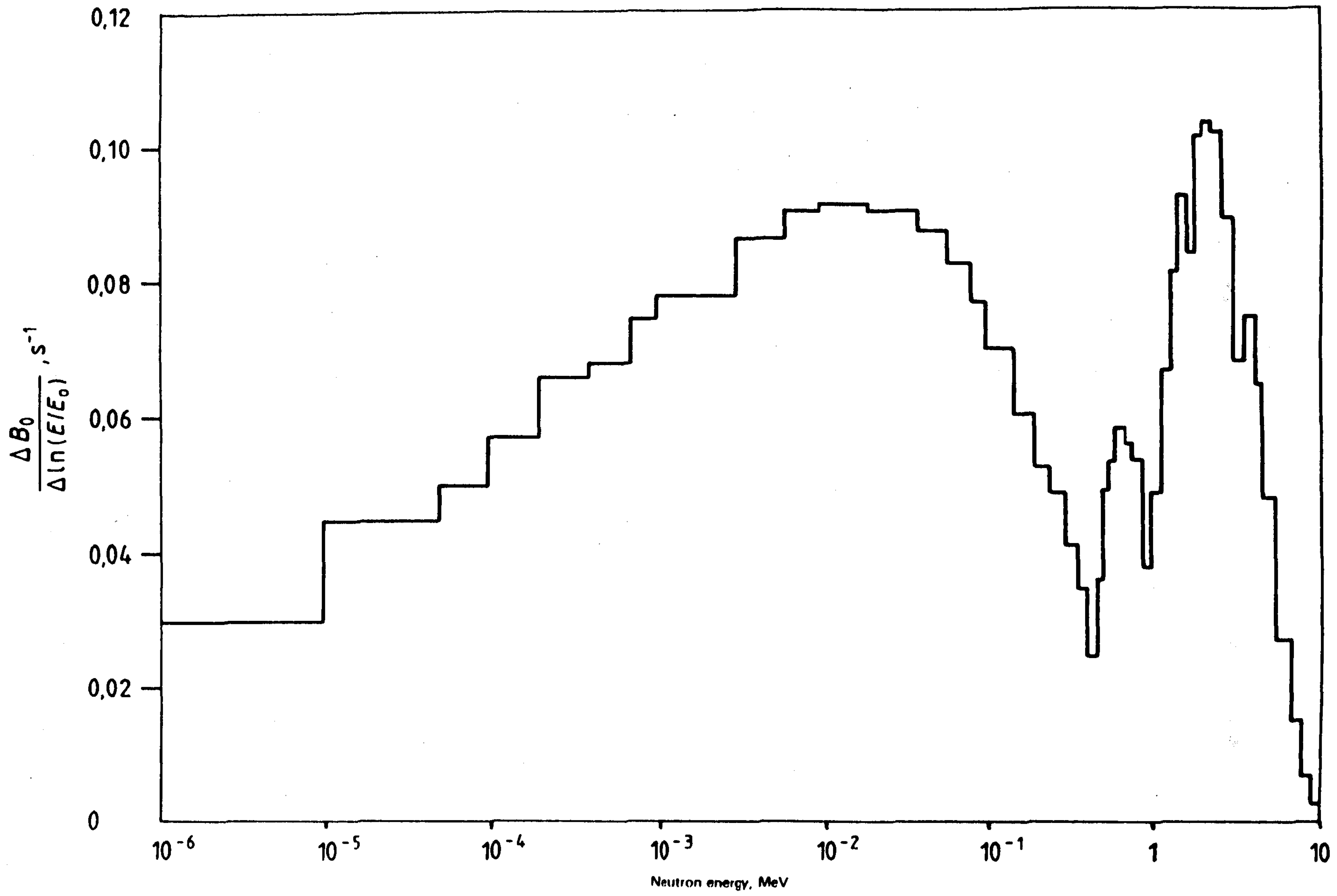

Figure 5 - Neutron spectrum from a ^{252}Cf spontaneous fission source in the centre of a D_2O sphere with a radius of 150 mm

Appendix E. Definitions

Taken from: NCRP Report No. 51, "Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities". National Council on Radiation Protection and Measurements, Washington, D. C. (March, 1977).

absorbed dose (D): The quotient of dE by dm, where dE is the mean energy imparted by ionizing radiation to the matter in a volume element of mass dm.

anisotropic (see also isotropic): Not isotropic; having different properties in different directions.

dose equivalent (H): The product of absorbed dose, D, and quality factor, Q, at the point of interest in tissue.

fast neutrons: Neutrons of energies above a few hundred keV.

fluence (Φ): The quotient of dN by da, where dN is the number of particles which enter a sphere of cross-sectional area da.

intermediate neutrons; slow neutrons: Neutrons with energies between about 1 eV and a few hundred keV.

inverse square law: That rule which states that the intensity of radiation from a point source decreases as $1/r^2$ from the source in a non-absorbing medium, where r is the distance from the source.

isotropic (see also anisotropic): A condition in which the properties are the same in whatever direction they are measured. With reference to radiation emission, this term indicates equal emission in all directions from a point source or each differential-sized element of an extended source.

linear energy transfer (LET): The average energy lost by a directly ionizing particle per unit distance of its path in a medium.

point source (of radiation): Any radiation source measured from a distance that is much greater than the linear size of the source.

quality factor (Q): A factor which is used in radiation protection to weight the absorbed dose with regard to its presumed biological effectiveness insofar as it depends upon the LET of the charged particles. The quality factor is a function of the LET of the charged particles which deliver the absorbed dose.

rem: A special unit of dose equivalent.