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ABSTRACT

This paper discusses the evaluation of dose-equivalent rates in mixed radiation environments such as are found, for example, around a high energy particle accelerator. It is shown that it is not possible to evaluate absorbed dose and dose-equivalent rates by any single measurement, in such complicated environments, with sufficient accuracy for purposes of radiation protection.

This paper studies in detail the problems of evaluating dose equivalent from measurements of absorbed dose made with a tissue equivalent ionization chamber. Recently the USAEC has published Tables of quality factors for monoenergetic neutrons as a function of neutron energy, but no values were given for the spectra spanning the large energy range typically found around high energy accelerators and reactors. By use of the values of quality factor recommended for monoenergetic neutrons, the QF for a variety of typical neutron spectra was calculated. The neutron spectra studied include the Watt fission spectrum, the PuBe spectrum, the cosmic-ray neutron spectrum, and three typical accelerator spectra measured at CERN and the Lawrence Radiation Laboratory. In addition, calculations were made for a variety of spectra expressed in simple exponential form. These calculations indicate the quality factor to be an extremely sensitive function of neutron spectrum and maximum-energy cutoff in the range of practical interest--the average quality factor varies by more than a factor of three with these parameters.

This work indicates the potential errors which may be made in estimating dose equivalent when making absorbed dose measurements and assuming a single value of quality factor. Knowledge of such errors is a valuable guide to operational health physicists.

I. INTRODUCTION

Historically, formulation of the fundamental concepts of dosimetry has centered around descriptions of integral properties of radiation fields such as exposure of absorbed dose.[1] As knowledge of the biological effects of radiation has improved, there has developed a framework of definitions and additional concepts designed to assist the health physicist in his work of radiation protection. These definitions are perhaps best and most recently expressed in ICRU Report 11.[2] Although the formulation of a system of units based upon the primary concept of absorbed dose and additional modifying factors has worked well for low-energy photons, it is our view that this success is primarily due to inherent simplicity of such radiation fields.

Around high energy accelerators the radiation fields potentially contain every fundamental particle known to man (and perhaps some still yet to be discovered!). Fortunately, despite this potential complexity, experience has shown that the dosimetry problems essentially are those due to neutrons and minimum-ionizing particles.[3] Thus the day-to-day problem in mixed-field dosimetry presented to operational health physicists at particle accelerators (and for that matter at nuclear reactors) is to evaluate from their experimental data a single number-the "Dose Equivalent"— which is "a simple, crude, but unambiguous quantity obtained by rules which are necessarily fairly arbitrary in character and which only broadly relate to biological effects."* In achieving this goal two things are required from the national and international regulatory and advisory bodies by the operational health physicist: first, some clear prescription that enables him to calculate an upper estimate of dose equivalent (The Maximum Dose Equivalent)

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* The authors are most grateful to Dr. H. Dunster for this extremely apt phrasing.

from his experimental data; and second, some indication of the accuracy of these procedures.

Increasing attention has recently been given in the literature to the difficulties in directly applying the recommendation of the ICRP—ICRU to radiation monitoring. For example, Wheatley[4] has discussed the difficulties of neutron monitoring and Neufeld[5] has drawn attention to logical inconsistencies in the interpretation of ICRP—ICRU recommendations because of different uses of the term Quality Factor.

This paper has three main divisions; in them we

a. Describe the practical situation at high energy accelerators and explain the guidance health physicists need to permit interpretation of their experimental data (Section 2).

b. Briefly discuss the fundamental definitions of dosimetric quantities by ICRP—ICRU. A logical inconsistency in the use of the term "quality factor" is indicated (Sections 3, 4, and 5).

c. Review the extant values of conversion factors and modifying factors recommended by ICRP (section 6) and indicate how the conversion factors and modifying factors needed in practical situations may be obtained.

II. Radiation Measurements at Particle Accelerators

At high energy particle accelerators the radiation environment is, ab initio, largely unknown. It thus is a prerequisite to the establishment of appropriate routine and personnel environmental monitoring programs to have an accurate understanding of the radiation fields in which routine dosimetry is to be carried out. Simplifying assumptions made in the evaluation of routine measurements can be justified only on the basis of such an understanding. This understanding at high energy accelerator laboratories has generally been achieved by measurements to investigate the physical properties of the radiation field.

The details of a measurement program depend upon the desired precision of the evaluation of dose equivalent rate and, of course, upon the complexity of the radiation field itself. All high energy laboratories have found it necessary to include the measurement of particle flux density, using threshold detectors. This technique is well known and has been described extensively in the literature.[6-8] If sufficient threshold detectors are used details of neutron spectra may be obtained with accuracy sufficient for radiation protection purposes (see Fig. 1). The technique of determining dose equivalent from such measurements has also been extensively discussed, and it is known that the technique is capable of a precise evaluation of dose equivalent in typical accelerator spectra.[9-10] However, if neutron flux density measurements are made conversion factors must be defined which permit calculation of dose-equivalent rate from such data.

Although neutron spectrometry can give accurate estimates of dose equivalent, it should be borne in mind that the techniques are reasonably complex and that several measurements are involved. Furthermore, measurements of other significant components of the radiation field must also be made.[3] The technique is therefore by no means simple, but it does have the great advantage of being comprehensive.

In addition to making neutron spectral measurements, many high energy accelerator laboratories augment them by the use of tissue-equivalent chambers to measure absorbed dose.[12, 13] Some care must be taken in the choice of the material used in the construction of such a chamber, but small deviations from true tissue equivalence are relatively unimportant. For example, such measurements give, in principle, a direct measurement of the absorbed dose in tissue, but practical difficulties arise in interpretation because the precise depth in tissue to which the measurement relates is uncertain. This uncertainty may be overcome by depth-dose measurements in simulated human phantoms to find where the maximum absorbed dose rate occurs. The evaluation of dose equivalent from a measurement of absorbed dose further involves

(a) a second measurement for estimating the appropriate modifying factor with, for example, an instrument such as the recombination chamber,[14-16] or

(b) determination of the LET spectrum of the radiation field and calculation of an appropriate modifying factor,[17-20] or

(c) knowledge of the spectrum of the radiation field, which permits calculation of the appropriate modifying factor (later in the paper we show how knowledge of neutron spectra is used for this purpose---Section 8) or

(d) choice of some prudently conservative estimate of modifying factor (because it never underestimates dose equivalent, this approximation usually results in unnecessary restrictions in operational procedures).

It can be seen from the above that it is now possible to evaluate the maximum dose-equivalent rate in a human body in an unknown radiation field by only a single measurement.

Moyer has summarized the use of tissue-equivalent chambers thus:[21] "If prior knowledge is available concerning the relative biological

effectiveness of the radiation field in question and it is assumed that energy absorption in soft tissue. . . multiplied by the relative biological effectiveness will give the desired hazard index, then the use of these chambers. . . is to be recommended." Despite these limitations the tissue-equivalent chamber is of great use in routine monitoring programs at accelerator laboratories. For this reason the health physicist needs from the ICRP—ICRU clear recommendations that will enable him to convert his absorbed dose measurements to a value of dose equivalent.

We now briefly discuss the current recommendations of the ICRP—ICRU that relate to these conversions. In addition we show that knowledge of particle spectra can be used to calculate modifying factors.

III. Fundamental Definitions of Dosimetric Quantities by ICRP—ICRU.

For clarity we briefly summarize the pertinent fundamental definitions by ICRP—ICRU, which (as we have noted in the introduction) are based upon the primary concept that an estimate of absorbed dose will first be obtained.

The relationship between dose equivalent and absorbed dose is authoritatively discussed by ICRU. Report 11 of the Commission states.[22]

"In radiation protection it is necessary to provide a factor that denotes the modification of the effectiveness of a given absorbed dose by LET (Linear Energy Transfer). Unlike RBE, which is always experimentally determined, this factor must be assigned on the basis of a number of considerations and it is recommended that it be termed the Quality Factor (QF). Provisions for other factors are also made. Thus a distribution factor, (DF), may be used to express the modification of biological effect due to nonuniform distribution of internally deposited radionuclides. The product of absorbed dose and modifying factors is termed the dose equivalent, (DE). As a result of discussions between the ICRU and the ICRP the following formulation has been agreed upon.

"The Dose Equivalent

"1. For protection purposes it is useful to define a quantity which will be termed the dose equivalent (DE).

"2. (DE) is defined as the product of absorbed dose, D, quality factor, (QF), absorbed dose distribution factor, (DF), and other necessary modifying factors:

$$(DE) = D(QF)(DF)$$

"3. The unit of dose equivalent is the rem. The dose equivalent is numerically equal to the absorbed dose in rads multiplied by the appropriate modifying factors."

For external exposure only one modifying factor is numerically defined—the quality factor in terms of linear energy transfer (LET).

ICRP Publication 4 states:[23]

"With regard to the actual values of QF that should be used for radiation protection calculations, the Commission endorses the RBE values which it published in 1955. These values are related to the LET of the radiation independently of other exposure factors. It is recommended that with regard to specification of radiation quality the basic parameter be LET (the "stopping power"), defined as the energy loss per unit distance of the charged particles originally set in motion by electromagnetic radiation or neutrons, or of the charged particles which originate in radiation sources (alpha-rays, beta-rays, etc.) i.e., the delta-rays are not counted as separate tracks. The DE (expressed in rems) is obtained by summation of the products of doses delivered at any LET and the appropriate QF factors, as well as any other factors recommended by the Commission. Simplifications of this procedure are allowed provided they do not result in an underestimate of the true DE. An example of such a simplification is the use of a single value of QF for all fast neutrons."

The arbitrary relationship between QF and LET recommended for radiation protection calculations is given in Table I.

This definition necessitates a further definition— that of linear energy transfer (LET). The most recent definition of this parameter is given in ICRU Report 11, which states[24]

"The linear energy transfer or restricted linear collision stopping power (L_Δ) of charged particles in a medium is the quotient of dE by dl, where dl is the distance traversed by the particle and dE is the mean energy-loss due to collisions with energy transfers less than some specified value Δ,

$$L_\Delta = \frac{dE}{dl} .$$

Note: Although the definition specifies an energy cutoff and not a

range cutoff, the energy losses are sometimes called "energy locally imparted."

In defining dose equivalent, ICRU Report 11 ends by saying: "Although this statement does not cover a number of theoretical aspects (in particular the physical dimensions of some of the quantities) it fulfills the immediate requirement for an unequivocal specification of a scale that may be used for numerical expression in radiation protection."

To say the least, this latter sentence seems to imply that there is little difficulty in applying these definitions to the interpretation of measurements made in the field. We believe that it is difficult because, as we have indicated in Section 2, if absorbed dose measurements are made, modifying factors appropriate to the condition of measurement are needed to evaluate dose equivalent. One solution is to choose a value of modifying factor that never underestimates the dose equivalent. In ICRP Publication 4 this point is made:[25]

"Most practical DE problems consist in the evaluation of the hazard due to a mixture of neutrons and gamma radiation. The QF of neutrons as a function of neutron energy has been evaluated for neutron energies up to 10 MeV. If the neutron energy distribution is known, the absorbed dose due to neutrons may then be multiplied by an appropriate QF to obtain the DE. If the precise neutron energy is unknown, the absorbed dose due to neutrons and gamma rays should be evaluated separately. The sum of the neutron doses multiplied by 10 and the gamma-ray doses multiplied by 1 may be considered an upper limit of the DE. Finally, the simplest approach is merely to measure the total absorbed dose and multiply it by a QF of 10. While being the simplest this method may result in an overestimate by a factor that can approach 10."

However, overestimates that may approach a factor of 10 are not permissible at high energy accelerator laboratories, where the additional shielding required or the operational inefficiencies produced by such an administrative decision would be economically intolerable.

The ICRP has recognized the need to specify both "Modifying Factors" and "Conversion Factors" for neutrons and protons as a function of particle energy, and ICRP Publication 4 contains appropriate recommendations (now somewhat outdated, but currently under review with a possible extension to higher energies).[26]

IV. Quality Factor or Modifying Factor?

As we noted in the introduction Neufeld[5] has drawn attention to the logical inconsistencies in ICRP—ICRU publications in the use of the term "Quality Factor." We had independently reached this same conclusion after reading the quotations from ICRP Publication 4 and ICRU Report 11 given in Section 3.

The confusion arises because of the simultaneous use of the term Quality Factor for:

a. A quantity defined in terms of linear energy transfer (ineffect, stopping power) for charged particles, and

b. the product of the modifying factors (QF)(DF)...and other necessary modifying factors as expressed in ICRU Report 11. In certain special circumstances the two definitions may be numerically identical, but in the general sense they are distinct quantities.

In this paper we will use the term "Modifying Factor" for the factor that converts absorbed dose to dose equivalent.

We strongly urge the resolution of this discrepancy in the ICRP—ICRU publications as soon as possible.

V. Dose Equivalent and Absorbed Dose Distributions in the Body and the Evaluation of Conversion Factors and Modifying Factors

The selection of conversion and modifying factors is a complex matter involving the calculation of particle spectra produced within irradiated tissue. Given the details of particle spectra within the tissue, the absorbed dose may be calculated from the known stopping power of each particle in tissue. Finally, from the defined quality factor—LET relation (Section 3) the dose equivalent is calculated.

Auxier et al.[27] have recently reviewed such calculations and discussed their limitations. Further details may be obtained in the original papers from the Oak Ridge groups making these calculations,[28-34] which are summarized on Table II.

From a knowledge of both the absorbed dose and dose equivalent distributions per unit particle fluence in a human phantom, it is a simple matter to calculate the appropriate conversion and modifying factors. It is conventional to evaluate these factors at the maximum dose equivalent (MADE) in the irradiated phantom.

VI. Recommended Values of Flux Density to Dose Equivalent Rate Conversion Factors and Modifying Factors

The only guidelines available to the health physicist until recently are derived from NBS Handbook # 63,[35] and ICRP Publication 4.[26] NBS Handbook # 63 limits itself to neutron energies of 30 MeV (in fact the data it utilizes extend only to 10 MeV). Values of "RBE" as a function of depth in a semi-infinite tissue slab are given for neutrons up to 10 MeV. At these energies the maximum dose equivalent always occurs in the first 1 cm of tissue, or effectively at the body surface.

The deficiencies of ICRP Publication 4 for energies above 10 MeV were suggested by one of us as early as 1965.[3] ICRP 4 gives conversion factors and modifying factors for neutrons and protons between 40 MeV and 1 GeV based upon calculations by Neary and Mulvey[36] of the average

dose deposited in the body irradiated by primary particles accompanied by their equilibrium cascades. It is more convenient in practice to have values of conversion and modifying factors for monoenergetic particles.

Based upon depth-dose calculations by Zerby and Kinney[31] and the estimates made by Neary and Mulvey[36] for monoenergetic particles, Thomas[3] proposed a set of analytical expressions for neutron conversion factors from thermal energies up to several hundred MeV. These expressions have been used at the Lawrence Radiation Laboratory for the past five years. The dotted line in Fig. 2 indicates these conversion factors.

More recently Shaw et al.[11] summarized the extensive data produced by groups working principally at ORNL,[27-34] and have suggested conversion factors with which they calculated dose equivalent —depth curves in phantoms irradiated in typical accelerator spectra. The values used by Shaw et al. are shown by the solid line in Fig. 2.

Finally, the USAEC[37] has published tables of values of modifying factors as a function of neutron energy for monoenergetic particles, also based upon Oak Ridge depth-dose calculations. No values of modifying factors have been recommended in the USAEC report for typical neutron spectra.

VII. Modifying Factors for Monoenergetic Neutrons

Table III gives the modifying factors for monoenergetic neutrons at the depth of maximum dose equivalent from the dose-depth calculations of the various ORNL groups.

At 60 MeV, for which two alternative sets of data are available,[30, 31] discrepancies approaching 40% are seen. At present insufficient information is available to permit an objective choice between these two calculations, but it seems likely that the nuclear model used by Zerby and Kinney[31] is the better of the two alternatives. With the

exception of the recent data due to Auxier et al.,[27] all the calculations shown were made with a semi-infinite tissue slab irradiated normally. The calculations by Auxier et al. were made for a finite cylindrical tissue phantom irradiated by a unidirectional beam. Neutron energies were limited to 15 MeV and below. Agreement to within less than 20% is in general obtained between the cylindrical and slab phantom data.

Figure 3 shows the smooth curve we have drawn through the calculated values to provide basic input data for our computer program. It closely corresponds to the values of modifying factors set forth by the USAEC.[37]

VIII. Modifying Factors for Neutron Spectra

Inspection of Fig. 3 reveals that neutron spectra relatively rich in neutrons between a few tenths MeV and a few MeV have a high effective modifying factor. It is particularly important, therefore, if absorbed dose measurements are made, to establish modifying factors appropriate to the neutron spectra in which the tissue-equivalent chamber is used. Furthermore, those conditions under which the modifying factor is strongly dependent upon neutron spectrum should be established.

Given the modifying factor MF(E) as a function of neutron energy (Fig. 3) and the neutron differential energy spectrum $\phi(E)dE$, we define an average modifying factor, $\overline{MF}$, for the spectrum given by

$$\overline{MF} = \frac{\int_{E_{min}}^{E_{max}} MF(E)\phi(E)dE}{\int_{E_{min}}^{E_{max}} \phi(E)dE}, \qquad (1)$$

where E_{max}, E_{min} are the upper and lower energy limits of the spectrum.

We have calculated $\overline{MF}$ for neutron spectra measured at the Bevatron, above the CERN Proton Synchrotron concrete shielding (CERN PS Bridge), and above the earth shielding of the CPS (CERN PS Ring Top). In addition we have chosen the Hess cosmic ray spectrum,[38] the Watt fission spectrum,[39] and two estimates of the PuBe spectrum (Fig. 4), that calculated by Hess[40] and that measured by Stewart.[41]

In an attempt to study the variation of $\overline{MF}$ with neutron spectrum in a more formal manner we also evaluated $\overline{MF}$ for spectra expressed in simple exponential form.

Thus $\phi(E)$ was expressed as

$$\phi_1(E) = E^{-\gamma} \text{ in the range } 0 < E < 2/3 E_{max}. \tag{2}$$

To simulate physically plausible spectra at energies greater than $2/3 E_{max}$ we write

$$\phi_2(E) = a + bE + cE^2, \text{ for the range } 2/3\ E_{max} < E < E_{max}. \tag{3}$$

The conditions

$$E_c = 2/3\ E_{max}, \tag{4}$$

$$\phi_1(E_c) = \phi_2(E_c), \tag{5}$$

$$\phi_1'(E_c) = \phi_2'(E_c), \tag{6}$$

and

$$\phi_2(E_{max}) = 0 \tag{7}$$

determine values of a, b, and c. Values of $\overline{MF}$ were calculated both as a function of γ for values between 0 and 2 and as a function of E_{max} between energies of 1 keV and 10 GeV.

An adaptive Simpson's rule integration algorithm was used to evaluate the integrals of equation (1) to a relative accuracy of 0.001.

Table IV summarizes the values $\overline{MF}$ calculated for typical high energy accelerator and low-energy (few MeV) neutron spectra. As

expected the PuBe and fission spectra have high values of $\overline{MF}$.

Figure 5 summarizes the results of our calculations made by use of analytical spectra, from which several conclusions may be reached:

a. For very steep spectra ($\gamma > 1.3$) $\overline{MF}$ is independent of energy cutoff, being determined by the dominance of neutrons in the eV range.

b. For low values of upper energy cutoff $\overline{MF}$ is a weakly varying function with E_{max} (for the same reasons as in a), changing only from 2 to 3 in the energy range thermal — 20 keV.

c. Beyond values of E_{max} of 20 keV the variation of $\overline{MF}$ becomes significant reaching a peak at $E_{max} \approx 1$ MeV, where values of $\overline{MF}$ of 9 are observed at low values of slope.

d. For values of γ close to 1 (1/E spectra) $\overline{MF}$ varies rapidly with spectrum slope greater than about 0.01 MeV for the cutoff energies studied.

It is thus evident that careful evaluation of the radiation fields is needed if accurate dosimetry is to be accomplished by using a tissue-equivalent chamber in neutron fields with low-energy cutoffs or slopes close to $\gamma = 1$, or both.

IX. Comparison With Other Data

Shaw et al.[11] have discussed the problem of dose equivalent evaluation from known neutron energy spectra. They show that an exact value of dose equivalent may be determined only by knowing the dose equivalent — depth curve in the human body when irradiated by the given neutron spectrum. Using the Monte Carlo calculation of depth dose data for neutron irradiation of tissue phantoms, Shaw et al. have calculated DE-depth and dose-depth curves in tissue phantoms irradiated by several typical accelerator spectra.

It is of interest to compare the values of $\overline{MF}$ evaluated by Shaw et al. at the maximum dose equivalent in the body with the values of $\overline{MF}$

calculated in this paper; this is done in Table V.

As expected, the small disagreement between the two calculations lies in the fact that the depth of the maximum dose equivalent is a function of neutron energy, which is not taken into account in our calculation described here.

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Table I. LET-QF relationship

LET_∞ (keV per micron in water)	QF
3.5 or less	1
3.5-7.0	1-2
7.0-23	2-5
23-53	5-10
53-175	10-20

Table II. Summary of depth-dose calculations in tissue for protons and neutrons.

Particle	Energy range	Incident angular distribution	Remarks	Reference	Phantom
1. Neutrons	Thermal	Normal	Snyder	28	Semi-infinite slab
2. Neutrons	Thermal—10 MeV	Normal	Snyder	29	"
3. Neutrons	0.5—60 MeV	Normal and isotropic	Irving et al.	30	"
4. Neutrons	60—400 MeV	Normal and isotropic	Zerby, Kinney, and Turner et al.	31 32	"
5. Neutrons	600—2000 MeV	Normal and isotropic	Neufeld et al.	33	"
6. Protons	100—400 MeV	Normal	Turner et al.	32	"
7. Protons	100—400 MeV		Neufeld et al.	33	"
8. Protons	600—2000 MeV	Normal and isotropic	Neufeld et al.	34	"
9. Neutrons	Thermal—15 MeV	Normal	Auxier et al.	27	Cylindrical

Table III. Modifying factors for monoenergetic neutrons

Neutron energy (MeV)	Modifying factor (MF)
2.5×10^{-8}	3.0
5	2.9
1×10^{-7}	2.8
2	2.8
5	2.6
1×10^{-6}	2.6
2	2.5
5	2.4
1×10^{-5}	2.3
2	2.2
5	2.1
1×10^{-4}	2.0
2	2.0
5	2.1
1×10^{-3}	2.2
2	2.3
5	2.7
1×10^{-2}	3.6
2	5.1
5	6.8
1×10^{-1}	8.0
2	9.2
5	10.0
1×10^{0}	10.0
2	8.8
5	7.5
1×10^{1}	6.7
2	5.9
5	5.0

Table III. continued

Neutron energy (MeV)	Modifying factor (MF)
1×10^2	4.4
2	3.8
5	3.0
1×10^3	2.4
2	1.9

Table IV. Modifying factors calculated for typical neutron spectra.

Spectrum	$\overline{MF}$
CERN PS Ring Top	5.4
CERN PS Shield Bridge	4.9
Bevatron	5.6
Cosmic ray spectrum (Hess)	6.5
PuBe spectrum (Hess)	8.1
PuBe spectrum (Stewart)	7.9
Fission spectrum (Watt)	9.0
"1/E Spectrum"	cutoff-dependent; 2.9 at E_{max} = 10 GeV

Table Comparison of $\overline{MF}$ estimates.

Spectrum	MF_{MADE} (Shaw et al.)	$\overline{MF}$ (this paper)
1/E	2.9	2.9 (at E_{max} = 10 GeV)
Cosmic ray	7.7	6.5
Bevatron	6.8	5.6
CERN Ring Top	4.8	5.4
CERN PSB	4.8	4.9

FIGURE CAPTIONS

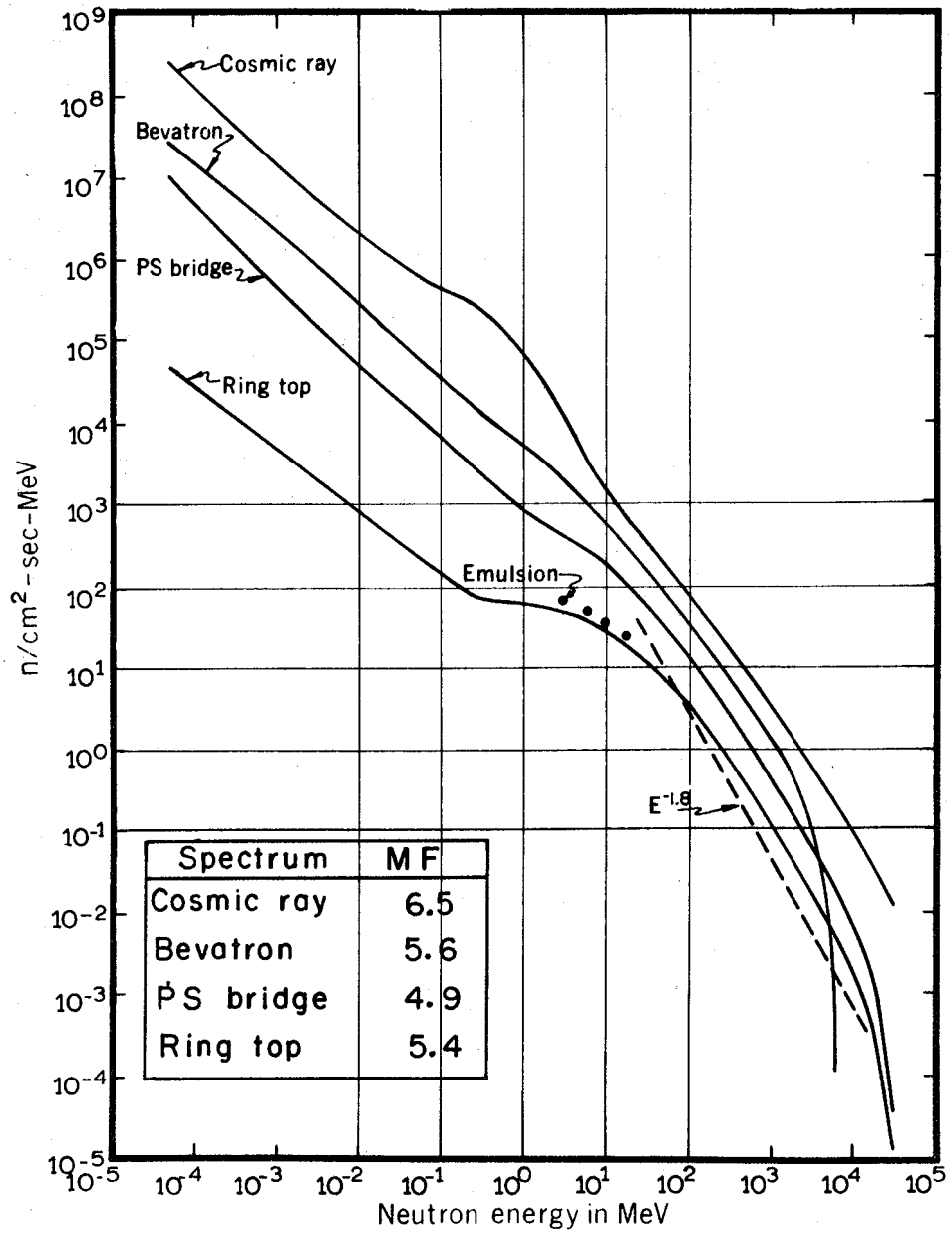
Fig. 1. Typical high energy accelerator spectra.

Fig. 2. Conversion factor as a function of neutron energy.

Fig. 3. Modifying factor as a function of neutron energy.

Fig. 4. PuBe neutron spectrum.

Fig. 5. Average modifying factor as a function of cutoff energy and slope.



XBL 682 4493

Fig. 1

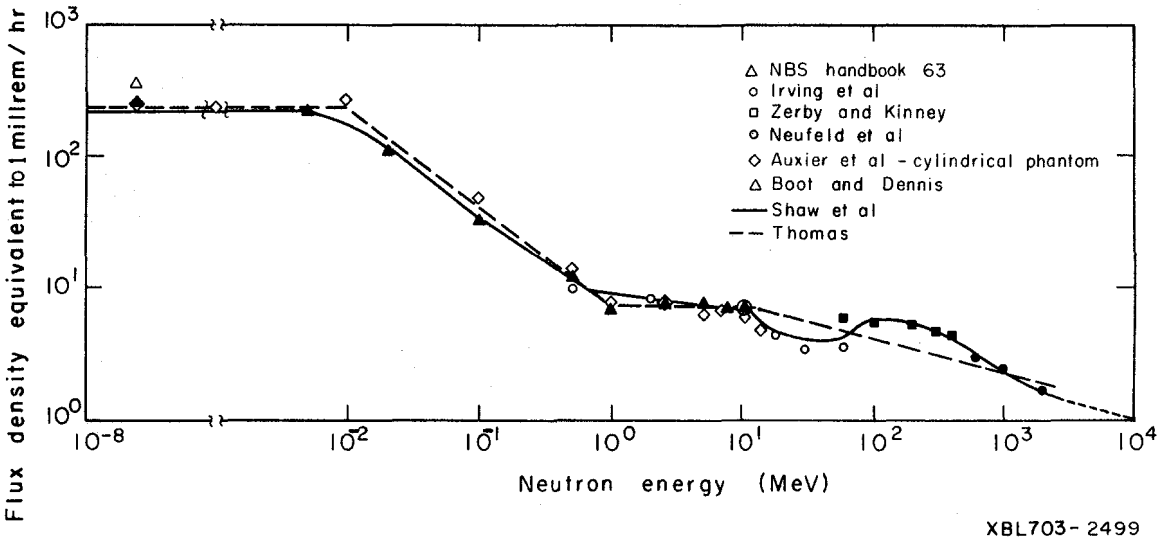
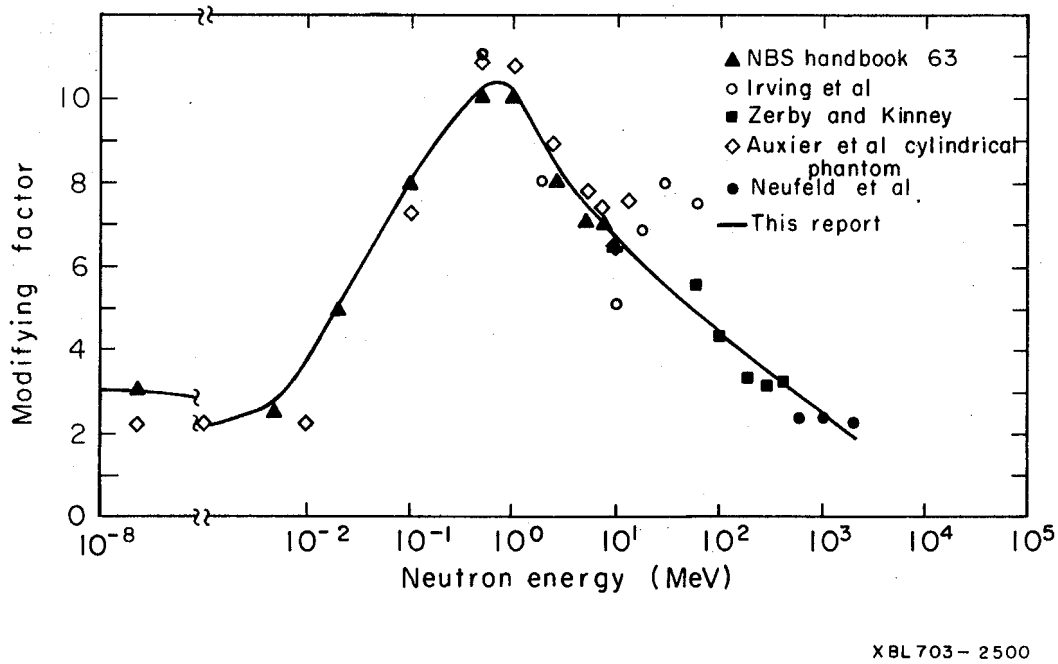

Flux density equivalent to 1 millirem / hr
10^3
10^2
10^1
10^0
10^{-8}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
Neutron energy (MeV)
△ NBS handbook 63
○ Irving et al
□ Zerby and Kinney
○ Neufeld et al
◇ Auxier et al - cylindrical phantom
△ Boot and Dennis
—— Shaw et al
– – Thomas
XBL703-2499

Fig. 2



XBL 703-2500

Fig. 3

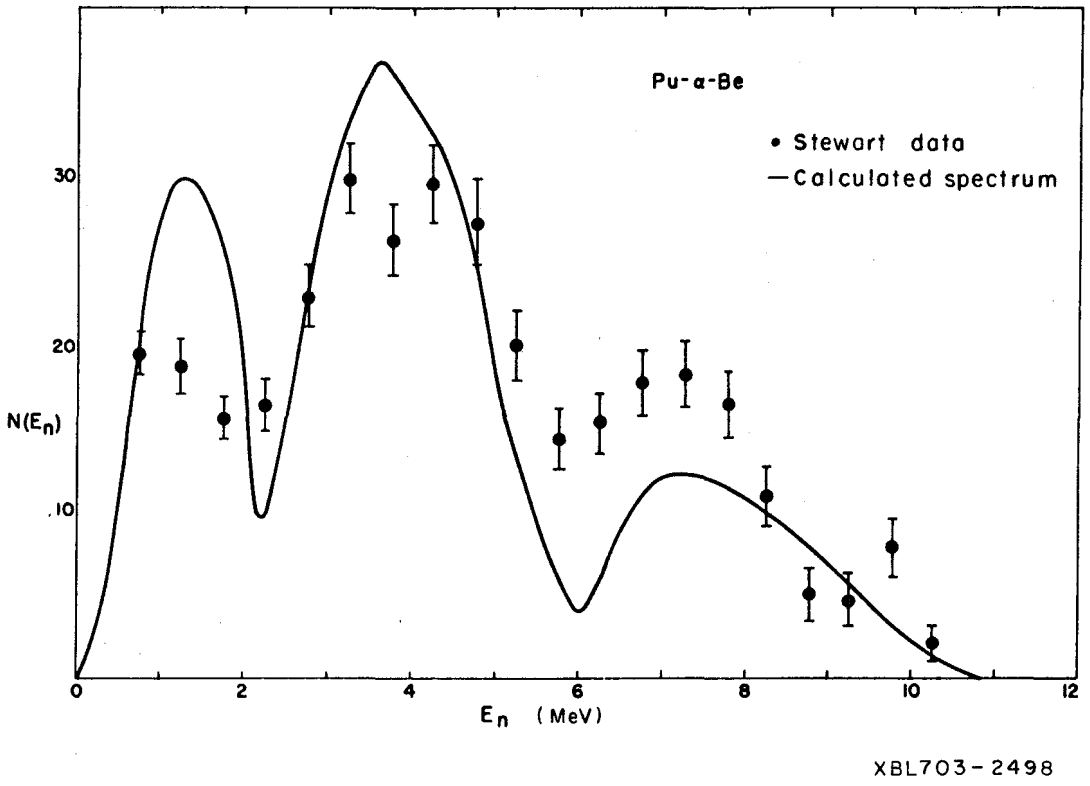

Pu-α-Be
• Stewart data
—Calculated spectrum
30
20
.10
N(En)
0
2
4
6
8
10
12
En (MeV)
XBL703-2498

Fig. 4

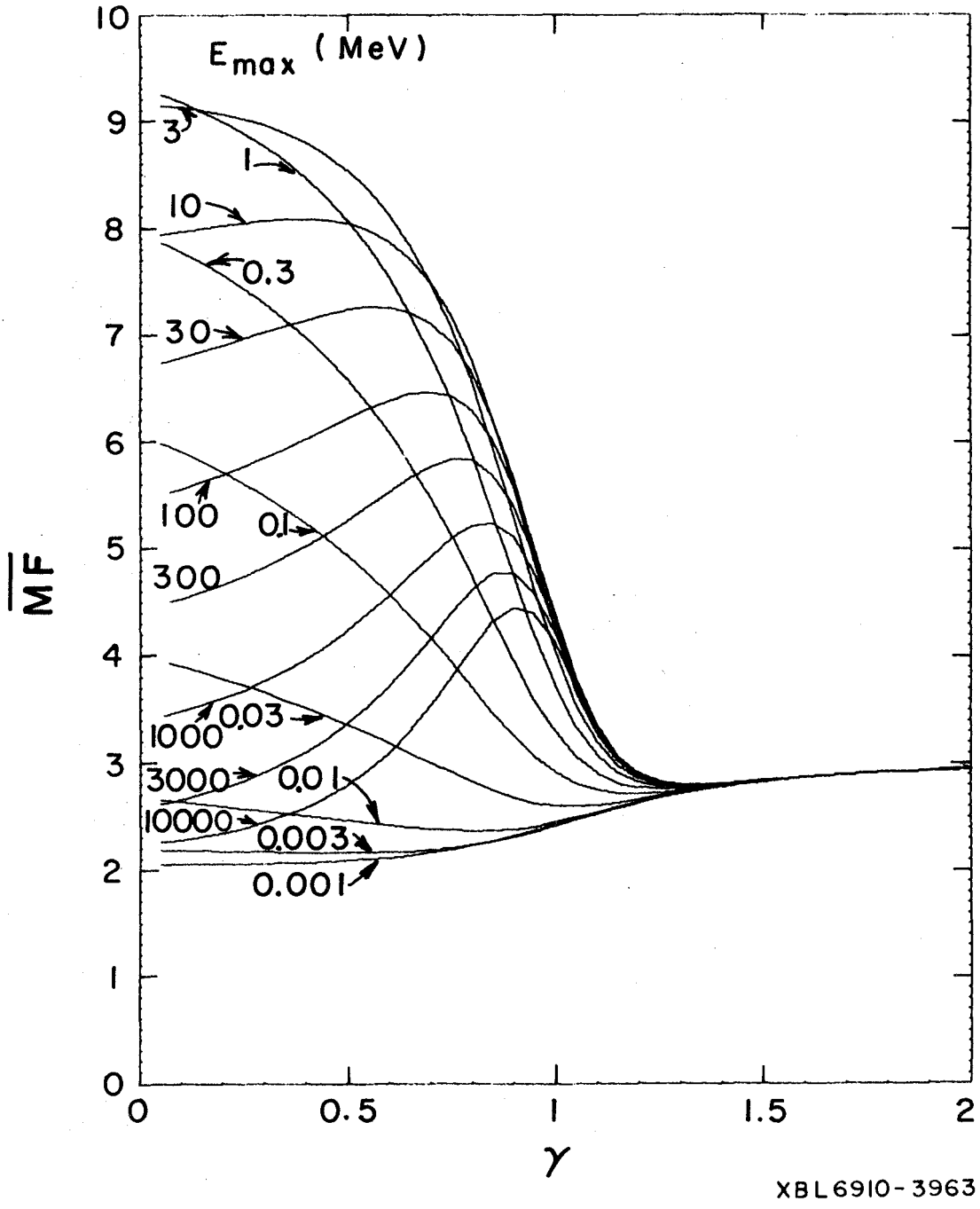

E_{max} (MeV)
3
1
10
0.3
30
100
0.1
300
0.03
1000
3000
0.01
10000
0.003
0.001
$\overline{MF}$
γ
0
0.5
1
1.5
2
0
1
2
3
4
5
6
7
8
9
10
XBL6910-3963

Fig. 5