Title

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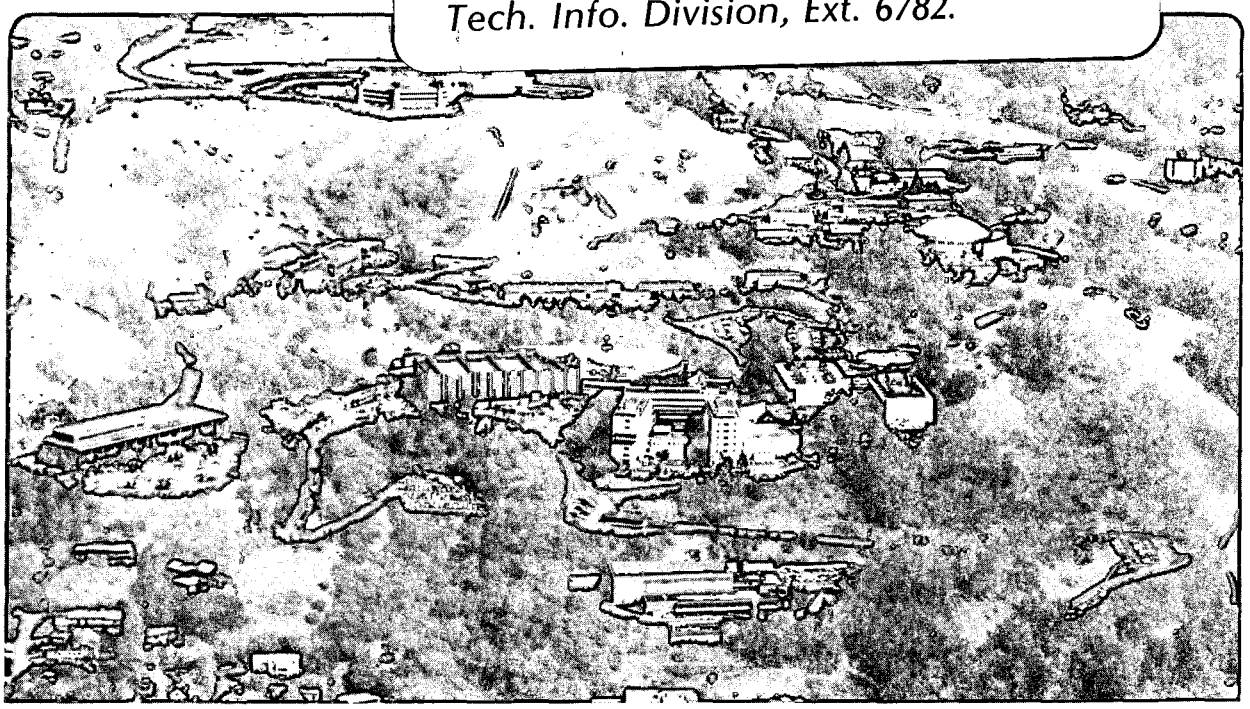

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Some Important Issues in Developing Basic Radiation Protection Recommendations: Dosimetric Aspects

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"The old order changeth, yielding place to new,
And God fulfills himself in many ways,
Lest one good custom should corrupt the world"

From: The Passing of Arthur,
Idylls of the King
Alfred Lord Tennyson
1809-1892

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Some Important Issues in Developing Basic Radiation Protection Recommendations: Dosimetric Aspects

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ABSTRACT

Some aspects of the difficulties encountered in the dose equivalent system used in radiation protection are explored and recent work to improve these deficiencies described. The philosophical advantages of a departure from the dose equivalent-based system and its replacement by a risk-based system are briefly discussed.

The definition of dose equivalent and the debate concerning its physical dimensions and units are described. Dose equivalent is related to other physiological quantities in physics and the treatment of these quantitities in the International System of Units compared.

Practical problems in the determination of dose equivalent are illustrated using neutrons as an example. The proliferation of operational quantities for the evaluation of neutron dose equivalent and the concomitant potential for confusion when determinations of neutron dose equivalent are intercompared is described.

The evaluation of fluence to dose equivalent conversion coefficients and methods of interpolation between recommended values are described. Particular emphasis is given to the accuracy and precision of dose equivalent estimation.

Recent work of a Task Group of the ICRP to improve recommended conversion coefficients and the work of an ICRU committee to improve the definition of operational dose equivalent quantities is summarized.

INTRODUCTION

The dosimetrist in radiological protection seems to be confined to Limbo "where the souls of the good people who never knew the truth yearn for the perfect bliss which they cannot hope to attain." [1]

This frustration is due to the fact that any measure of the detriment to humans exposed to ionizing radiation requires a physical quantification of the exposure, followed by an interpretation of the measurement in biological terms. While the first stage of the process may, at least in principle, be achieved with good accuracy our assessment of biological effects to humans at low doses largely depends upon hypothesis, extensive extrapolation and is, therefore, inexact.

This situation has led to a subconscious dichotomy in the minds of dosimetrists who, while correctly recognizing that, in the absolute sense, "limited accuracy is required in radiation protection," [2] have confused the term accuracy with precision. Despite the poor absolute accuracy of our measures of biological harm in radiological protection, we nevertheless need measures which are reproducible with good precision, so that instruments and detectors may be calibrated and measurements intelligently compared. Dosimetrists have therefore continuously worked to improve the precision of the conceptual definitions of radiation protection.

Emerson, in a well known essay, wrote:

> "A foolish consistency is the hobglobin of little minds, advanced by little statesmen and philosophers and divines. With consistency a great soul has simply nothing to do..." [3]

However, the consistency which is sought here is not "foolish" [4,5] and the author hopes that Emerson would not include dosimetrists among those with little minds!

In this pursuit of greater precision a large number of dosimetric quantities have been defined--dose equivalent, MADE, ceiling dose equivalent, dose equivalent index, effective dose equivalent--and this proliferation adds a complexity which makes understanding difficult [6-10].

This paper will discuss some aspects of the historical development of the concept of dose equivalent; describe some of the practical problems which have been identified in the determination of dose equivalent for neutrons; discuss some of the ongoing work in the ICRU and ICRP, and, finally, comment briefly on the implications for dosimetry of a risk system in radiation protection [11].

DOSE EQUIVALENT

The Quantity Dose Equivalent

The quantity dose equivalent was first formally defined as recently as 1968 [2], although its origins go back a further twenty years to the application of RBE-dose to radiological protection [6].

For sources of radiation exposure external to the body the dose equivalent, H, is defined by the equation:

$$H = \int_0^\infty Q(L_\infty) \frac{dD(L_\infty)}{dL_\infty} dL_\infty \qquad (1)$$

where

L_∞ = the linear collision stopping in water

$\frac{dD(L_\infty)}{dL_\infty}$ = the absorbed dose in the stopping power increment from L_∞ to $L_\infty + dL_\infty$

and the integral of Equation (1) is evaluated over the entire L_∞ spectrum.

Recently there has been considerable discussion in the literature [12-20] concerning the definition of the unit of dose equivalent in the International System of Units (SI) [21-22]. However, as Chilton has pointed out, "this is an argument of long standing, going back to the days of the rad and rem and thus not related so much to the specific unit, the sievert, as to the more general concept of dose equivalent." [16] In fact, almost since its introduction there has been a continuing debate concerning various aspects of the definition of dose equivalent [5,23-28].

Several papers in the literature of the late 60's and early 70's discussed the concept "quality factor" [4,29-33]. There was particular interest in the physical dimensions of dose equivalent [34,35]. ICRU Report 11 [2] had left this matter undetermined, but after considerable debate first the British Committee on Radiation Units and Measurements and then the ICRU determined that the quantities absorbed dose and dose equivalent had the same physical dimensions [34,36]. This decision seemed to be a natural conclusion from the

historical development of the definition of dose equivalent from the RBE dose [35].

In the mid-70's there was a spate of discussion concerning the unit of dose equivalent in both the cgs [37-41] system and SI, and this discussion has continued to the present day [12-20,42-46]. Nelson, among others, has shown that similar debates have arisen over physiological and other quantities in physics [22,47-49].

Physiological Quantities in Physics

Dose equivalent is but one member of a group of quantities that have the common property that they all measure the physiological response of humans exposed to a physical phenomenon rather than the physical properties of the phenomenon itself. Other examples from this group are luminous intensity, I, (whose unit is the candela) and loudness level, L_N, (whose unit is the phon).

These physiological quantities are obtained by some procedure of weighting results of a physical measurement by a physiological response function.

Acoustics-- Loudness Level. Thus, for example, the perceived loudness level, L_N, of a pure tone may be expressed analytically [22] as:

$$L_N = K\eta(f,I)L_p \qquad (2)$$

where

L_p = the sound pressure

K = a constant

$\eta(f,I)$ = a weighting factor, which is a function of frequency and intensity of the sound.

Loudness level is not a purely physical quantity, but entails a subjective evaluation. The internationally recognized unit of loudness is the phon. One phon is the loudness of a sound which is judged by a normal observer, under standard listening conditions, as being equally as loud as a sound wave having pressure level of 1dB (20 μPa) at 1 kHz [22,50].

Photometry--Luminous Intensity. The luminous intensity, I, of a surface area has been described as spectrally weighted radiant intensity, I_e [51]. The reason for this may be understood from the equations defining both quantities:

$$I_e = A\int_0^\infty L_{e\lambda}\, d\lambda \tag{3}$$

$$I = AK_m\int_0^\infty V(\lambda)L_{e\lambda}\, d\lambda \tag{4}$$

where

A = the area of the surface

K_m = an arbitrary constant

$L_{e\lambda}$ = the spectral radiance (the radiance per unit interval of wavelength at a given wavelength, λ).

$V(\lambda)$ = a weighting function called the spectral luminous efficiency and is a function of wavelength, λ.

Thus, the luminous intensity is a fraction of the total radiant intensity emitted from a source computed using a standard weighting procedure.

Historically the weighting function used -- the spectral luminous efficiency -- depended upon visual experience (see Fig. 1). "Since the spectral sensitivity of the eye is not rigorously identical from one individual to another, it was necessary to either have the measurements made by a large number of persons or to use several observers who possessed the 'average eye'...this average eye has been defined since 1924..." [52-54]

Radiation Protection -- Dose Equivalent. As we have seen, the dose equivalent, H, is defined in a manner very similar to that of luminous intensity (Eq. 4), and there is, then, a strong similarity between the weighting functions $n(f,I)$ in acoustics, $V(\lambda)$ in photometry, and $Q(L_\infty)$ in radiation protection (see Fig. 2). There are, however, important differences which are revealed by comparing the treatment of $V(\lambda)$ and $Q(L_\infty)$ in SI.

The Physiological Units and the Internal System of Units

The similarity between the equations defining luminous intensity, I_e, and radiant intensity, I, (Eqs. 3 and 4), on the one hand, and those defining dose equivalent, H, and absorbed dose, D, (Eqs. 1 and 5), on the other, is obvious:

$$H = \int_0^\infty Q(L_\infty) \frac{dD(L_\infty)}{dL_\infty} dL_\infty \qquad (1)$$

$$D = \int_0^\infty Q(L_\infty) \frac{dD(L_\infty)}{dL_\infty} dL_\infty \qquad (5)$$

where the quantities L_∞, $Q(L_\infty)$ and $D(L_\infty)$ have already been defined.

The treatment of the units of these quantities by the General Conference on Weights and Measures (CGPM) has, however, been somewhat different.

In the case of luminous intensity the unit candela has been recognized as a base unit of SI. The physical dimensions of the quantities radiant intensity (watt Sr^{-1}) and luminous intensity (candela, lumen Sr^{-1}) are not the same and have been related in 1979 by definition [55] as:

683 lumens = 1 watt .

As a result of this definition there are those who now take the view that it no longer is necessary for the candela to remain as a base unit in SI [22].

On the other hand, absorbed dose and dose equivalent are defined in similar terms by the CGPM. Thus, in 1975 the CGPM adopted the gray as the unit of absorbed dose in the following terms:

> "The 15th CGPM--adopts the following special name for an SI in the field of ionizing radiation: gray, symbol Gy, equal to one joule per kilogram." [21]

When the CGPM adopted the sievert as the special name for the unit of dose equivalent in 1979 it did so in similar language:

> "The 16th CGPM--adopts the special name sievert, symbol Sv, for the SI unit of dose equivalent in the field of radioprotection. The sievert is equal to the joule per kilogram." [21]

To quote from Nelson:

> "As defined by the General Conference on Weights and Measures, the gray and the sievert are dimensionally equivalent and are both equal to the joule per kilogram. These units have the same relationship to one another as the older, non-SI units rad and rem, respectively

(1 rad = 0.01 Gy; 1 rem = 0.01 Sv). The decision by the CGPM to adopt two separate names for the same derived unit was based on recommendations from the International Commission on Radiation Units and Measurements and the International Commission on Radiological Protection in order to emphasize the distinction between the absorbed dose and dose equivalent.

The sievert has the same unit dimensions as the gray because the International Committee for Weights and Measures arbitrarily decided to regard the quality factor and other modifying factors used to calculate dose equivalent from absorbed dose as dimensionless.[1] However, in the case of luminous intensity, the candela and the watt per steradian are not dimensionally the same, because the 'maximum spectral luminous efficacy,' K_m, used in the calculation of photometric quantities has been given dimensions. According to the 1979 definition of the candela, the value of K_m is 683 lumens per watt. If the same principle were applied to the candela as has been applied to the sievert, the value of K_m would be the pure number 683 and the candela would be dimensionally equal to the watt per steradian. Thus, there is an inconsistency due to historical practice. The CIPM specifically avoided giving separate dimensions to the sievert because it did not want to add to the list of base units.... [see Ref. 56.]

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[1] A similar situation exists in the Gaussian electrical units, where the unit of magnetic field B is the gauss and the unit of magnetizing field H is the oersted. These quantities have different unit names because they are regarded as physically distinct even though they are dimensionally equivalent. They are related by $B = \mu H$ where the permeability μ is a dimensionless number.

> The gray was adopted by the 15th CGPM in 1975 as the SI unit for absorbed dose and was defined as 'equal to one joule per kilogram.' However, when the sievert was adopted by the 16th CGPM in 1979 as the SI unit for dose equivalent, it was defined by the similar statement, 'The sievert is equal to the joule per kilogram'...[see Ref. 21]." [22]

Thus, it is evident that the physiological quantities have been handled differently in SI. No specific quantity for loudness level has been adopted. The candela is a base unit of SI, whereas the sievert is a derived unit. The spectral luminous efficiency has physical dimensions, the quality factor is dimensionless.

It is perhaps this inconsistency in the treatment of the physiological quantities by the CGPM that has caused the prolonged smoldering debate on the definition of dose equivalent, the ambers of which have recently glowed more brightly. The status quo has its supporters [42,43] and its detractors [44,45], with many others acknowledging that a problem of communication exists and urging remedial action but not radical surgery of the type recommended by Ruby.

Nelson suggests that a new class of physiological units be recognized in SI. These units "would be neither base, supplementary, nor derived units. Derived units could be formed by the combination of base units and supplementary units with physiological units." [22]

Quite recently Attix has suggested that it might have been more acceptable to the health physics community if it had been decided to not define dose equivalent as a physical quantity, by specifying dimensions to the quality factor. In SI Q would have the units Sv Gy^{-1} and the sievert would not be equated to 1 J kg^{-1}. Attix comments "I think this alternative approach, if

adopted initially, would have been more readily accepted by the health physics community. However, changing to it now probably would not be worth the extra confusion attending any such change." [46]

It is apparent from the literature that there are strongly held differences of opinion. Such debates are not unique to the physiological units, and in their resolution it is important to recognize that there are no correct or "absolute" solutions. What is needed is a generally agreed convention for communication.

In his book Nelson refers to an earlier debate over the units of permittivity and permeability of free space and the physical nature of the fields B and H [47]. Both Birge and Bridgeman have expressed the view [48,49] that the "dimensions of physical quantities are arbitrary or conventional rather than unknown. Moreover, one cannot, from the adopted dimensions of a quantity, draw any firm conclusions as to its physical nature." [48]

A useful clarification to the confusion arising over the relationship between the gray and the sievert has been given in a footnote in the 1981 edition of NBS 330-SP--"The International System of Units-SI." [57]

> "Translators' note: it should be noted that the quantity dose equivalent, H, is the product of the absorbed dose, D, of ionizing radiation, and the dimensionless factors Q (quality factor) and N (product of any other multiplying factors) stipulated by the International Commission on Radiological Protection. Thus, for a given irradiation, the numerical value in joules per kilogram of these two quantities D and H may differ, depending on the values of Q and N. To avoid any risk of confusion, the special names for the respective units should be used; i.e., D should be expressed in grays, and H should be expressed in sieverts." [57]

THE EVALUATION OF DOSE EQUIVALENT PRODUCED BY NEUTRONS

The evaluation of dose equivalent from neutrons, particularly at high energies, poses severe technical difficulties which are compounded by "inadequate or incomplete definition of the quantity to be measured." [5] McCaslin and Thomas have reviewed neutron dosimetry intercomparisons made by several high-energy laboratories and while they found reasonable agreement in the determination of the physical parameters of the radiation field, the conversion of these data to dose equivalent produced disagreement by almost as much as a factor of two [58]. They concluded that these discrepancies were often due to the use of different dose equivalent quantities.

Operational Dose Equivalent Quantities for Neutrons

The primary limits for radiation exposure recommended by ICRP are expressed in terms of the dose equivalent to various tissues, H_T, the whole body dose equivalent, H_{wb}, and the effective dose equivalent, H_E. For external radiation exposure secondary limits are expressed in terms of the shallow and deep dose equivalent indexes $H_{I,s}$ and $H_{I,d}$ [10]. Since, in general, neither the primary nor the secondary limits may be measured directly operational quantities must be developed [5,59,60].

The most widely used operational quantity used for neutrons is the dose equivalent H_c determined using the fluence to dose equivalent conversion coefficients, h(E) or g(E),[2] such as those given in NCRP Report 38 [61] or

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[2]Two conversion coefficients have been in common use. The first h(E) is expressed in units of dose equivalent per unit fluence (e.g., rem cm^2 or Sv cm^2) while the second g(E) (now obsolete) was expressed in units of fluence rate required to produce a dose equivalent rate of 2.5 millrem h^{-1} or 1 millirem h^{-1}.

ICRP Publication 21 [62,63] (See Figs. 3-5.) These conversion coefficients were determined for an incident broad parallel beam of incident neutrons on a phantom (e.g., 30 cm thick tissue equivalent slab, 30 cm diam. by 60 cm high tissue equivalent cylinder [64-70], or the ICRU sphere [71-75]). The conversion coefficients determined in this manner may be used to derive the maximum dose equivalent (MADE) for monoenergetic neutrons. However, their use for the practical evaluation of dose equivalent resulting from neutron spectra leads to overestimation because the location of the MADE varies with neutron energy. Considerations such as these led Harvey to define ceiling quantities, which are a special subgroup of aligned quantities [5] (see section entitled "The Evolution of the Dose Equivalent Quantities").

To avoid the overestimation resulting from the use of the ceiling quantities a new operational quantity was defined at the European Centre for Nuclear Research (CERN), where measurements of neutron fields were made around high-energy particle accelerators [76,77].

Stevenson and his colleagues argued that the high-energy radiation which emerged from substantial shielding had achieved an equilibrium which would not be significantly altered by the presence of the human body. Thus, the conversion coefficients for monoenergetic neutrons at or near the surface of the body were more appropriate. Values of conversion coefficients at a depth of 10 mm in tissue irradiated by a broad parallel beam of neutrons were selected, $h_{10\ mm}(E)$, and the evaluation of the integral:

$$H_{10\ mm} = \int_{E_{min}}^{E_{max}} h_{10\ mm}(E)\ \phi(E)dE \qquad (6)$$

then gives the dose equivalent at a depth of 10 mm in tissue.

Stevenson and Thomas [78] have compared the values of MADE, ceiling dose equivalent, and $H_{10\ mm}$ calculated from several typical high-energy accelerator spectra. Table 1 summarizes these calculations. Column 2 gives the ceiling dose equivalent while column 3 gives $H_{10\ mm}$, both calculated as a ratio of the "practical" dose equivalent, H_p, in the tissue equivalent phantom. Shaw et al. [79] defined the practical dose equivalent, H_p, by determining the maximum dose equivalent in 30 cm thick tissue equivalent slab phantom irradiated bilaterally by the neutron spectrum under consideration.

The neutron spectra referred to in Table 1 may be briefly described thus:

RT a neutron spectrum determined at the CERN 28 GeV proton synchrotron (CPS) above the earth shielding with a target intercepting the beam as a primary radiation source.

PSB measured at the CPS above a concrete shield, again with a target acting as the primary source.

BEV measured at the University of California Radiation Laboratory (now Lawrence Berkeley Laboratory) 6.3 GeV proton synchrotron.

X2 measured at the 7 GeV proton synchrotron of the Rutherford Laboratory, outside concrete shielding.

P1 measured as for X2 but outside steel shielding.

PLA the ambient neutron spectrum around the 50 MeV proton linac of the Rutherford Laboratory.

CR the Hess Comic Ray neutron spectrum.

They conclude that while the ceiling dose equivalent consistently overestimates H_p, sometimes by as much as a factor of two, $H_{10\ mm}$ does not underestimate H_p by more than 15 percent, but may overestimate it by as much as 70 percent [78].

This incomplete review of the profusion of operational quantities indicates the current rather unsatisfactory situation in neutron dosimetry and provides a basis for understanding apparent inconsistencies between measured data.

Currently Recommended Fluence to Dose Equivalent Conversion Coefficients (MADE) from Neutrons

Several sets of recommended conversion coefficients have been published in the literature not only by advisory boards such as the NCRP and ICRP [61,63] but, in the United States of America, by regulatory and other government agencies [80,81].

In general there are differences between these sets of recommendations, which although themselves small in an absolute sense (e.g., by comparison with our uncertainty in the risks resulting to humans from chronic neutron irradiation at the rate of a few millisieverts per annum), are nevertheless disconcerting to dosimetrists who seek to improve the precision with which their data may be expressed. These differences have been much criticized in the literature [82-84]. Thus, for example, in remarks specifically addressed to the NCRP and ICRP, Rogers has written:

> "I would hope that the NCRP and ICRP would adopt a joint recommendation to minimize future confusion. Neutron dosimetry already has enough real factors of two uncertainties. We do not need any additional 'unreal uncertainties.'" [82]

This is a viewpoint with which most can agree, and it is worth taking a little trouble to explore the reasons for these uncertainties.

The difference between recommended values of conversion coefficients may arise from a variety of causes including:

- Calculational models (phantoms; nuclear physics)
- Interpretation of basic calculated data
- Techniques of interpolation between recommended data points.

While investigation of the first of these causes provides an objective assessment of real uncertainties (due either to incomplete knowledge of the nuclear processes that take place in the irradiated human body, or to deficiencies in the phantom used to represent the human body in which the absorbed dose distributions are calculated), the second and third causes arise from subjective considerations and may, in principle, be eliminated by an appropriate consensus of opinion or an agreed convention.

Accuracy and Precision Required in Monitoring

ICRP Publication 12 recommended that the uncertainty in assessing the upper limits to the annual dose equivalent to the whole body should not exceed 50 percent [85]. Others have suggested a precision of 20-30 percent [86]. It is thus not entirely clear whether it is the precision or absolute accuracy of measurement which is intended in these recommendations.

NCRP Report 57 separates the issues of both accuracy and precision. It recommends that dose equivalent be determined to an accuracy of ±20 percent at doses higher than the MPD and to ±30 percent at the level of the MPD. However, the report suggests that precision is most important and recommends that the assessment of personal dosimeters be reproducible to within ±10 percent [87].

There are some dosimetrists, the present author included, who are skeptical that absolute accuracies of ±30 percent may be obtained in most practical situations in personal dosimetry.

To put this question in perspective it is of interest to know the accuracy required for delivery of tumor dose in radiotherapy. Cunningham has reviewed these uncertainties for photon radiotherapy [88]. ICRU Report 24 [89] has suggested that an accuracy of ±5 percent is required, and Cunningham states that this is "possible" but requires both detailed and accurate anatomical information as well as a rather sophisticated calculation procedure. Cunningham cites data that demonstrate that if anatomical structures are ignored substantial errors in dose delivery are possible (e.g., as high as 40 percent in the chest using ^{60}Co radiation). It is therefore unlikely that the recommendations of NCRP Report 57 or ICRP Publication 12 will be often met in the less than ideal situations for personal dosimetry which occur in the workplace.

U.S. Standards for personal neutron dosimeters require an accuracy of ±50 percent [90,91]. As we shall show uncertainties introduced by (a) the interpretation of the basic data uses to recommend conversion coefficients and (b) by the interpolation between recommended conversion coefficients can approach or even exceed this recommended (or required) accuracy.

(It is appropriate to comment that for the purposes of regulation the estimate of dose equivalent is, to all intents and purposes, required to be absolute [91].)

Calculations of Basic Data

The conversion coefficients recommended by the NCRP and ICRP are largely derived from Monte Carlo calculations of the absorbed dose distributions in semi-infinite tissue equivalent slabs or tissue equivalent cylinders [61-70]. Chilton and his colleagues [71-75] have subsequently reported calculations within an ICRU sphere up to neutron energies of 14 MeV.

Chilton [73] has reviewed these calculations and has concluded that the shape of the phantom has little effect on values of maximum dose equivalent calculated. In comparing the data used in ICRP Publication 21 with his own he concludes:

> "(a) The shape of the phantom seems to have little effect on the values of the maxima, at least within this energy range.[3] (One should not expect this to be true for other beam-directional cases, such as the isotropic case.)[4]
>
> (b) The values of the data on maximum dose equivalent, even from older calculations, seem sufficiently accurate and consistent (if the point values are used) to permit the passage of a conversion curve through them rather closely. It would appear that the curve recommended by the ICRP, as shown in Figure 1,[5] and the ICRP values taken from that curve could and should be re-established in a more accurate manner without the clearly excessive degree of smoothing out of the data.
>
> (c) There is reason to believe that the irregularities in the slopes of the line connecting the points on this "conversion factor" plot are not due to computational inaccuracies so much as to a genuine structural complexity, which probably has some relation to the structural complexity of the cross sections for some of the important constituents of tissue above 0.4 MeV. Thus, more work needs to be done to fill in the intermediate points on the graph." [73]

Nevertheless, despite this good agreement of the basic data differences in interpretation are possible.

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[3]Thermal to 14 MeV.
[4]Broad parallel beam incident beam case considered here.
[5]Figure 1 is shown as Fig. 3 in this report.

Derivation of Recommended Conversion Coefficient from Basic Data

Such a difference in interpretations arose in 1971 when both the NCRP and ICRP approved revised sets of neutron fluence to dose equivalent conversion coefficients [61-63]. The ICRP recommendations extend beyond the upper energy limit of 400 MeV of the NCRP data to a neutron energy of 3 GeV. Table 2 compares the two sets of recommendations from thermal energies to 500 MeV, which are also plotted in Fig. 4.

As we have already mentioned there are some differences between these two sets of recommended conversion coefficients, and these differences have been much criticized in the literature. At this juncture it is perhaps necessary to comment that these differences do not arise from any particular institutional perversity, but simply reflect honest differences of opinion in the interpretation of data. This is clearly seen from the quotations given below.

In the case of the neutron conversion coefficient recommendations both NCRP and ICRP committees had access to the same basic data [64-70]. Furthermore, there was considerable informal contact between individual committee members so that both Council and Commission were well informed of what the other was doing.

Chilton and others have discussed the detailed technical reasons for the apparent differences [93]. The most serious discrepancy occurs in the energy region between 10 MeV and 100 MeV. ICRP Publication 21 draws particular attention to this fact:

"Below 10 MeV, there is good agreement between the various calculations, but in the 10-100 MeV region, some discrepancies are in evidence. Differences in the nuclear models used in the calculations explain the discrepancy between the Irving et al. (1967) results and the others. Although insufficient experimental data are available at the time of writing to permit an objective choice, it seems most likely that the nuclear model used by Irving et al. yields a too cautious answer, and less weight is therefore given to their data. Above 100 MeV, there is also good agreement between the calculations, and the curve has been drawn in an intermediate position compatible with the decision at lower energies.

The inherent limitations contained in the definitions of conversion factor and effective quality factor and the accuracy of the calculations on which they are based should be firmly kept in mind when applying them." [63]

In NCRP Report 38 the following comment may be found on the same subject:

"The maximum dose equivalent for a unit incident-neutron fluence at any depth in the tissue is shown in Figure 47[6] as a function of neutron energy. The plotted points show the results of the calculations.

Several features of the results are worthy of note. The abrupt increase in the dose equivalent just above 10 MeV arises because in the nuclear model used, alpha-particle emission begins to become an

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[6]Figure 47 is shown as Fig. 5 in this report.

important process just above 10 MeV. The dose equivalent decreases in going from 30 to 60 MeV (Irving calculations) because the alpha particles emitted from the higher energy neutron collision have higher energy and thus a smaller quality factor.

The most notable characteristic of the results in Figure 47 is the discontinuity at E=60 MeV. The calculations of Irving et al. and those of Zerby and Kinney do not agree at 60 MeV because of the different models used to describe production from neutron-nucleus collisions in the 50-60 MeV energy range. The discrepancy arises primarily because the evaporation theory used by Irving gives more alpha particles than does the cascade theory used by Zerby and Kinney. This discontinuity is undesirable, but unfortunately the experimental information needed to resolve it, that is, the energy and angular distributions of neutrons, protons, and alpha particles emitted when a 60 MeV neutron collides with light elements such as carbon, nitrogen, and oxygen, is not available.

The solid curve in Figure 47 has been drawn by eye to more or less average the values for the normally incident fluence in the vicinity of 60 MeV. The fact that the curve is biased toward the Irving calculations at 60 MeV is not intended to imply that the Irving calculations are thought to be more valid, but is rather an attempt to be conservative." [61]

In fact, the agreement between the two sets of recommendation is, on the whole, remarkably good. Nevertheless, some uncertainties arise in using these recommended values to determine dose equivalent from neutron spectra.

Interpolation Between Recommended Values

Inspection of Table 2 shows that the specific conversion coefficients recommended by NCRP and ICRP are rather widely separated in energy. Conversion coefficients are presented graphically as a function of neutron energy with a smooth line joining the points (see, e.g., Figs. 3-5).

When dose equivalent is evaluated by determining the value of the integral

$$H = \int_{E_{min}}^{E_{max}} h(E)\ \phi(E)\ dE \qquad (7)$$

it is often desirable to have values of conversion coefficients at closer intervals of energy than specified in by either NCRP or ICRP.

The intention of ICRP Committee 3 was that the smooth curve should form the basis for the interpolated recommendations, and the curve was drawn smoothly (by eye) through the data points of log g(E) plotted versus log E.

The data in NCRP Report 38 are also presented on log-log graph paper (Fig. 5) and it is this author's personal view that it was probably the intention of the NCRP that logarithmic interpolation also be used. However, NCRP Report 38 states:

> "...it is sufficiently safe for planning purposes to derive flux densities for protection planning for any neutron energy between thermal levels and 400 MeV by linear interpolation between neighbouring energies in (the) table...." [61]

Cross and Ing [94,95] and others have pointed out that it is not unreasonable to interpret this guidance as linear interpolation on a linear plot. It is this interpretation that Rogers and others [82-84,96,97] have used in presenting their argument (Fig. 6). This interpretation, however, is somewhat surprising in view of the fact that the author, as early as 1965, had suggested a set of empirical formulae for calculating conversion coefficients for neutron energies up to 1000 MeV [98,99]. These empirical formulae (see Table 3 and Fig. 7) were in use at high-energy laboratories in the United Kingdom and the United States of America by 1966, anticipating the recommendations of NCRP Report 38 and ICRP Publication 21 [100,101].

It is a simple matter to show that if the relationship between the conversion coefficient g(E) and neutron energy E is of the form:

$$g(E) = a\,E^{n} \quad , \tag{8}$$

then linear interpolation can result in serious errors if n departs greatly from unity. With n = -3/4 linear and logarithmic interpolation between the ICRP data points at 10^{-2} and 10^{-1} MeV confirms Rogers' assertion that interpolation conversion coefficients differ by more than a factor of two at 50 keV.

In practice the consequence of these interpolation errors is not large. It is in only extremely rare circumstances (if ever) that radiation workers are exposed to monoenergetic neutrons, and it is of greater importance to understand the magnitude of differences produced by alternative interpolation techniques in the estimate of dose equivalent produced by actual neutron spectra.

Sims and Killough [84] have calculated spectrum averaged fluence to dose equivalent conversion coefficients for several characteristic neutron spectra at the Health Physics Research Reactor (HPRR) of Oak Ridge National Laboratory. Table 4 summarizes some of these data, comparing spectrum averaged conversion coefficients combining linear or logarithmic interpolation with data from NCRP Report 38. The differences are always less than 20 percent. Eisenhauer and Schwartz, however, were able to show that for a neutron spectrum measured at a PWR dose equivalent estimates differed by as much as 29 percent, due to difference in interpolation methods [97]. Even larger differences are possible if the variability due to the use of the various sets of conversion coefficients is taken into account. Thus Sims and Killough identified differences as large as 41 percent in estimates of the dose equivalent in the spectrum of HPRR when shielded by 13 cm steel [84]. These authors indicate that within the United States the accuracy currently required for neutron personal dosimeters is ±50 percent [90,91]. Comparable errors may therefore be introduced into personal dosimetry systems by purely administrative decisions--a most unhappy situation! They conclude: "Neutron dosimetrists would benefit if universal agreement on a preferred data set and interpolation method could be reached."

Eisenhauer and Schwartz have commented that the question of preferred interpolation techniques is best settled by calculation of conversion coefficient in a sufficiently fine energy mesh that interpolation will not introduce significant errors. Cross and Ing reported such calculations in 1981, giving data for 23 energies between thermal and 14.7 MeV. They concluded the logarithmic interpolation used by ICRP between 10 keV and 500 keV was appropriate. However they caution that in the region 1-3 MeV the ICRP 21

curve seems low because it was drawn through a point at 1 MeV which corresponds to a resonance peak in the oxygen cross section (see also comments by Chilton in Ref. 73).

RECENT WORK IN RADIATION PROTECTION DOSIMETRY

The first part of the paper has been devoted to a discussion of some of the deficiencies of our current dose equivalent-based system of dosimetry. The remainder of the paper will describe some aspects of the work of both the ICRP and ICRU over the past five years to correct some of these deficiencies.

First the work of the ICRP in recommending conversion coefficient for neutrons will be described, followed by a brief summary of the evolution of thinking concerning operation dose equivalent within the ICRU. Finally, some philosophical advantages of a total departure from the dose equivalent system will be discussed.

Recent Work of the ICRP on Conversion Coefficients for Neutrons

During the decade since the publication of NCRP Report 38 [61] and ICRP Publications 15 and 21 [62,63] there have been significant changes in neutron dosimetry. These include the introduction of the quantities dose equivalent index [9,36], effective dose equivalent [10].

Since 1980 an ICRP Task Group of Committee 3, Chaired by Dr. M. O'Riordan, has been working to improve the data contained in ICRP Publication 21. The work of this task group is now well along, and it is possible to give a preview of their data [102].

The preponderance of our information on absorbed dose and dose equivalent distributions is obtained by calculation. In principle it is now possible to calculate the dose distributions in the human body resulting from any radiation field. Even if the physical parameters of the radiation field were previously known, there are, however, intrinsic uncertainties in such calculations. These uncertainties arise from three principal sources:

- The accuracy with which the phantom used actually represents (or fails to represent) the human body
- Uncertainties in interaction processes or in interaction parameters
- Computational techniques.

The ideal phantom of the human bodies for radiation protection purposes has been defined by the ICRP to be Reference Man [103]. In fact dose distributions have been calculated in a variety of phantoms ranging from a semi-infinite tissue equivalent slab to versions of the MIRD phantom [104].

The dose equivalent indexes must be determined by calculation in the ICRU sphere [9,36], and over the last 5 years or so considerable effort has been devoted to their determination. The ICRU sphere has some special advantages in that it has been defined and recommended by the international bodies for the purposes of dosimetry, it is not likely that its definition will be changed in the foreseeable future (it is stable), and it has an isotropic angular response.

As we have seen the values of the deep dose equivalent indexes do not differ greatly from values of the maximum dose equivalent calculated in slab or cylindrical phantoms. Values of $H_{I,d}$ are therefore adequate for determining the conversion coefficient given in NCRP Report 38 and ICRP Publication 21. The calculations now available span the energy range from 10^{-2} MeV to 15 MeV in some detail (see Fig.8), much reducing the uncertainties in interpolation errors discussed in the section entitled "The Evaluation of Dose Equivalent Produced by Neutrons. Figure 8 shows the results of calculations of both the shallow and deep dose equivalent indexes by two groups -- by Chilton and his colleagues at Urbana-Champaign [71-75] and by Burger and his

colleagues at Neuherberg [105,106]. Agreement between the two sets of calculations is seen to be fairly good.

Effective dose equivalent must, of course, be calculated in a humanoid phantom. Kramer et al. have described two sex-specific adult human phantoms ADAM and EVA, derived from the original MIRD phantom, which have been used for extensive calculations of effective dose equivalent [107-108] (see Fig. 9).

Kramer and Drexler [109] have drawn attention to one possible source of ambiguity in the definition of H_E. As currently defined effective dose equivalent requires a weighing factor of 0.06 to be applied to each of the five organs or tissues -- "the remainder" -- receiving the highest dose equivalent, and for this sum to be added to the sum of the weighted dose equivalents to the six principal organs. The organs and tissues which comprise "the remainder," vary with radiation type, energy and radiation geometry. It is not therefore appropriate, as is done by some workers to predetermine which organs or tissues comprise the remainder. Calculations of effective dose equivalent are phantom dependent, and it will be important to reach general agreement in the model to be used.

Conversion coefficients from fluence to dose equivalent are now available from thermal energies to 14 MeV for several dose equivalent quantities including: effective dose equivalent, the deep and shallow dose equivalent indexes, and for $H_{0.07\ mm}$ and $H_{10\ mm}$ (the dose equivalent on the principal axis, if the ICRU sphere at depths of 0.07 mm and 10 mm, irradiated by a broad parallel beam of neutrons, Fig. 10) [102].

For higher energies (up to 10^{12} MeV) there is no single set of data that spans the entire energy range, and calculations of H_E or H_I have not yet been made. Conversion coefficients are therefore obtained from calculations

in a 30 cm thick tissue equivalent slab phantom. (These, however, should be a good approximation to $H_{I,d}$; see Fig. 11 [67-69,75,110-112].)

The Evolution of the Dose Equivalent Index Quantities

ICRP Publication 26 suggested that for "external exposures to ionizing radiation, on those occasions when information is lacking concerning the actual distribution of dose equivalents in the bodies, it is possible to assess the maximum value of dose equivalent that would occur in a 30 cm sphere (the deep dose equivalent, $H_{I,d}$)."[7] [10] Almost immediately, following the publication of ICRP 26 there were debates published in the literature that the dose equivalent indexes might not necessarily provide precise estimates of the effective dose equivalent [114-116]. It was necessary to establish a considerable quantity of data, showing the relationship of many dosimetric quantities to the geometry of the irradiation and physical parameters of the radiation field, in order to be able to determine the accuracy with which the index quantities approximate the effective dose equivalent.

Over the past nine years a great many data have been accumulated for photons of energy up to 10 MeV [102,107,109] and for neutrons of energy up to 14 MeV [71-76,102,105,106,108].

Two international committees have had a special interest in these data. We have already briefly described in the previous section the work of the ICRP Committee 3 Task Group on External Radiation. This group, which is revising the data in ICRP Publication 21, will be able to provide improved fluence to

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[7]This original version has been modified to ensure adequate protection for shallow organs, e.g., skin and eye lens [113].

dose equivalent conversion coefficients for the MADE but also for effective dose equivalent, the dose equivalent index quantities, and for $H_{10\ mm^{\circ}}$.

The second international group, chaired by Prof. T.E. Burlin, that has been studying the new data is the Committee on the Practical Determination of Dose Equivalent of the International Commission on Radiation Units and Measurements. This committee was established in 1979 and charged with the task of recommending a method of quantitatively assessing the irradiation of persons from sources of imaging radiation external to the body, in the light of recommendations of both the ICRP and ICRU made during the last decade and taking into account the new data which have been developed. This committee has developed a methodology for assessing the various possible alternatives and compiled the supporting data. At the present time its recommendations are under consideration by the Commission. It is therefore not possible to discuss these recommendations here, but it is hoped that a report may be issued before the end of the year.

The charge given to the Burlin Committee was sufficiently important for the European Community to organize a "Seminar on Radiation Protection Exposure Quantities for External Exposure" held at the Physikalische-Technische Bundesanstalt in Braunschweig in October 1980. The published proceedings of the seminar is an invaluable source of information [117].

Dose equivalent quantities have one important property for radiation protection — they provide a system which is unified for all radiations. [At the present time different operational quantities are used for photons (exposure), β-particles and electrons (absorbed dose in air or tissue), and for neutrons (fluence, dose equivalent ceiling)]. There is then some argument

for retaining the use of some form of dose equivalent quantity(ies) in the future. The dose equivalent indexes have, however, not been widely used in radiation monitoring because of both practical and the theoretical difficulties in their application. In searching for improved quantities it is possible to list the desirable properties of dose equivalent operational quantities used in monitoring. They should be:

- Measurable under operating conditions
- Compatible with existing instruments
- Physically realizable in standards laboratories
- Calculable
- Related to primary limits
- Durable
- Additive, single-valued, point specific
- Relatable to a specific phantom.

The choice of a specific phantom is not easy. The ICRU sphere has the advantage of being uncomplicated and accepted by international authorities; detail of its composition (tissue) is unlikely to be changed; it has an isotropic response to radiation. Furthermore it is a reasonable phantom for calibration purposes (e.g., for personal dosimeters worn on the human abdomen). Such properties make it suitable for the basis of a calibration standard to be set up in a National Standards Laboratory.

The ICRU sphere, however, can clearly never be used to determine organ dose equivalents or the effective dose equivalent. For this purpose an anthropoid phantom is needed. Several simple alternatives to the sphere have been used for calculation (the 30 cm thick tissue slab, cylinder, etc.) but all have the principal defect of the sphere. Several complex anthroid phantoms have been

constructed to facilitate organ dose measurements both for photons (e.g., Alderson Rondo phantom, Plastinaut, Mr. Adam). However, as we have seen extensive calculations of effective dose equivalent have been made in the modified MIRD-5 phantoms ADAM and EVA (see the previous section). Such phantoms are most important for accurate calculation but doubtless will be subject to continuing improvement as facility is available. Furthermore individual anatomical variation in monitored individuals is quite significant, and the accurate determination of organ dose and effective dose equivalent most always demand individual attention. Such arguments tend to suggest that measurements made based upon calibrations with the ICRU sphere may be linked, with sufficient accuracy for routine monitoring, both to radiation field quantities and to calculations of dose equivalent in anthropoid phantoms.

The development of suitable operational dose equivalent quantities requires one further set of simplifications. It is only practicable, for routine monitoring, to specify maximal conditions. (Consideration of the host of alternative radiation conditions is just too complicated.) Such conditions are, in general, obtained when the human body is irradiated by a broad unidirectional parallel beam of radiation incident on the anterior face of the body and leaving from the posterior face.

In discussing radiation fields it is then convenient to define two concepts: expansion and alignment of a radiation field.

An <u>expanded field</u> is a hypothetical infinite-uniform-radiation field in vacuo having the same particles fluence, energy spectrum, and angular distribution as does an actual field at the point of interest. <u>An expanded and aligned radiation field</u> is a hypothetical infinite-uniform-radiation field

in vacuo and has the same particle fluence and energy spectrum as does an actual field at the point of interest, but being unidirectional.

With these conditions of the radiation field specified it is then possible to define quantities including these conditions--making it possible to calibrate physically small instruments, which have an isotropic response, in terms of these quantities which are then referred to as "aligned dose equivalent quantities."

As we have seen as early as 1973 workers at high-energy accelerator laboratories have found it helpful to define what is, in effect, the aligned dose equivalent at a depth of 10 mm in a tissue equivalent phantom [76,77]. Other depths at which these aligned dose equivalents might be specified are 0.07 mm and 3 mm, because of the specification of the thickness of the skin and the depth of the lens by ICRP [10].

Another concept which is of great value in clarifying dose equivalent quantities is that of "energy summation." Here the separate maximum dose equivalents from each energy increment of the incident aligned and expanded radiation field, irrespective of where these maximum dose equivalents occur, are summed. The value of the "energy-summed" quantity is equal to this sum. Aligned and energy-summed quantities were first identified as ceiling quantities by Harvey in 1975 [8], and are of great practical importance because the so-called neutron "rem-meters" are designed to measure this quantity.

The Implications of a Risk-Related System on Radiation Protection for Dosimetry

The NCRP has for some years now been exploring the merits and disadvantages of a risk-based system of radiation protection [11].

While there would not appear to be any significant consequences for the techniques of dosimetry if such a change were to be made, there do seem to be important philosophical and logical advantages.

While the concept of dose equivalent has served radiation protection well it is not without its difficulties, both theoretical and practical -- some of them have been already discussed in this paper. It is an appropriate time therefore to discuss whether we may move toward the removal of the concept of dose equivalent from radiation protection dosimetry.

To many dosimetrists the calculation of dose equivalent has seemed almost irrelevant to the purpose of radiation protection and carried out largely for legal requirements. The basic goal of radiation protection is to limit the interaction of ionizing radiations with people. The amount of radiation can be specified directly in terms of the radiation field itself. This is, of course, the reason for the creation of the operational quantities and leads to the determination of the conversion coefficient described in the previous section. In order to determine an acceptable limit to the exposure some specific radiobiological model may have to be used, but there is no pressing need to express the radiation field in "biological units."

One clear advantage of measurements which define the physical parameters of radiation fields is that they are immutable. Quantities which are administratively defined, such as dose equivalent, are transient and may vary in their definition. Administrative quantities required for radiation protection purposes may be derived from field quantities, but the converse is not necessarily true. It is partly for this reason that radiation protection

measurements at accelerators are made to define the parameters of radiation fields as accurately as possible [58,78,101]. Burlin and Wheatley have strongly urged the definition of photon field in terms of photon fluence [118], while Burlin has recently indicated the unified value of such an approach for all ionizing radiations [119].

Casarett has succinctly evaluated the disadvantages of our present dose equivalent-based system of radiation [120].

> "It is proper to distinguish the dose equivalent from biological risk. The utilization of rem for dose is inappropriate in the context of risk because the rem is frozen within the LET-dependent quality factor system. Because of the rigidity of his interlocking physically defined system, a change in MPD for one radiation, e.g., on the basis of a new risk estimate, requires, for consistency, changes in the MPDs for the other radiation. If an exception were made and, in effect, the Q for that one radiation were changed instead, that would be tantamount to injecting a bit of the risk system into the current system. For consistency, either the other Q values would need to be changed according to the LET-dependence in the current system, or changed on the basis of risk. With the current system, Q is an especially knotty problem in regard to the internal emitter field."

In some sense the dose equivalent-based system is now a liability, inhibiting communication between the Radiobiologist and Health Physicist. The basic premises of the dose equivalent system (no threshold, linearity of dose effect relationship, Q-LET relationship) form a consistent set which cannot be changed piecemeal and yet which does not correspond to the natural world as understood by radiobiologists.

Over the past 15-20 years great efforts have been made to determine the risks associated with exposure to ionizing radiations. An important example of the risk approach is the development of radon daughter limits for mine workers in terms of a readily measurable quality -- the working level month. Limits may be established from the data provided by epidemiological studies without reference to LET, Q, or absorbed dose [121].

Similar approaches have been used at particle accelerator facilities. Swanson has estimated the risk of fatal malignancies induced by leakage neutrons to patients undergoing high-energy photon therapy. These risk estimates were obtained without reference to neutron RBE or quality factor, but did require a knowledge of risk in terms of absorbed dose [122]. A similar approach has been taken by Smith et al. to determine the risk of cataract and leukemia to patients undergoing radiotherapy of the head by 720 MeV alpha particles from neutrons produced by alpha particle interactions in tissue [123].

Lave has summarized the need for risk estimates in regulation in the following words:

> "This widespread concern for lowering risks to health resulted in major new legislation in the 1970s and more stringent standards for activities already regulated (for example, a miner's exposure to coal dust). This legislation can be divided into two basic types. The first requires the regulators to lower risks from a substance to zero or negligible levels without concern for the resulting costs; technological feasibility is the only constraint. The second requires the regulators to balance some measure of the benefits from lowering

the risk against the costs of doing so. I have shown elsewhere the first framework is self-contradictory...[See Ref. 124.] In each regulatory action there is at least an implicit weighing of costs and benefits; the second type of legislation differs from the first only by making the balancing explicit.

Whether the balancing is implicit or explicit, crucial pieces of information are the magnitude of risk and how risk will change with alternative regulations. Without being able to measure risks quantitatively and to estimate the effects of proposed standards, regulation is reduced to guesses based on what are called prudent judgments. These guesses uncover and exacerbate value conflicts between those who are opting for greater safety, and are thus willing to accept less consumption, and those who are not. Without estimates of risk, guesses or value judgments are the only devices for setting standards, and the inherent differences in values inevitably lead to maximal conflict." [125]

In conclusion I would like to remind the reader of the intriguing speculation — shared by many — that had nature revealed her secrets in a different order, the entire progress of radiation protection might have been very different. Had energetics of high-LET radiations been discovered before x-rays we might never have had to invent dose equivalent!

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Table 1 -- Comparison of Calculated Values of Various Dose Equivalent Quantities in Several Typical Accelerator Neutron Spectra*

Spectrum	$H_{ceiling}/H_p$	$H_{10\ mm}/H_p$
RT	1.21	0.86
PSB	1.33	0.99
BEV	1.58	1.26
X2	1.23	0.96
PI	1.73	1.49
PLA	1.94	1.68
CR	1.73	1.00

*See text for the definition of H_p.

Table 2 -- A Comparison of Neutron Fluence to Dose Equivalent Conversion Coefficients Recommended by the NCRP and ICRP

Neutron Energy (MeV)	Conversion Coefficient ($n\ cm^{-2}s^{-1}\ mrem^{-1}\ h$) NCRP	ICRP	Percentage Difference NCRP-ICRP/ICRP
2.5×10^{-8}	272	260	+ 4.6
1.0×10^{-7}	272	240	+13.3
1.0×10^{-6}	224	220	+ 1.8
1.0×10^{-5}	224	230	- 2.6
1.0×10^{-4}	232	240	- 3.3
1.0×10^{-3}	272	270	+ 0.7
1.0×10^{-2}	280	280	0.0
1.0×10^{-1}	46	48	- 4.2
5.0×10^{-1}	10.8	14	-22.9
1.0×10^{0}	7.6	8.5	-10.6
2.0×10^{0}	-	7.0	-
2.5×10^{0}	8.0	-	-
5×10^{0}	6.4	6.8	- 5.9
7×10^{0}	6.8	-	-
1.0×10^{1}	6.8	6.8	0
1.4×10^{1}	4.8	-	-
2.0×10^{1}	4.4	6.5	-32.3
4.0×10^{1}	4.0	-	-
5.0×10^{1}	-	6.1	-
6.0×10^{1}	4.4	-	-
1.0×10^{2}	5.6	5.6	0
2.0×10^{2}	5.2	5.1	+ 2.0
3.0×10^{2}	4.4	-	-
4.0×10^{2}	4.0	-	-
5.0×10^{2}	-	3.6	-

Table 3--Analytical Expression for the Calculations of Neutron Fluence to Dose Equivalent Conversion Coefficients*

Energy Range (MeV)	g(E) $cm^{-2}s^{-1}$ $mrem^{-1}$ h
$<10^{-2}$	232
$10^{-2} \leq E \leq 10^{0}$	$7.20\ E^{-3/4}$
$10^{0} \leq E \leq 10^{1}$	7.20
$10^{1} \leq E \leq 5000$	$12.8\ E^{-1/4}$

*See References 98-101 and Fig. 7.

Table 4--Spectrum Averaged Fluence to Dose Equivalent Conversion Coefficients for HPRR Spectra*

Neutron Spectrum	Conversion Coefficient (10^{-10} Sv cm^2) NCRP (Linear Interpolation)	NCRP (Logarithmic Interpolation)	Percentage Difference
Unshielded Reactor	2.47	2.62	- 5.7
13 cm Steel Shield	1.77	2.04	-13.2
20 cm Lucite Shield	1.15	1.19	- 3.4
20 cm Concrete Shield	1.06	1.14	- 7.0
5 cm Steel and 10 cm Concrete Shield	0.96	1.06	- 9.4

*See Reference 83.

Figure Captions

Fig. 1. A graph of the relative spectral luminous efficacy (efficiency), V (λ) as a function of wavelength λ. The values shown are those adopted by the Commission Internationale de l'Eclairage for photopic vision (daytime vision).

Fig. 2. Quality factor, Q, as function of linear energy transfer, LET_{∞}.

Fig. 3. Conversion factors for neutrons. Unidirectional broad beam, normal incidence. The curves indicate the values recommended by the Commission (ICRP Publication 21).

Fig. 4. A comparison of neutron fluence rate to dose equivalent rate conversion coefficients recommended in ICRP Publication 21 and NCRP Report 38.

Fig. 5. Maximum dose equivalent for a unit incident-neutron fluence at any depth in tissue as a function of neutron energy (NCRP Report 38).

Fig. 6. A graph showing the differences between linear-linear and log-log interpolation techniques. The recommended conversion coefficient of ICRP 21 are shown as a solid line and those of NCRP 38 as points. Linearly interpolated values between the NCRP 38 points are shown as a dashed line.

Fig. 7. Fluence rate to dose equivalent rate conversion coefficients--a comparison between values computed from analytical expressions and calculated data.

Fig. 8. Dose equivalent indexes per unit fluence for neutrons incident in a broad unidirectional parallel beam on the ICRP sphere.

Fig. 9. Effective dose equivalent per unit fluence for neutrons incident in AP and PA geometry upon an anthropomorphic phantom.

Fig. 10. Dose equivalent per unit fluence at depths of 0.07 mm and 10 mm on the principal axis of an ICRU sphere (broad unidirectional parallel beam).

Fig. 11. Maximum dose equivalent per unit fluence for neutrons incident on a 30 mm thick equivalent tissue slab (broad unidirectional parallel beam).

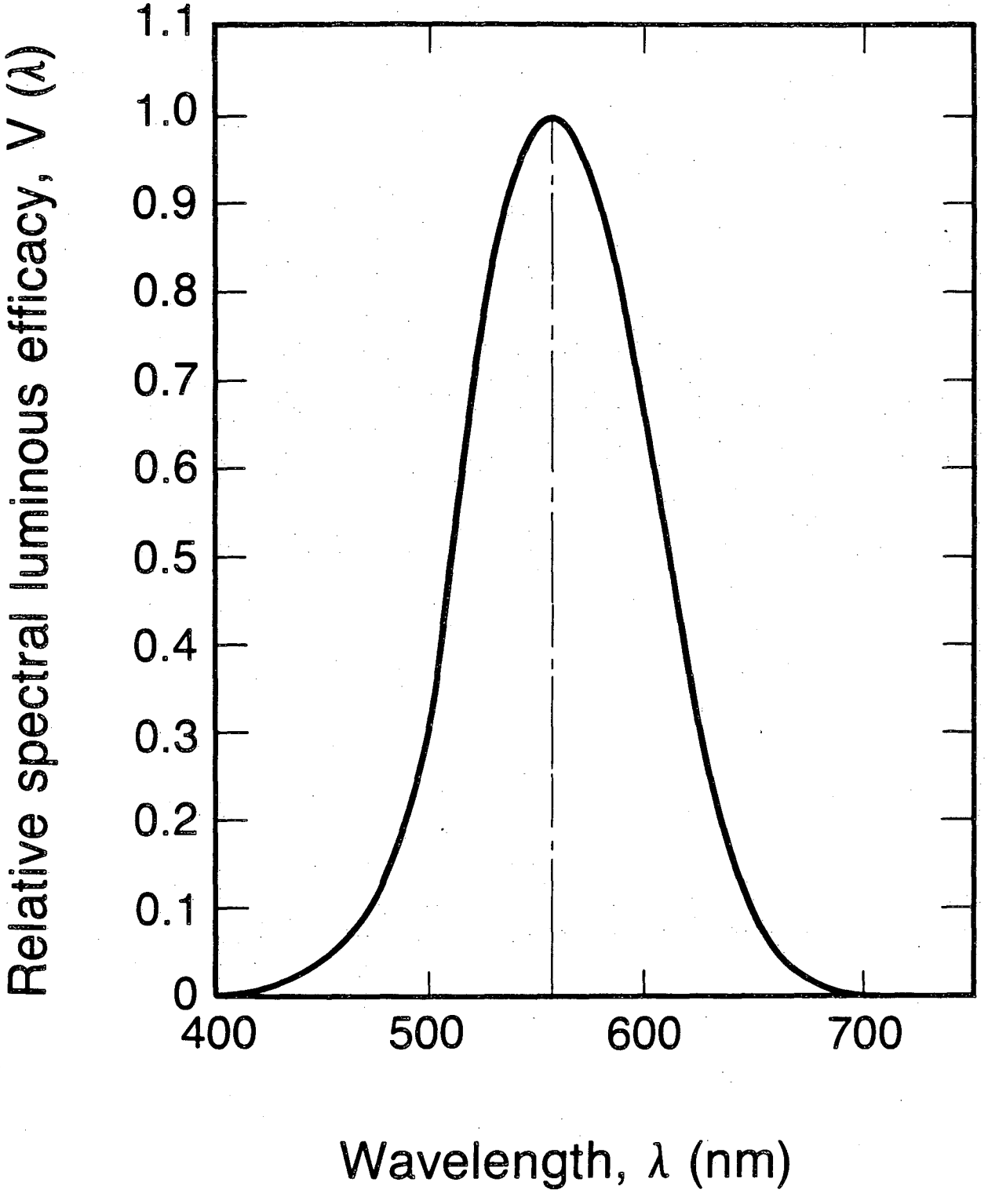


Fig. 1 XBL 843-10141

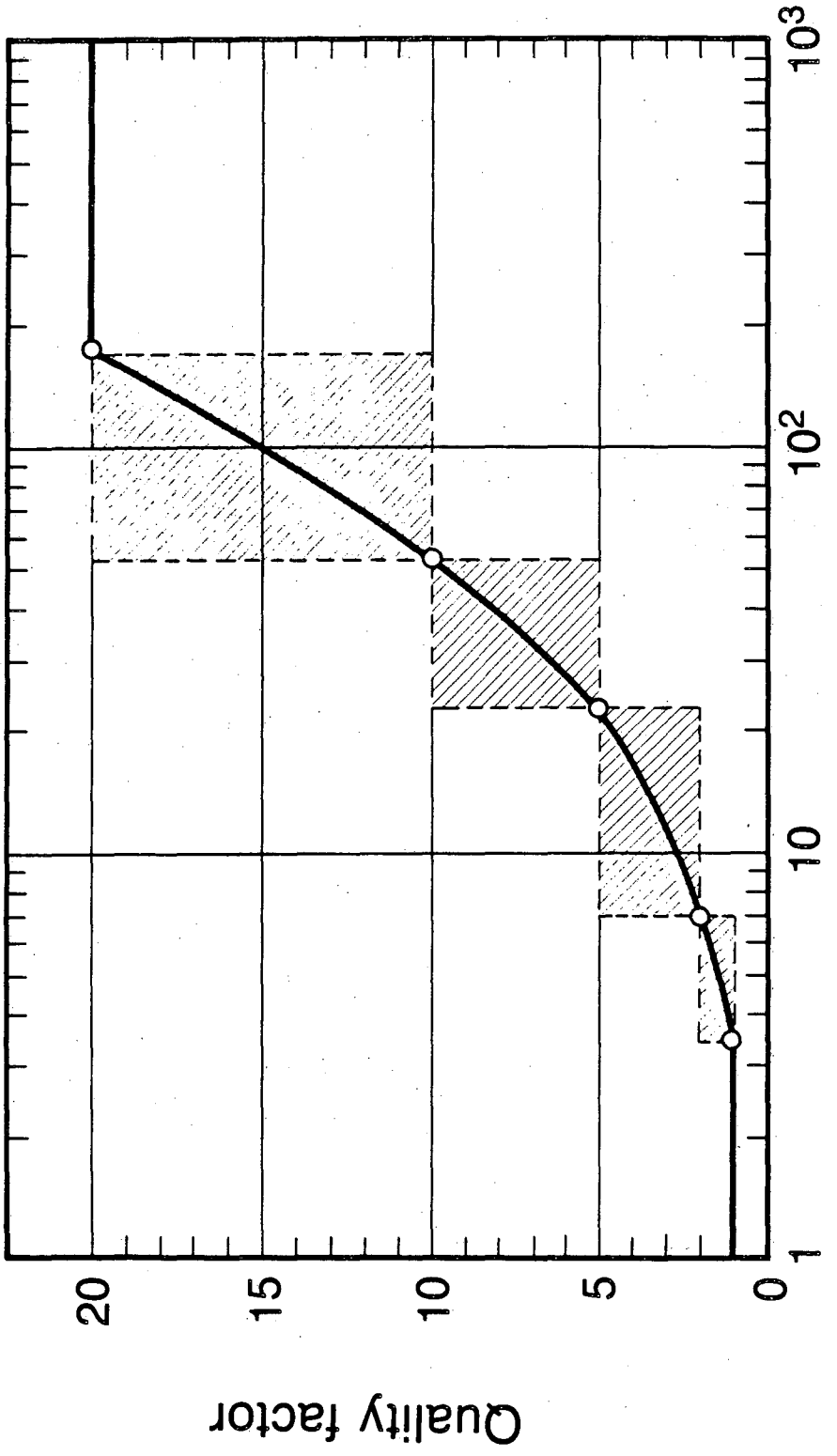


Fig. 2

XBL 843-10142

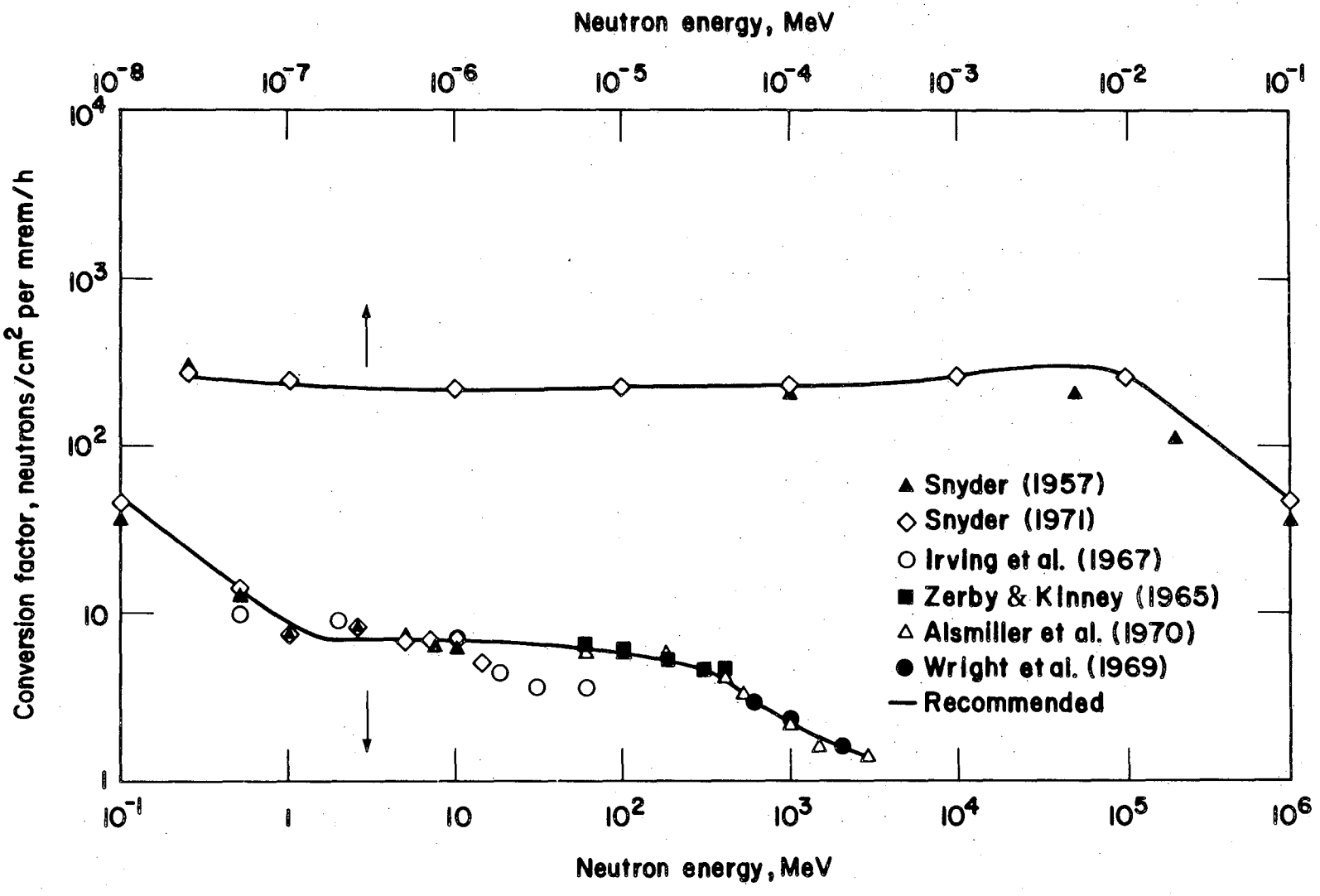


Fig. 3

XBL 843-1001

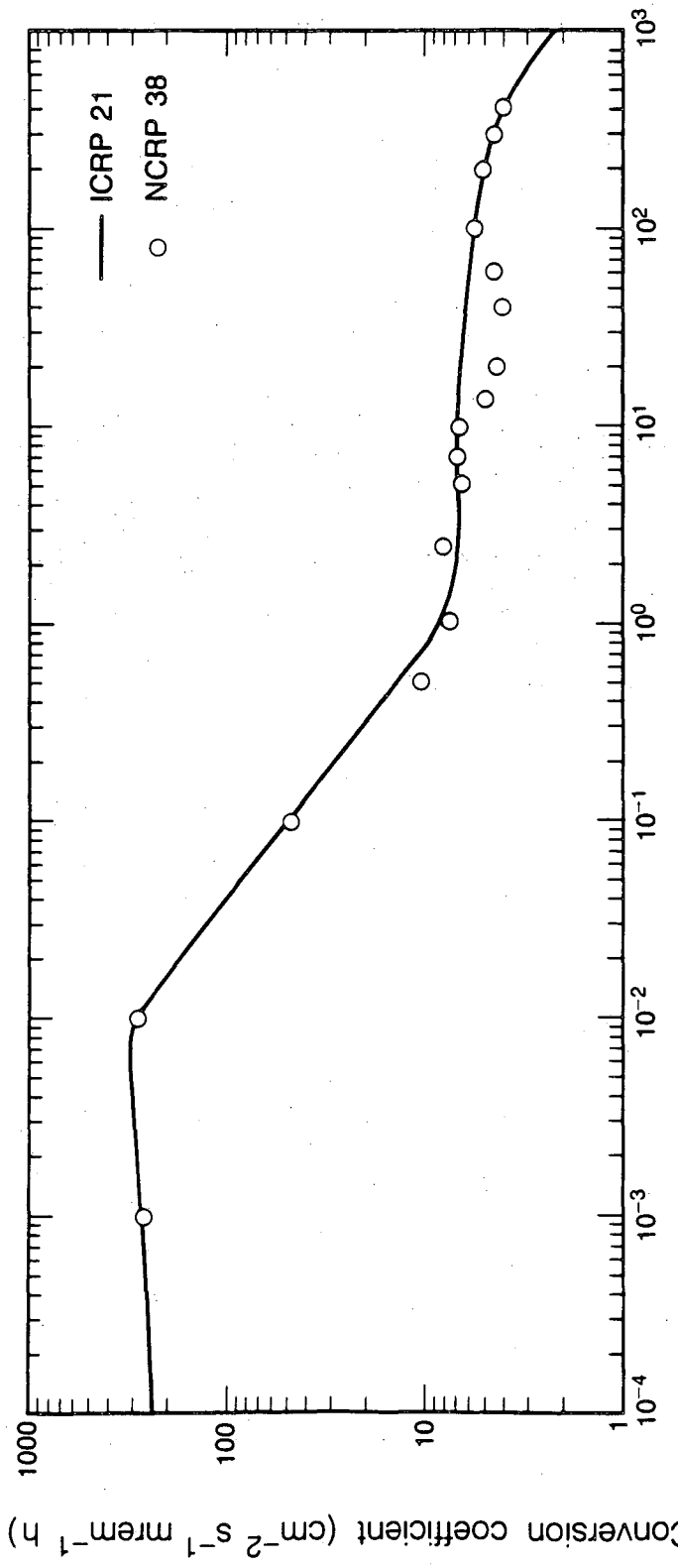

ICRP 21
NCRP 38
Conversion coefficient (cm^{-2} s^{-1} mrem^{-1} h)
Neutron energy (MeV)
1000
100
10
1
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
XBL 843-10144

Fig. 4

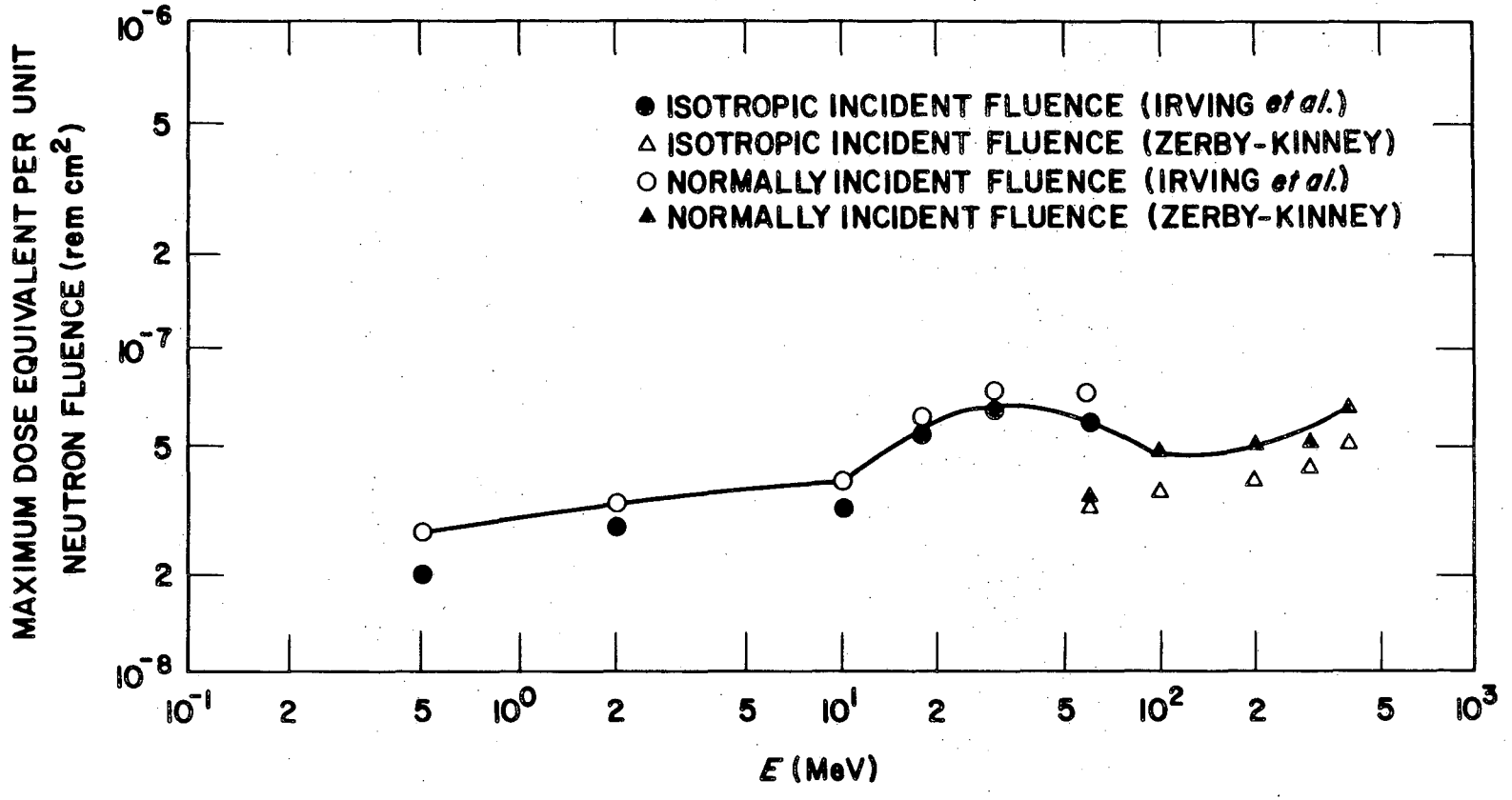


Fig. 5

XBL 843-999

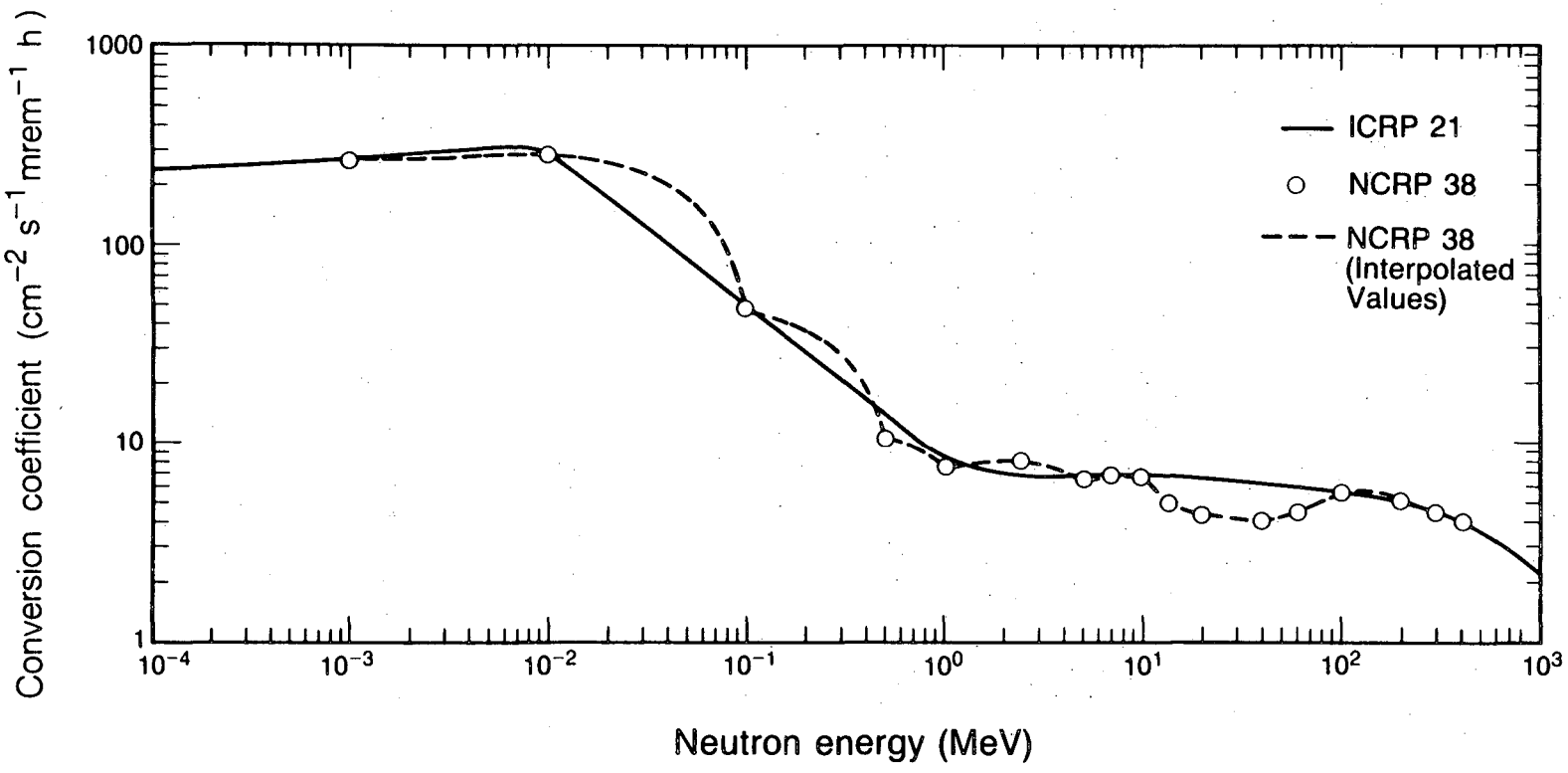


Fig. 6

XBL 843-10143

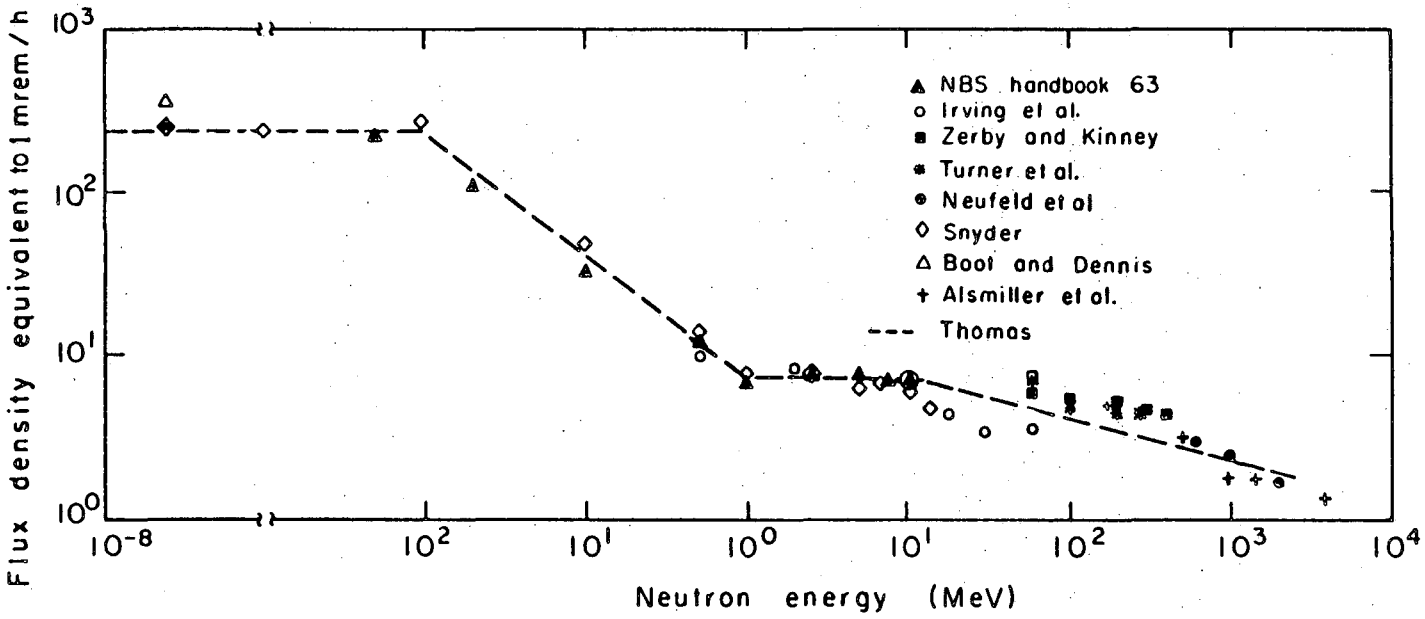


Fig. 7

XBL703-2499

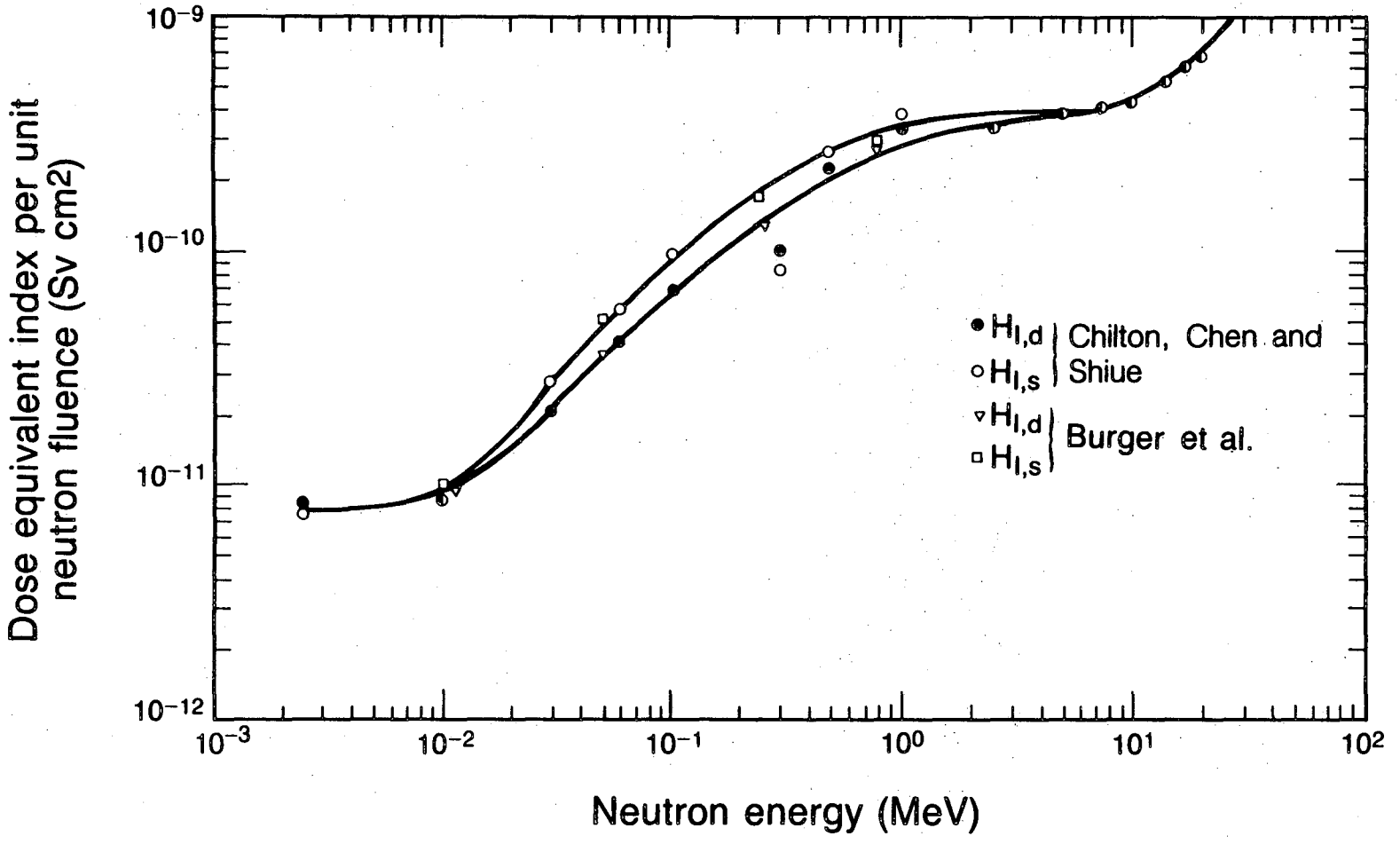


Fig. 8

XBL 843-10196

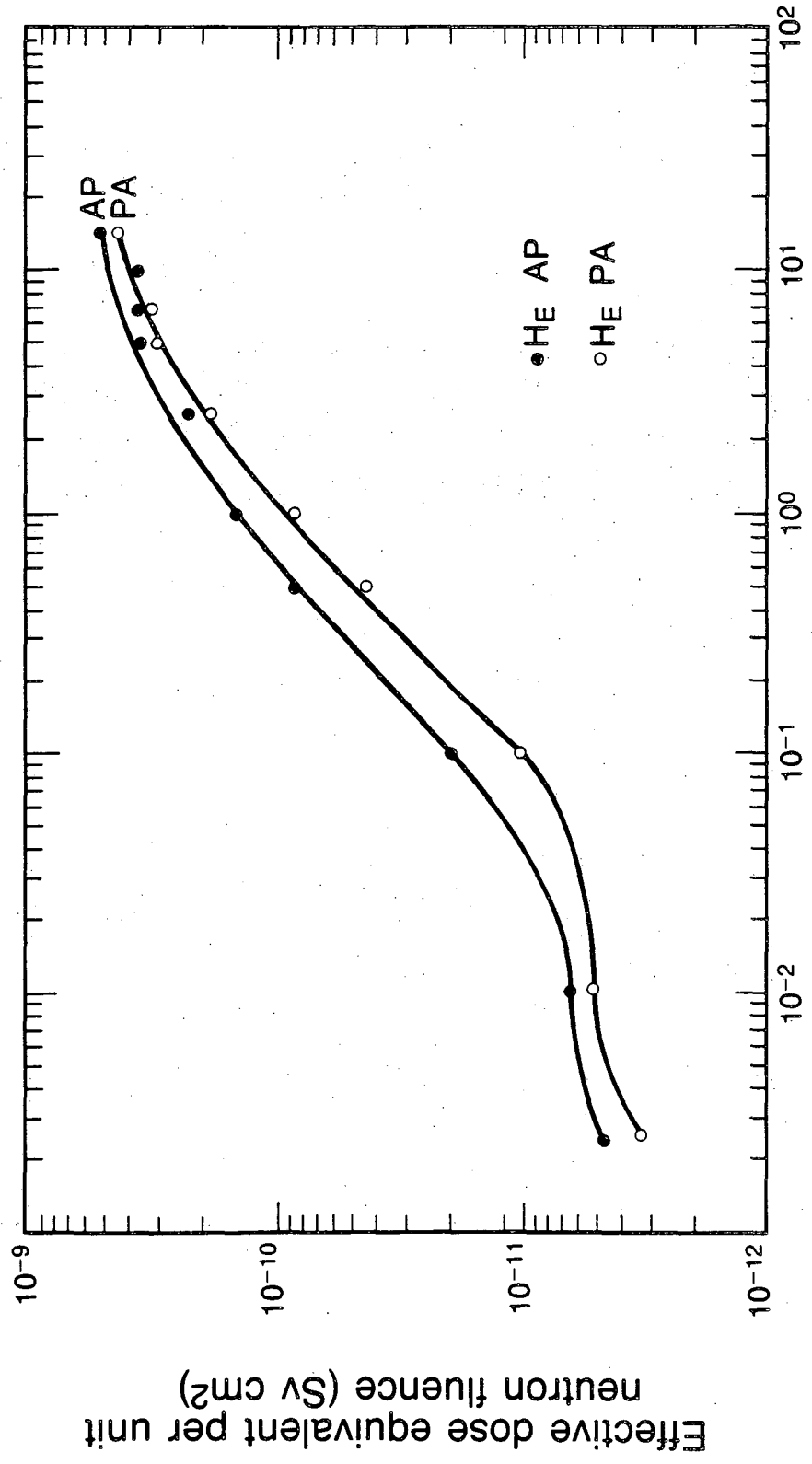
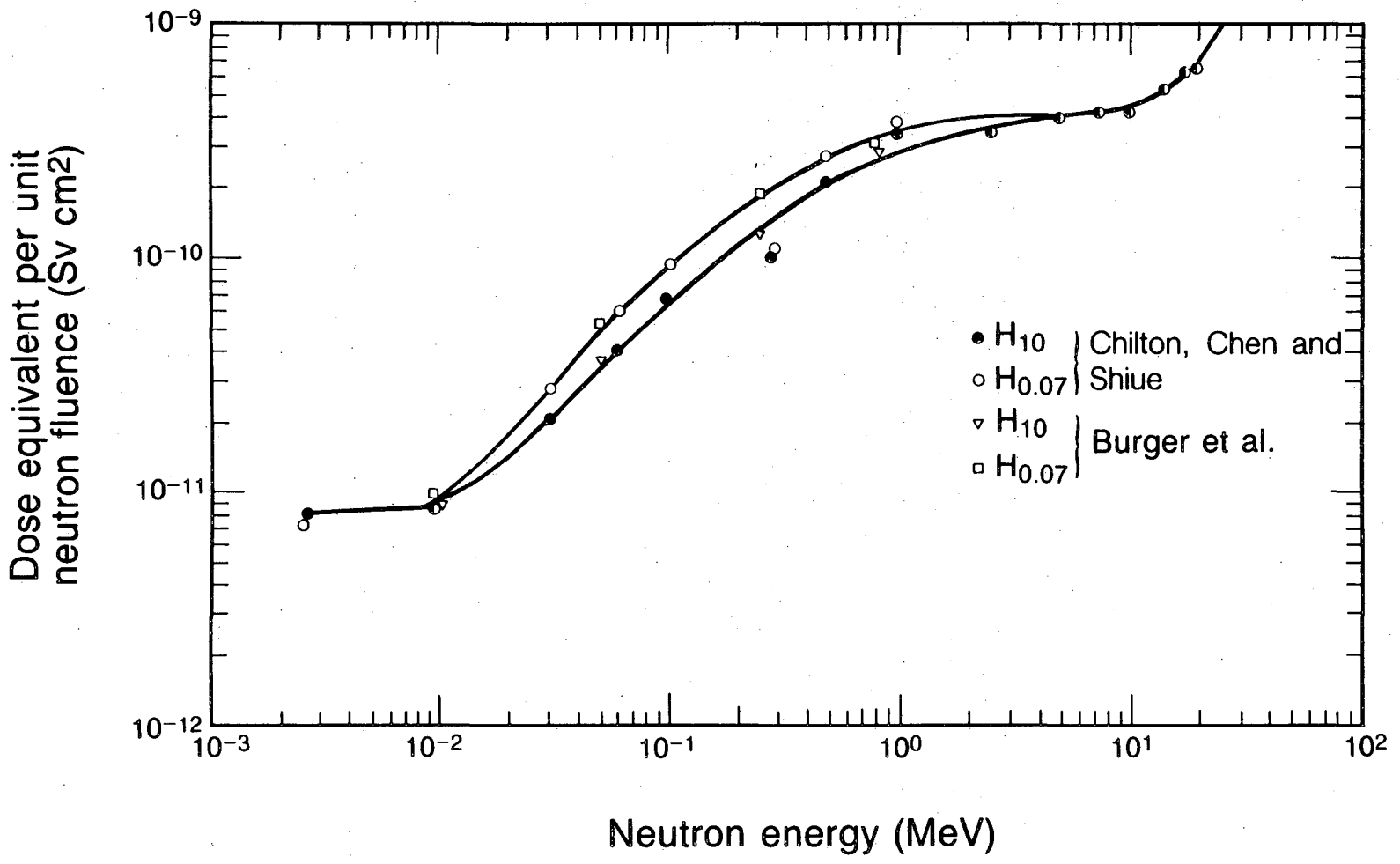
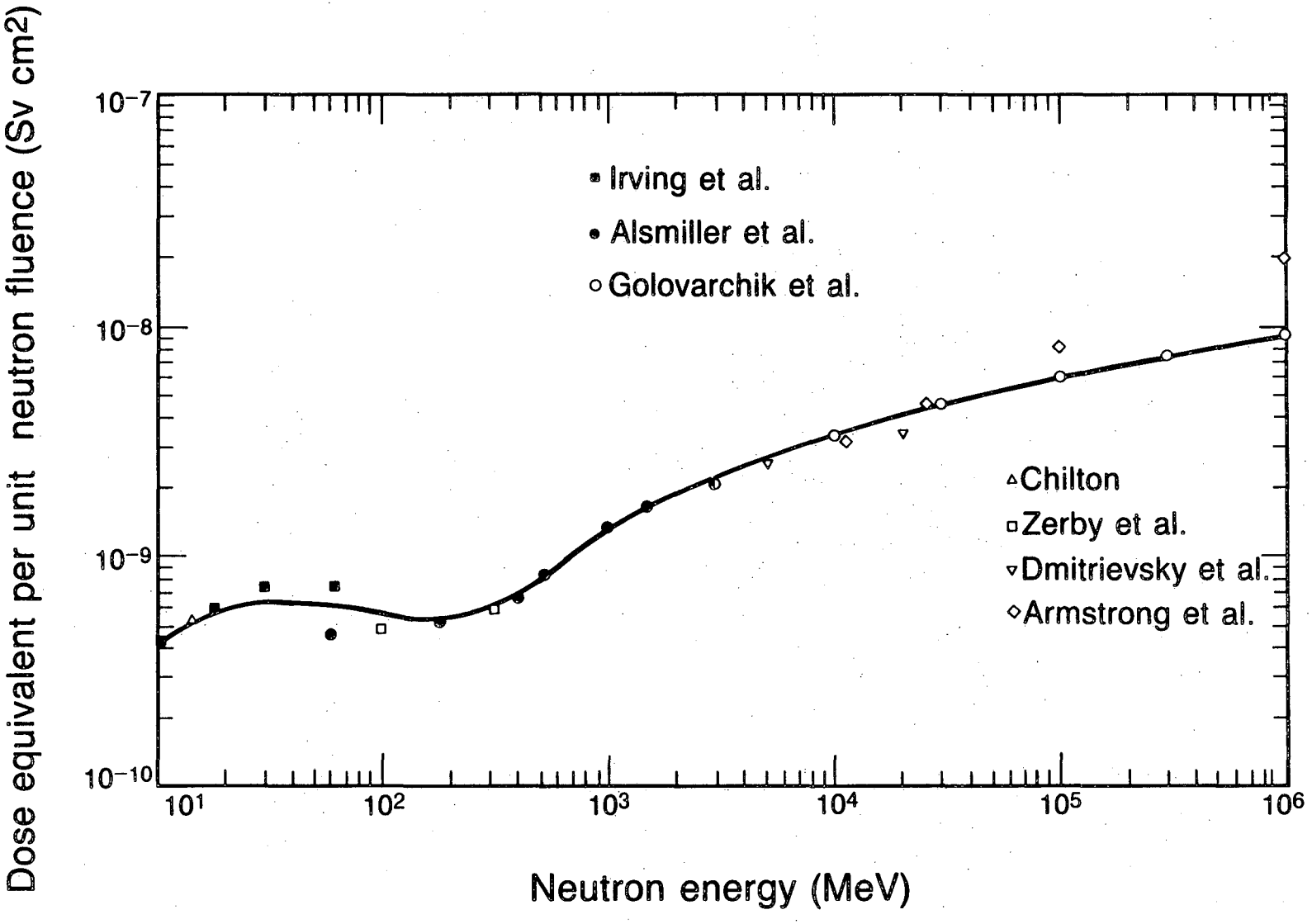

Effective dose equivalent per unit
neutron fluence (Sv cm2)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁻²
10⁻¹
10⁰
10¹
10²
Neutron energy (MeV)
AP
PA
•HE AP
○HE PA
XBL 843-10193

Fig. 9



XBL 843-10200

Fig. 10



XBL 843-10205

Fig. 11

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