NEUTRON DEPTH DOSE IN MAN AND CORRESPONDING QUALITY FACTORS. SOME HERETICAL CONSIDERATIONS

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DEFINITIONS

Introducing new concepts in a field already characterized by much confusion is risky. Therefore it is an absolute necessity to define as accurately as possible all quantities and symbols utilized. These definitions are listed below in a pedantic way. Because of unavoidable repetitions, the reading of these definitions can be tedious. An important part of the "philosophy" of this study is already contained in the following definitions:

E_n = neutron initial energy = energy of neutrons incident in the human body.

D = absorbed dose (= energy dose) measured in rad, as defined by ICRU, (1).

The D curves (Fig. 4) have been calculated (3) with Monte Carlo methods on the basis of the formula:

$$D \text{ (in element } \Delta V) = \frac{\sum_{i=1}^{N} \int_{0}^{L_i} LET_i\,(x_i) \cdot dx_i}{\Delta m}$$

The symbols appearing in this formula are explained below, in relation with the definition of QF and DE.

rad = unit in which the absorbed dose D is expressed

$$1 \text{ rad} = 100 \frac{\text{erg}}{\text{g}}$$

D_{Max} = absorbed dose in the volume element of the central slab (Fig. 3) of the phantom (Fig. 2) where D is a maximum. In the case of a normally incident broad beam, this happens in the front element no.57, when $E_n \lesssim 25$ MeV. For increasing E_n, the location of this maximum moves inward.

D_{Mean} = absorbed dose, averaged over all 30 volume elements of the central slab (Fig. 3).

$D_{Midline}$ = absorbed dose, averaged over the 6 central elements (41, 42, 42, 43, 43, 44) of the central slab.

R = fraction of the total absorbed dose (in the case of an irradiation by neutrons) which is due to the capture gamma rays (Fig. 1).

R_{Max} = R in the phantom element where it has the highest value. This occurs mainly in element 60 (back element).
Therefore $R_{Max} \cong R_{60}$.

R_{Min} = R in the phantom element where it has the lowest value. This occurs mainly in element 57 (front element).
Therefore $R_{Min} \cong R_{57}$.

R_{Mean} = Average of R over all 30 elements of the central slab (see Fig. 3).

$R_{Midline}$ = Average of R over the 6 central elements of the central slab (41, 42, 42, 43, 43, 44).

qf = Quality factor as a function of the stopping power (LET_∞) in tissue. This concept is based on microscopic considerations along the tracks of charged particles (Fig. 5).

(qf) = qf in the case of low doses or of chronic exposure at low dose rates, when genetic damages and damages to critical organs are of primary importance. (qf) is chosen conservatively in order to eliminate uncertainties. It is used for preventive purposes. (qf) has been defined by ICRP and ICRU in function of LET_∞ (Fig. 5). (qf) applies only when doses and dose-rates stay within the permissible ICRP limits for professionally exposed workers.

{qf} = qf in the case of acute exposure at high doses and dose-rates which may be encountered in radiation accidents, in radiotherapy and in nuclear war situations. {qf} is a new concept. It can be evaluated indirectly from experiments (Fig. 5). {qf} is used for the evaluation of the true overall somatic damage to the whole body. {qf} is expressed as realistic as possible. It does not contain any safety factors.

QF = Quality factor defined as $\frac{DE}{D}$ when all other modifying factors are equal to unity. This concept is a macroscopic one. QF can be interpreted as being a weighted average of qf along all tracks.
If one considers a volume element ΔV containing N tracks numbered by i, the length of a track as L_i, and a location on the track defined by x_i with $0 \leqslant x_i \leqslant L_i$ then the relationship between qf and QF can be written:

$$QF = \frac{\sum_{i=1}^{N} \int_{0}^{L_i} qf_i\,(x_i) \cdot LET_i\,(x_i) \cdot dx_i}{\sum_{i=1}^{N} \int_{0}^{L_i} LET_i\,(x_i) \cdot dx_i} = \frac{DE}{D}$$

$LET_i\,(x_i)$ is the $\frac{dE}{dx}$ for the track i at the location x_i.

(QF) = QF in the case of low doses or of chronic exposure at low dose rates, when genetic damages and damages to critical organs are of primary importance. (QF) is conservative and is used for preventive purposes. (QF) can be calculated by Monte Carlo methods on the basis of (qf) using the formula above. (QF) applies only when doses and dose-rates stay within the permissible ICRP limits for professionnally exposed workers. According to ICRU, (QF) is one of the modifying factors by which the absorbed dose D must be multiplied in order to obtain the dose-equivalent (DE). Some authors like Patterson et al. (6) wish to designate (QF) by MF = Modifying Factor (see Fig. 6).

$(QF)_{Max}$ = (QF) in that volume element of the anthropomorphic phantom (Fig. 2 and 3) where $\frac{(DE)}{D}$ is a maximum (Fig. 6).

$(QF)_{MADE}$ = (QF) in that volume element of the antropomorphic phantom where (DE) is a maximum (Fig. 6).
MADE = Maximum Dose Equivalent

$(QF)_{MADE}$ is also designated as $QF_{effective}$ by Neufeld.

$(QF)_{Mean}$ = (QF) averaged over all 30 volume elements of the central slab (Fig. 3) of the anthropomorphic phantom (Fig. 6 and 8).

$(QF)_{Midline}$ = (QF) averaged over the 6 central elements of the central slab of the anthropomorphic phantom.

$(QF)_{ICRP}$ = official (QF) curve recommended by ICRP (23). It is in principle a $(QF)_{MADE}$ curve, but for a phantom which was an infinite slab of tissue-equivalent material 30 cm thick (Fig. 8).

$(QF)^*$ = $R_{Mean} + 10 \cdot (1 - R_{Mean})$

This crude equation was intended to show an approximative way to relate QF and R (See § 1 and Fig. 8). It is interesting to verify that $(QF)^*$ and $(QF)_{Mean}$ are almost identical curves.

$\{QF\}$ = QF in the case of acute exposure at high doses and dose-rates which may be encountered in radiation accidents, in radiotherapy and in nuclear war situations. $\{QF\}$ is approximately the RBE corresponding to $LD_{50/30}$ or $LD_{10/30}$ for man. The relationship between $\{QF\}$ and $\{qf\}$ is also given by the above formula. $\{QF\}$ is used for the realistic evaluation of the true overall somatic damage to the whole body. It does not contain any safety factors.

$\{QF\}_{\text{best guess}}$ = $\{QF\}$ in function of E_n (Fig. 8) drawn as well as possible from available literature.

DE = Dose-equivalent defined by ICRU as follows:

$DE = D \cdot QF \cdot$ other modifying factors

For the purpose of this study it will be supposed to have conditions at which all "other modifying factors" are equal to unity. The DE curves (Fig. 9) have been calculated (3) with Monte Carlo methods on the basis of the following formula:

$$DE\ (\text{in element } \Delta V) = \frac{\sum\limits_{i=1}^{N} \int_{0}^{L_i} qf_i\,(x_i) \cdot LET_i\,(x_i) \cdot dx_i}{\Delta m}$$

where Δm is the mass of the matter contained in element ΔV. The other symbols appearing in this formula were already defined. DE is expressed in rem.

(DE) = DE in the case of low doses or of chronic exposure at low dose rates. (DE) is defined as long as it stays within the permissible ICRP limits for professionally exposed workers. (DE) is conservative and usually takes account of the worst case: the maximal damage appears in the most critical organ. (DE) is used for perventive purposes and is expressed in (rem). The quantity (DE) has been chosen by ICRP to state the basic official limits in radiation protection.

(rem) = unit in which (DE) is expressed. There is so much safety included in the (rem) that the original significance "Röntgen Equivalent Man" does not apply anymore. Only low (DE), within ICRP permissible limits, can be expressed in (rem). Example: 5 (rem)/year is a famous limit.

$(DE)_{Max}$ = (DE) in that volume element (usually 57 or 53 provided E_n is not too high) of the central slab (Fig. 3) where it is a maximum.

$(DE)_{Mean}$ = (DE) averaged over all 30 elements of the central slab.

$(DE)_{Midline}$ = (DE) averaged over the 6 central elements 41, 42, 42, 43, 43, 44. (Fig. 3)

$(DE)_{ICRP}$ = Old $(DE)_{Max}$ from (19). Also to be found in (14), (15). This is $(DE)_{Max}$ related to the infinite slab of tissue-equivalent material 30 cm thick (Snyder).

$(DE)_{reasonable} = D_{Max} \cdot (QF)_{Mean}$

$(DE)_{Min} = D_{Max} \cdot \{QF\}_{\text{best guess}}$

$\{DE\}$ = DE in the case of acute exposure at high doses and dose-rates which may be encountered in radiation accidents, in radiotherapy and in nuclear war situations. $\{DE\}$ describes the true overall somatic damage to the whole body. $\{DE\}$ is based on realistic considerations; it does not contain any safety factors.

$\{rem\}$ = unit in which $\{DE\}$ is expressed. $\{rem\}$ really means "Röntgen Equivalent Man". For example, an exposure of 400 Röntgen or a dose-equivalent of 400 $\{rem\}$ measured in the same conditions at the surface of the body both should produce (by definition) the same lethality in a human population.

$\{DE\}_{\substack{\text{best}\\\text{guess}}} = D_{\text{Mean}} \cdot \{QF\}_{\text{best guess}}$

$\{DE\}_{\text{Min}} = D_{\text{Midline}} \cdot 1$

anthropomorphic phantom : most of this study refers to a cylindrical phantom (see Fig. 2 and 3) composed homogeneously of tissue equivalent material. This phantom was used by Auxier, Snyder and Jones (3) for their Monte Carlo calculations (statistical sampling method).

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§ 1 GAMMA COMPONENT OF THE NEUTRON DOSE

It is often not realized that an important part of each neutron dose is absorbed by the human body in the form of a gamma dose.

These gamma rays have an initial energy of 2.2 MeV and originate from the $^1H\ (n, \gamma)\ ^2H$ capture reaction, which happens mainly to neutrons already slowed down by one or several other reactions. In general, these 2.2 MeV photons will deposit their energy, or part of it, at locations remote from the capture site, and many of them will escape from the human body. (Their relaxation length in tissue is $\sim$ 20 cm).

There are many other reactions neutrons can undergo in tissue, the most important of them being (for $E_n < 5$ MeV), the elastic scattering with hydrogen. All these reactions are characterized by the fact that, the energy deposition occurs mainly at or very close to the reaction site.

When considering a small mass of tissue in free space, or when irradiating an insect with neutrons, the $^1H\ (n, \gamma)\ ^2H$ reaction can be neglected because practically all capture γ-rays escape from this small mass and therefore do not contribute to the dose. Neglecting the dose contribution from the $^1H\ (n, \gamma)\ ^2H$ reaction, is practically equivalent to considering the First Collision Dose (5) only (see also Fig. 4).

This practice leads to erroneous results when extrapolating to man without reconsidering the $^1H\ (n, \gamma)\ ^2H$ reaction.

The importance of this reaction in man is shown in Fig. 1. R is the fraction of the absorbed dose, due to the capture gamma rays. R is reported from the most recent computations made in Oak Ridge (3) for an anthropomorphic phantom (see Fig. 2). Its central slab has been considered in detail (Fig. 3).

R can refer to different locations in the human body, and this has been indicated with corresponding subscripts (see the DEFINITIONS).

It is felt that the curve R_{Mean} might be the one with the highest significance, whereas all others refer to rather local situations in the human body. A close observation of Fig. 1 leads to several important conclusions:

- For neutrons with incident energies below 1 MeV the dominant part of the neutron absorbed dose is absorbed by man in the form of gamma rays.
- For a typical fission neutron spectrum, approximately one half of the total midline dose absorbed by the human body will be from capture gamma rays (16).
- Any usual gamma dosimeter worn by a person will therefore detect a substantial part of the neutron dose.
- An important portion of the neutron dose will therefore often be registered twice.
- If the neutron dosimeter of a worker shows an abnormally high dose, then his gamma dosimeter will also give abnormally high readings.
- Incident neutrons with energies below ~ 0.1 MeV should have a quality factor very close to one.

An excellent illustration of these conclusions is given by the Yugoslav accident at Vinca. Hurst et al. (18) summarized the situation as shown in the table below.

Individual	Neutron Dose		External γ-Dose	Total
	charged particles dose	H (n, γ) D γ-Dose		
H	66	99	158	323
V	89	133	214	436
G	90	135	189	414
M	87	130	209	426
D	91	136	192	419
B	45	67	95	207

(all values are in rad units)

For the people involved in that accident, an $R \cong 0.6$ was evaluated, and the overall gamma contribution to the total dose was approximately 80%.

Such facts are important when making cost/benefit evaluations in order to decide if a neutron dosimeter system should be introduced for a given group of persons.

Anticipating for the next chapters it is possible to write in a very simplified manner (assuming $E_n < 5$ MeV):

$$\boxed{\begin{array}{l}\text{Neutron}\\ \text{Dose D}\end{array}} \cong \boxed{\begin{array}{l}\text{Gamma component}\\ \text{D} \cdot \text{R with QF} = 1\end{array}} + \boxed{\begin{array}{l}\text{Proton component}\\ \text{D} \cdot \text{(1-R) with QF} = 10\end{array}}$$

It must be remarked that, assuming QF = 10 for the proton component is rather conservative. In order not to be over-conservative, $R = R_{\text{Mean}}$ was chosen (from Fig. 1). A very simplified formula for the quality factor then is:

$$(QF)^* = [R + (1-R) \cdot 10]$$

$(QF)^*$ has been drawn, in Fig. 8, as a function of the incident neutron energy. It is interesting to verify that,

$$(QF)^* \cong (QF)_{\text{Mean}}$$

This tends to confirm that $(QF)_{\text{Mean}}$ is conservative enough.

§ 2 SYMBOLISM

It can be seen from the DEFINITIONS (see above) that the following basic distinction have to be made for the proper comprehension of the next chapters:

( ): Quantities appearing in these brackets are conservative, used for preventive purposes and referring to low doses, or to chronic exposure at low dose rates. They are only defined for situations within the ICRP limits for professionally exposed workers.

{ }: Quantities appearing in these brackets are realistic, related to the actual somatic damage by acute exposure at higher doses and dose rates. They do not include any safety factors. They are generally defined, but relate mostly to situations beyond ICRP limits. Such situations may be encountered in radiation accidents, in radiotherapy and in nuclear war.

It is suggested that a distinction such as that proposed by Neufeld (22), or the one described here, should be introduced in the ICRU-Definitions in order to improve the mutual comprehension.

§ 3 ABSORBED DOSE PER UNIT NEUTRON FLUENCE

This important conversion factor is represented graphically in Fig. 4 and 4a, which will be discussed here.

The human body can be irradiated by different manners. The two basic types of irradiation are:

- irradiation by a broad beam of monoenergetic, monodirectional neutrons, with a velocity vector perpendicular to the axis of the body (normal incidence).
- irradiation of the body by a pure isotropic field of monoenergetic neutrons (isotropic incidence).

In both cases, the fluence is measured as the number of neutrons which enter a sphere of cross-sectional area of 1 cm^2 [see (1), (25) and (27)].

In practice, most irradiations will generally be complicated mixtures of the types defined above.

Several authors (25), (27) have shown that for any E_n, the normal incidence leads to higher doses than the isotropic incidence (Fig. 4a). As is known, the internationally accepted conversion factors are based on a normal incidence; therefore, this constitutes a first step toward conservatism (see Fig. 11).

Fig. 4a can be summarized by saying that D_{Max} for normal incidence is 1.2 to 2.5 times higher than D_{Max} for isotropic incidence (28).

Fig. 4 refers solely to normal incidence.

In conclusion it is suggested to apply our symbolism as follows:

(D) = D_{Max} in Fig. 4 or
upper border of the strip in Fig. 4a

{D} = according to the conditions, something like D_{Mean}
or $D_{Midline}$ in Fig. 4

§ 4 LET DEPENDENCE OF qf

The energy deposition in tissue occurs finally in the form of ionizations and excitations along the path of charged particles such as electrons, protons, alphas and recoil nuclei. The Linear Energy Transfer LET $= \frac{\Delta E}{\Delta x}$ varies along each path and is a function of the size, the charge and the momentary energy of the particle. It is widely accepted that the biological effectiveness is correlated to the LET. In general, a high LET is responsible for a higher biological damage. The ICRP recommends that a quality factor (qf) be used to account for differences in linear energy transfer (see Fig. 5).

Therefore, in fact, (qf) varies along every track. Yet, the LET is sometimes given in the form of a value averaged along the total track length. So the corresponding (qf) is already in the form of a track average.

To take account of this complex situation, the ICRP has chosen to recommend quite a conservative, and rather arbitrary, relationship between LET and (qf).

This relationship (fig. 5) is the main cause of the exaggerated conservatism which characterizes neutron dosimetry at the present time. It is felt that the (qf) — LET relationship should be chosen more realistically; for example, with maximum values of (qf) around 7 for LET = 110 keV/μm (from 10). This is then early enough to introduce conservatism in the steps leading to (D), (QF) and (DE) (see Fig. 11).

Fig. 5 shows also a "best guess" curve for {qf} . Several authors (4), (8) have already demonstrated that {qf} does not rise much above unity.

§ 5 QF FOR MONOENERGETIC NEUTRONS

Under given irradiation conditions, and using the statistical sampling method, the absorbed dose D in element ΔV is obtained (22) using the formula:

$$D = \frac{\sum\limits_{i=1}^{N} \int\limits_{o}^{Li} LET_i \ (x_i) \cdot dx_i}{\Delta m} \qquad \text{(see the DEFINITIONS)}$$

On the basis of the (qf) — LET relationship recommended by ICRP, the energy deposited along each Δx of every charged particle track is properly weighted by the local (qf). This leads to the evaluation (22) of the dose-equivalent DE in element ΔV of the anthropomorphic phantom:

$$DE = \frac{\sum_{i=1}^{N} \int_{o}^{L_i} qf_i\,(x_i) \cdot LET_i\,(x_i) \cdot dx_i}{\Delta m} \qquad \text{(see the DEFINITIONS)}$$

Therefore, the "macroscopic" quality factor QF for a given volume element is simply:

$$QF = \frac{DE}{D}$$

Because of the conservatism of the (qf) – LET relationship underlaying these computations, this QF must be written (QF).

The volume element(s) to which (QF) refers are characterized by using the following subscripts:

$(QF)_{Max}$ $(QF)_{MADE}$ $(QF)_{Mean}$ $(QF)_{Midline}$ $(QF)_{ICRP}$

(see the DEFINITIONS)

These (QF) are shown in Fig. 6 as a function of the energy of the incident neutrons. Among these curves, the decision to choose $(QF)_{Max}$ or $(QF)_{MADE}$ as an international standard represents another conservative step (see Fig. 11).

Leaving for a moment the theoretical considerations: Many QF values, determined experimentally for mammals by several authors (4), (10) were compiled. According to the biological criteria chosen by the experimentalists, the data were separated into a (QF) and a {QF} group represented in Fig. 7. This graph may not have much scientific significance, but it shows where the most frequent experimental values are situated:

for $(QF)_{experimental}$: between 3 and 4

for $\{QF\}_{experimental}$: between 1.5 and 2

On the other hand, the use of the $(QF)_{ICRP}$ curve (Fig. 8), for calculating average (QF), weighted by different neutron spectra (6), leads to values typically situated between 5 and 8.

This comparison confirms, that the recommended $(QF)_{ICRP}$ values are too high.

It would be of highest interest to rerun the Monte-Carlo programs made by Auxier et al. (3), Snyder (19), Thomas (6), Shaw et al. (9) and Neufeld et al. (21), (25) on the basis of a more realistic (qf) – LET relationship (Fig. 5), in order to avoid over-conservatism.

In the meantime it is proposed to accept,

$$\left.\begin{aligned}(QF) &= (QF)_{Mean}\\ \{QF\} &= \{QF\}_{best\ guess}\end{aligned}\right\}\ \text{(see Fig. 8)}$$

For practice it is suggested to use the following values:

Thermal and intermediate neutrons	(QF) {QF}	≈ ≈	1.5 1
fast neutrons	(QF) {QF}	≈ ≈	7 3
high energy neutrons ($E_n \leqslant$ 1 GeV)	(QF) {QF}	≈ ≈	4 1

§ 6 DOSE-EQUIVALENT PER UNIT NEUTRON FLUENCE

It has already been stated, in § 5 and in the DEFINITIONS, how the dose-equivalent DE in element ΔV has been computed. The volume element(s) to which DE refers, and the "amount" of conservatism contained in a particular DE, are indicated using subscripts and the appropriate brackets (see § 2). Several different DE have been defined (see the DEFINITIONS) and reported in Fig. 9.

All of the curves in Fig. 9 form a thick ribbon representing many possibilities to relate dose-equivalent to neutron fluence. The upper part of the ribbon is (DE) and the lower part is {DE}.

Arguments can be found for, and against, all 8 curves shown in Fig. 9. Because of practical considerations it is felt that it does not make sense to strike upon this. What can be done at the present time, is to group these curves in two strips, as shown in Fig. 10.

The (DE) strip includes the curves: $(DE)_{Max}$, $(DE)_{ICRP}$, $(DE)_{reasonable}$, and $(DE)_{Min}$, which all correspond approximately to D_{Max}, weighted by different possible quality factors. This (DE) strip relates, therefore, to the location in the body where the biological damage is maximum. When using this (DE) strip to convert a neutron fluence into a dose-equivalent, the result should be given in (rem). – See the DEFINITIONS.

The {DE} strip (also in Fig. 10) includes the curves: $\{DE\}_{best\ guess}$ and $\{DE\}_{min}$, which correspond either to D_{Mean} or $D_{Midline}$, weighted by some realistic {QF}. This {DE} strip relates, therefore, to the midline of the body, or can be understood as being an average {DE} over the entire body volume. The quantity {DE}, obtained using the {DE} strip, should be expressed in {rem}. It is certainly well correlated to the early clinical response following an acute exposure.

In practice, the dose-equivalent per neutron fluence "curve" is used in the following way: An instrument, which gives its readings in rem, is used for measurement. It is constructed so that its sensitivity for monoenergetic neutrons follows a curve very similar to the DE per neutron fluence curve. The calibration consists then, of matching, as well as possible, one curve with the other (15), (16). This matching cannot be perfect for all neutron energies. Therefore, a certain imprecision must be taken into account.

Here it is proposed that, instead of matching a curve with another curve, a curve would be matched with a strip.

In other words the calibration instructions are:

- for a (rem)-counter or any (rem)-response detector used for preventive purposes and situations within ICRP limits: match the sensitivity curve (sensitivity vs. neutron energy) of the instrument as well as possible with the (DE) strip of Fig. 10.
- for a critical dosimeter or any {rem}-response detector used for the evaluation of the early response to large doses delivered at high dose-rate: match the sensitivity curve as well as possible with the {DE} strip of Fig. 10.

People involved in civil defense, military evaluations, or in the analysis of serious radiation accidents, are concerned with the estimate of casualties and lethalities. The problem often arises for them, as to how to add the effects of a gamma irradiation to those of a neutron irradiation. Several solutions are used in practice but only two of them can be considered as acceptable. These will now be reviewed:

A) $D_{\text{Max}}[\gamma+n] = D_{\text{Max}}[\gamma] + D_{\text{Max}}[n]$ in rad units

This $D_{\text{Max}}[\gamma+n]$ is poorly correlated to the overall somatic damages. Therefore, this method should be avoided.

B) $D_{\text{Midline}}[\gamma+n] = D_{\text{Midline}}[\gamma] + D_{\text{Midline}}[n]$ in rad units

This $D_{\text{Midline}}[\gamma+n]$ is quite well correlated to the overall early clinical response, and this method is not only acceptable, but also recommended. This means indirectly that {QF}, for all neutron energies, can never greatly exceed unity.

C) $(DE)[\gamma+n] = DE[\gamma] + (DE)[n]$ in ? units

This is an incorrect method, which is still too often utilized. The unit "rem" used to express (DE) [n], is in fact a "(rem)" unit; it is not a "Röntgen equivalent" and is not defined at high doses. Therefore, the two quantities DE $[\gamma]$ and (DE) [n] cannot be added, as they do not contain the same amount of conservatism.

D) $\{DE\}[\gamma+n] = DE[\gamma] + \{DE\}[n]$ in {rem} units

This is the second acceptable method. {DE} [n] is defined by the {DE} strip of Fig. 10, and is expressed in {rem} units which are "Röntgen equivalent". Therefore, this addition is correct.

§ 7 CONSERVATISM AND OVER-CONSERVATISM

It can be seen that in every step leading, in practice, to the dose-equivalent (DE), some conservatism is included (see Fig. 11). At the end (DE) can be quite over-conservative.

It is felt that this over-conservatism should be replaced by a reasonable conservatism, which takes the worst case into account. The worst case occurs when absorbed dose and quality factor are both a maximum within the critical organs (blood-forming organs, lens of the eye and gonads). Therefore, in the chain of conservative steps, there is one conservative step too many: LET → (qf).

Instead of departing from an already conservative $(qf)_{LET'}$ it would be safe enough to use a more realistic $(qf)_{LET}$ which in Fig. 5 is somewhere between $(qf)_{ICRP}$ and $\{qf\}$.

A more realistic $(qf)_{LET}$ (Fig. 5) could lead to a (QF) probably similar to $(QF)_{Mean}$ or $(QF)^*$ (Fig. 8), and finally to something like $(DE)_{reasonable}$ in Fig. 9.

At the present time, the recommended $(DE)_{ICRP}$ is definitely over-conservative. As compared to the protection against gamma quanta, the protection against neutrons is exaggerated.

The use of the (DE) strip of Fig. 10 instead of the $(DE)_{ICRP}$ curve, is already a practical way of replacing over-conservatism by a reasonable conservatism.

Finally it is suggested that:

- All existing Monte Carlo programs (3), (19), (6), (9), (21), (25) should be rerun on the basis of a more realistic (qf)—LET relationship.
- The conditions of irradiation should be a linear combination of broad beam incidence and isotropic incidence.
- The anthropomorphic phantom used should **really be** anthropomorphic (e.g. cylindrical), and provision should be made for rotating it during irradiation.

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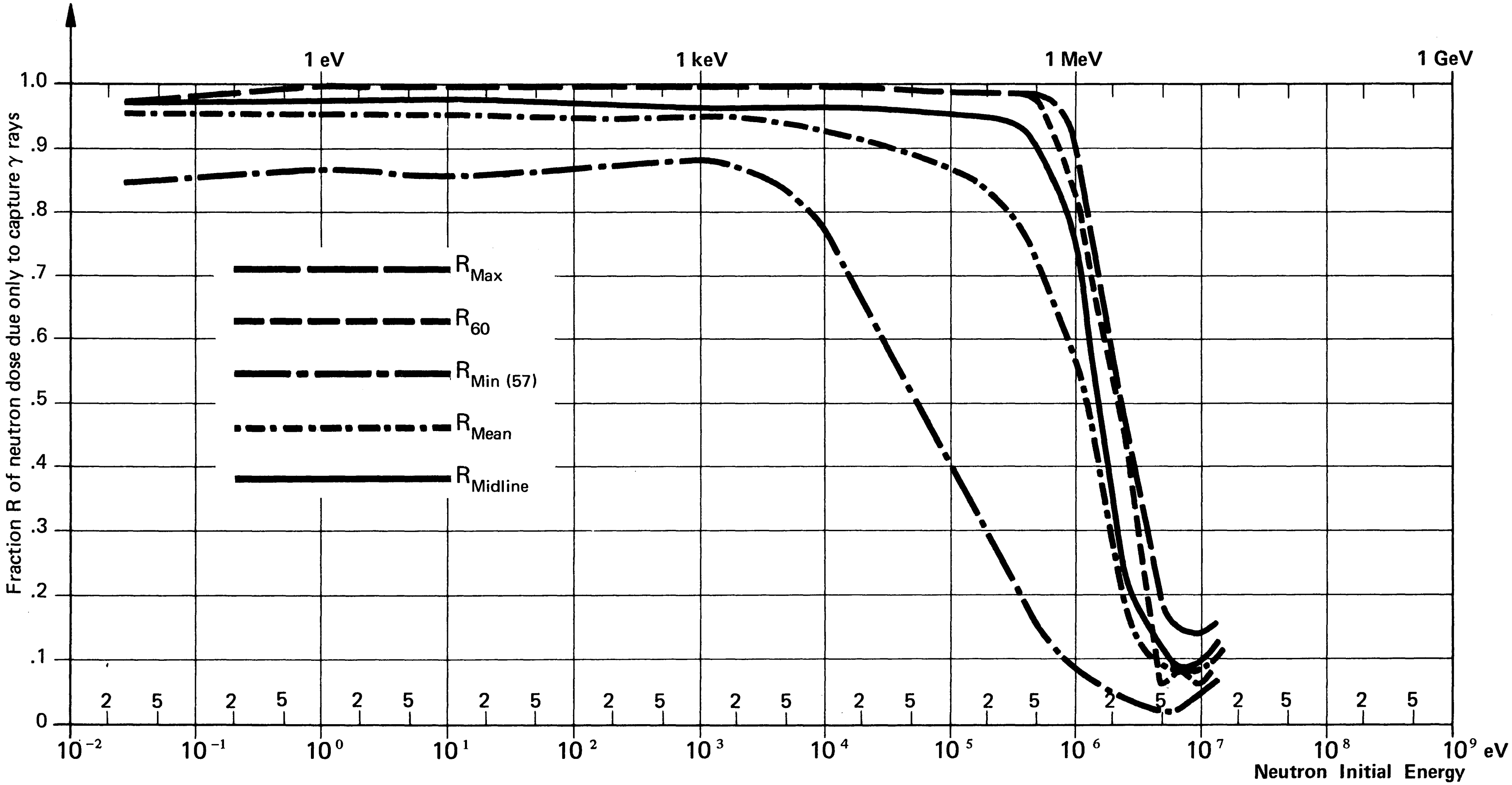


Fig. 1

When the energy of the incident neutrons is below 1 MeV, the dose due to capture gamma rays from the H (n, γ) D reaction is predominant (see §1).

— Reported from (3) —

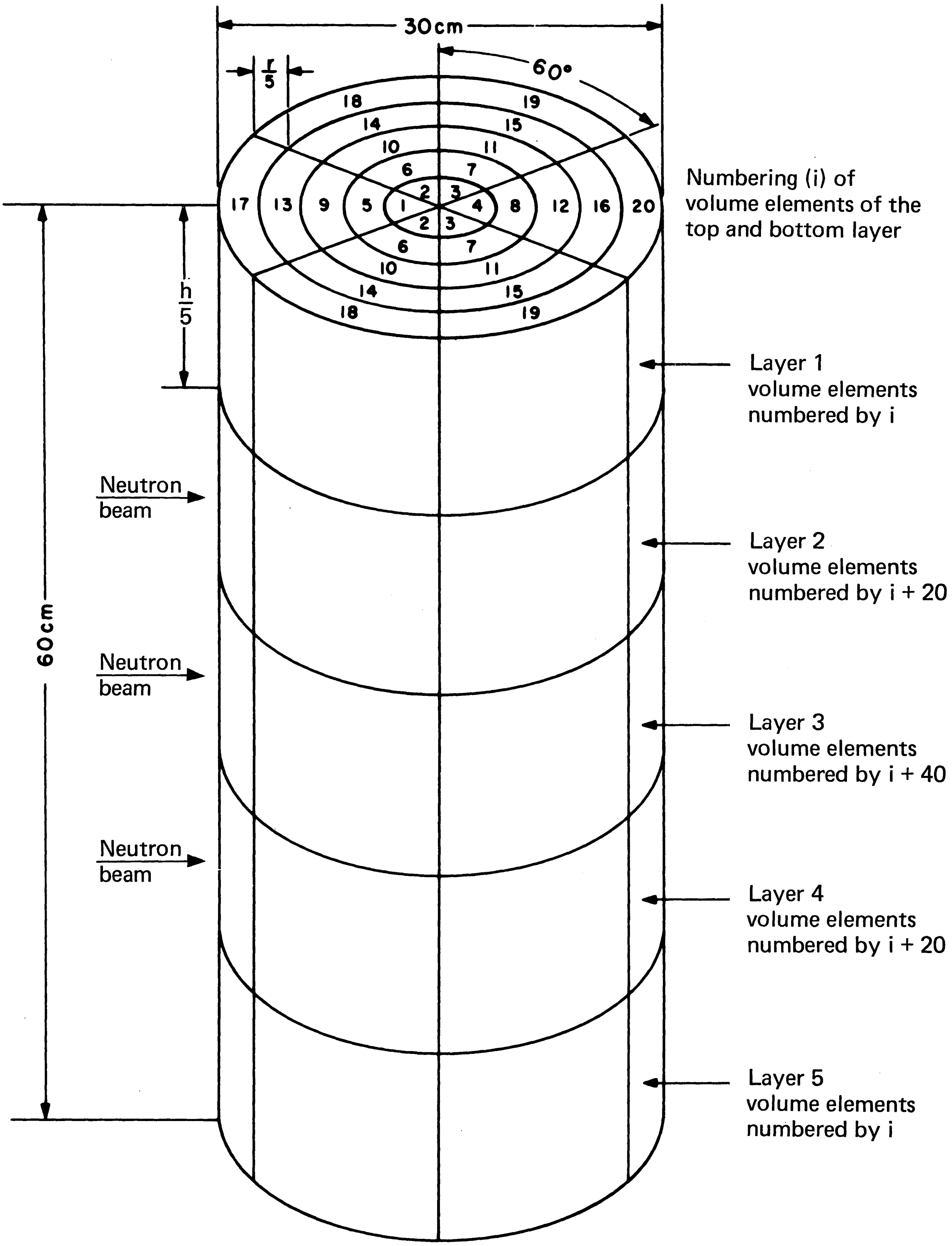


Fig. 2 The cylindrical phantom used in the Monte Carlo calculations
– from (3) –

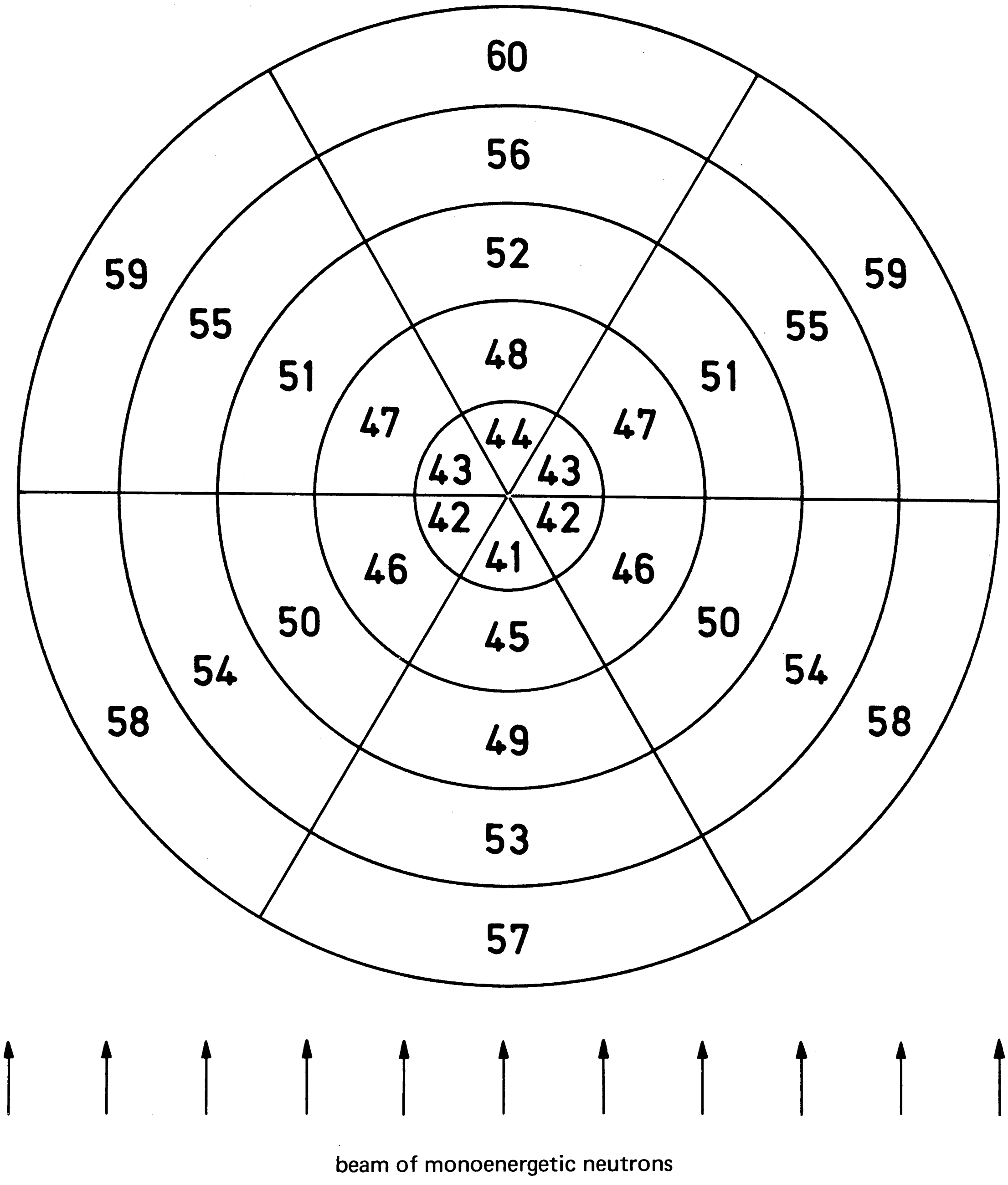


Fig. 3 Central slab of the cylindrical phantom with its 30 volume elements numbered from 41 to 60

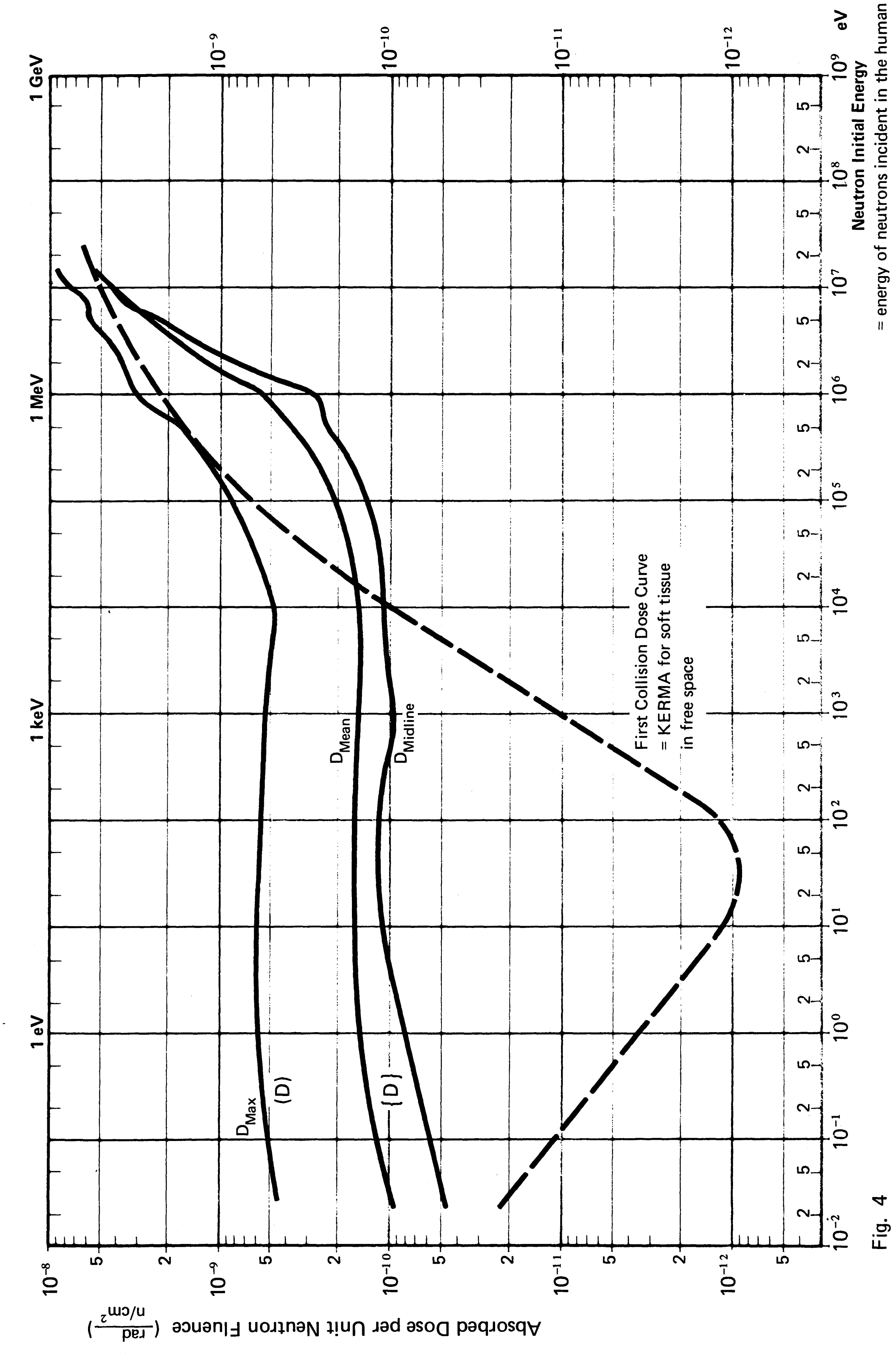


Fig. 4

D_{Max}, D_{Mean} and $D_{Midline}$ refer to the cylindrical phantom computations made by Auxier et al (3)

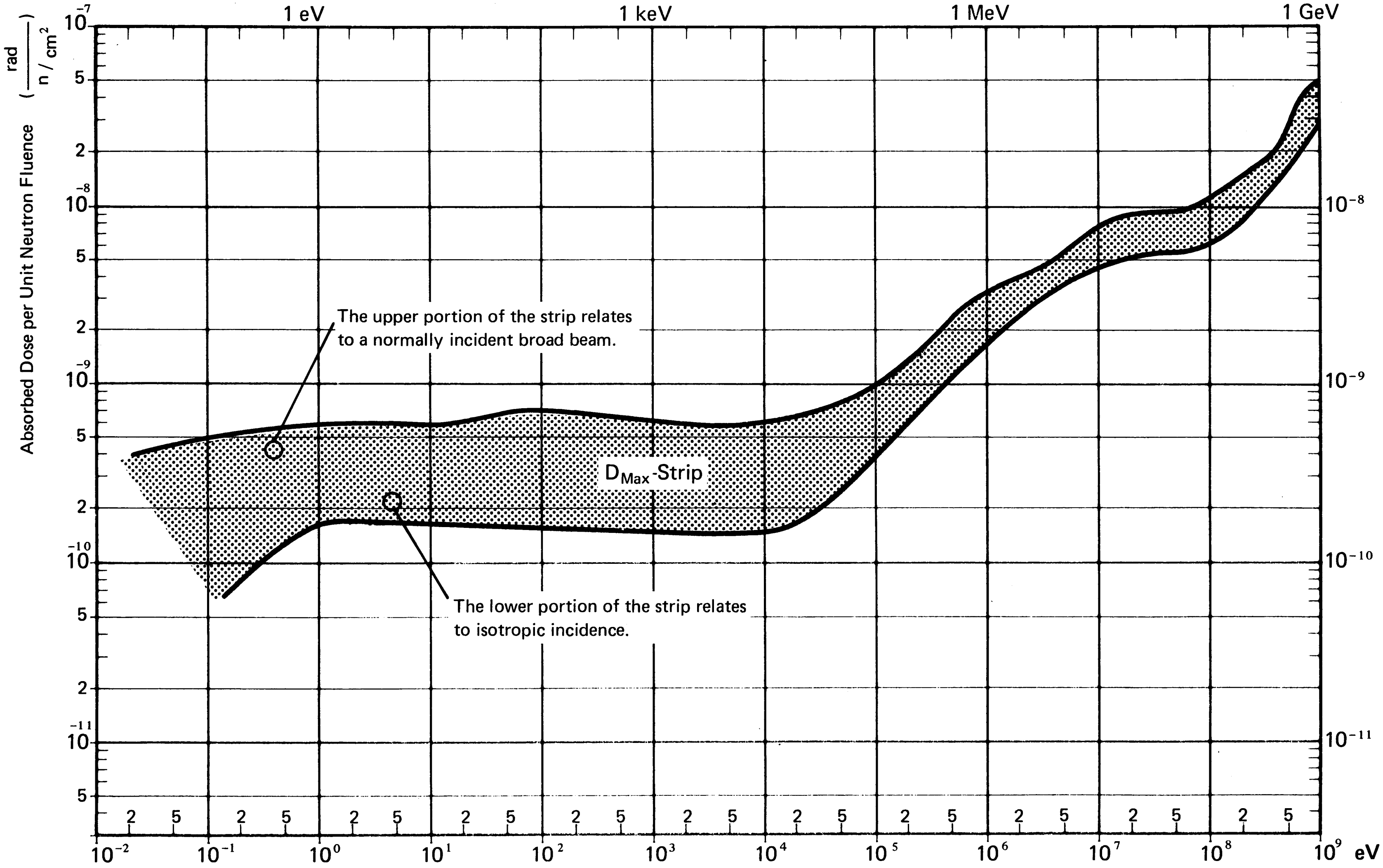


Fig. 4a

Neutron maximum absorbed dose in man. The curves from several authors (19), (3), (24), (21), (25), (26), (23) and (27) were assembled to form this strip.

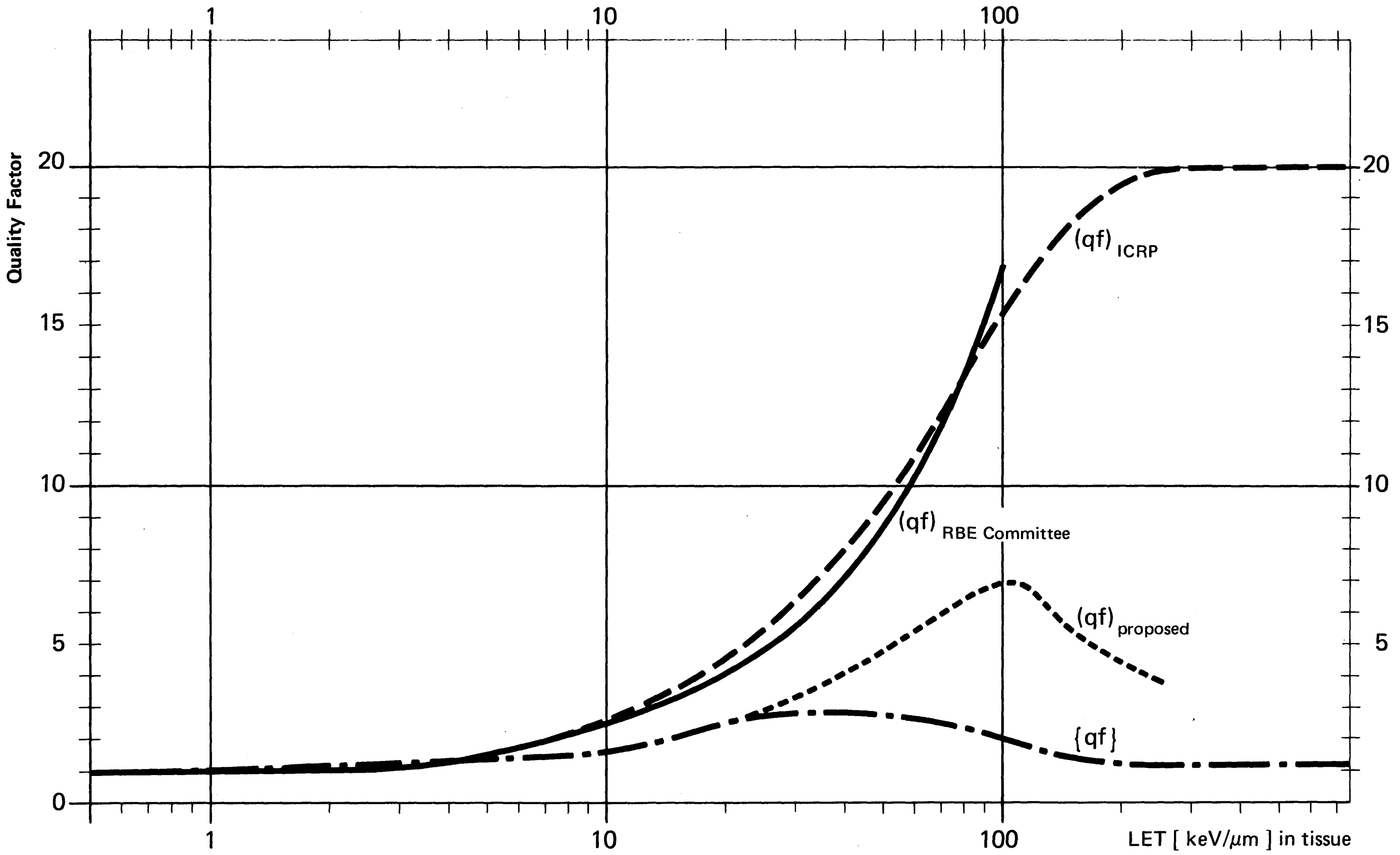


Fig. 5

"Microscopic" quality factor as a function of the stopping power of the charged particles produced in tissue. (qf) is the rather conservative curve recommended by ICRP (2), (3) or by the RBE Committee (11) and {qf} is a compilation from Graul (4), (8). $(qf)_{proposed}$ would represent a more realistic relationship (10).

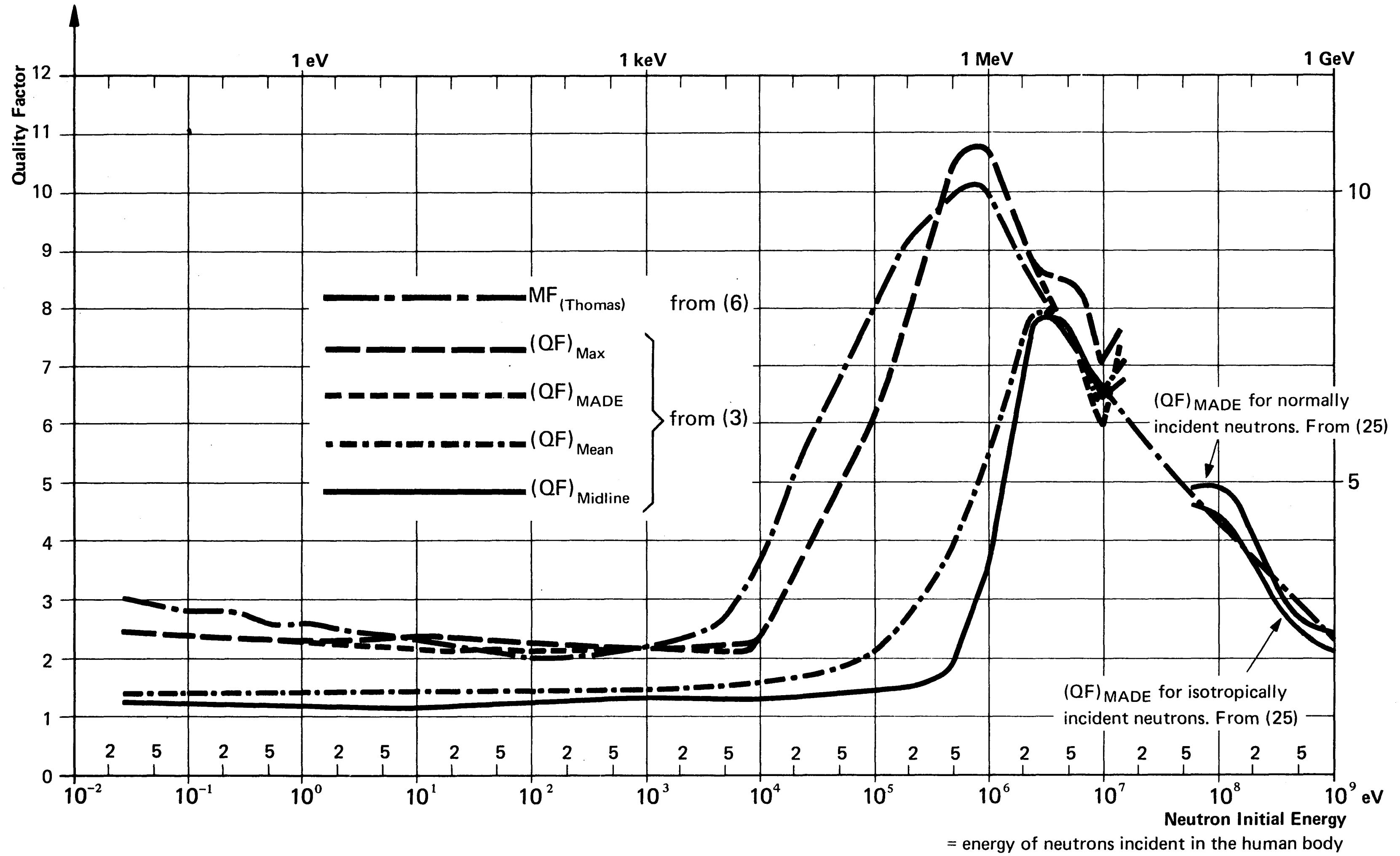


Fig. 6

It is a question of opinion to decide which of these curves should be used. However it should be remembered that they all rely on a LET dependence of (qf) which in itself is already conservative (see Fig. 5). Therefore it is felt, that $(QF)_{Mean}$ or $(QF)_{Midline}$ are reasonable curves whereas all others are over-conservative.

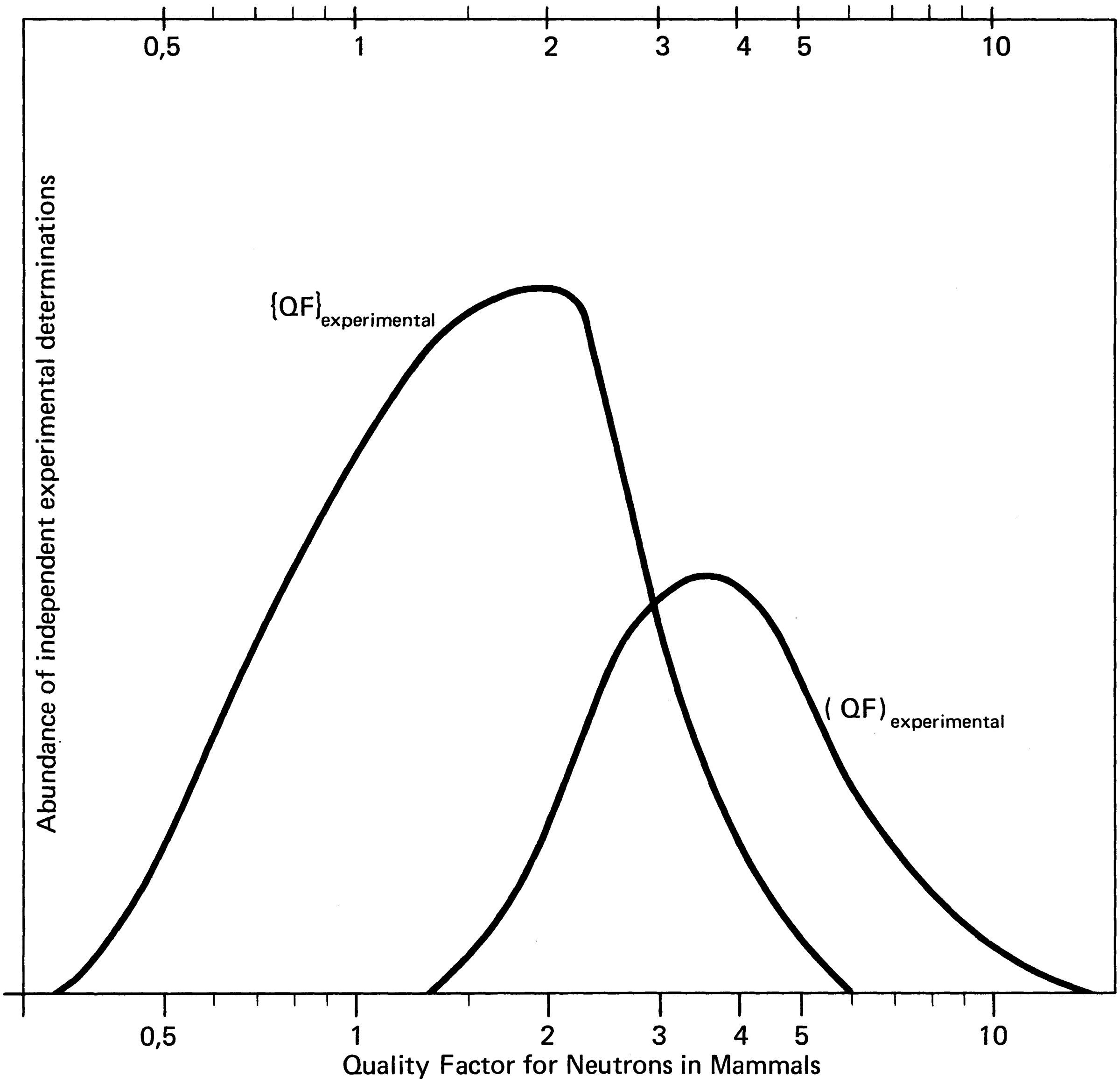


Fig. 7

Experimental Determinations of QF for Neutrons

(QF):	most frequent values situated between 3 and 4 most values situated between 2 and 7
{ QF }:	most frequent values situated between 1.5 and 2 most values situated between 0.6 and 3.5

In these experiments all kinds of neutron energies and neutron spectra were used. The QF rely on several different biological criteria.
– Compilation from (4) and (10). –

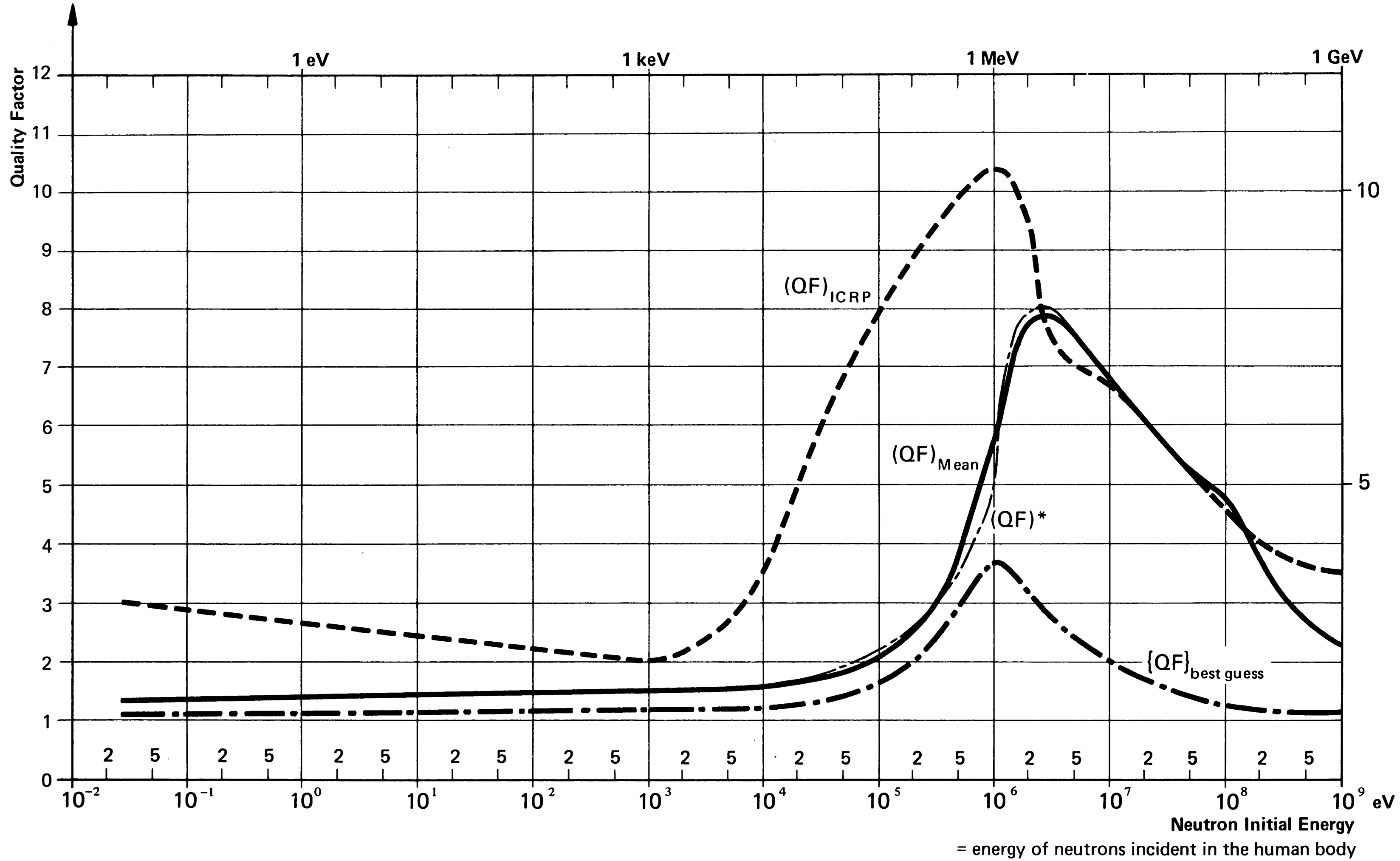


Fig. 8

$(QF)_{ICRP}$ was reproduced from (14), (15), (17) and (23). It is an over-conservative curve similar to MF (Thomas), $(QF)_{Max}$ and $(QF)_{MADE}$ (see Fig. 6). It is proposed to use $(QF) = (QF)_{Mean}$ from Fig. 6, which is reasonably conservative and practically equal to $(QF)^*$ (see §1). From Fig. 5 and 7 as well as from (4) and (10) $\{QF\}_{best\ guess}$ was drawn.

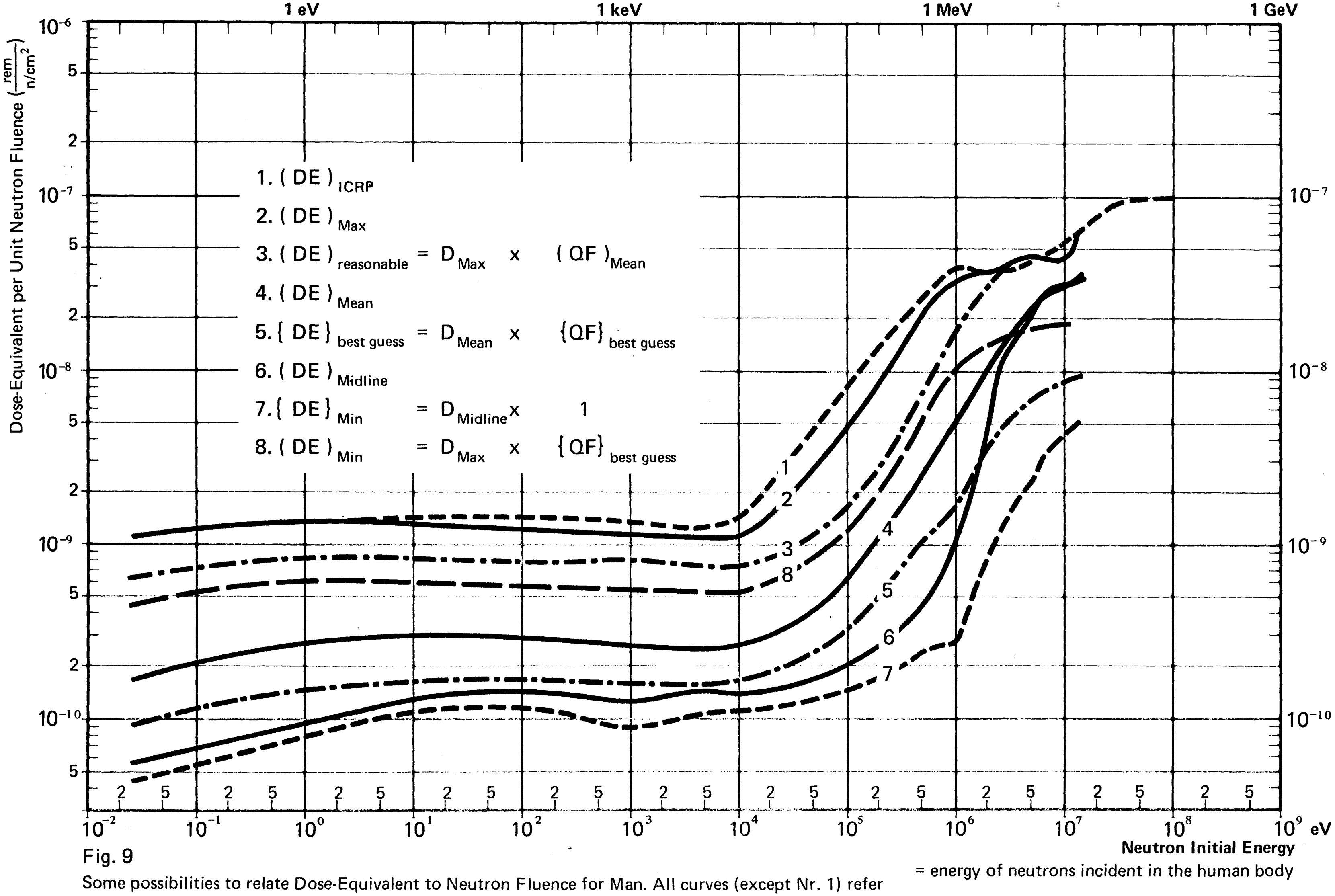
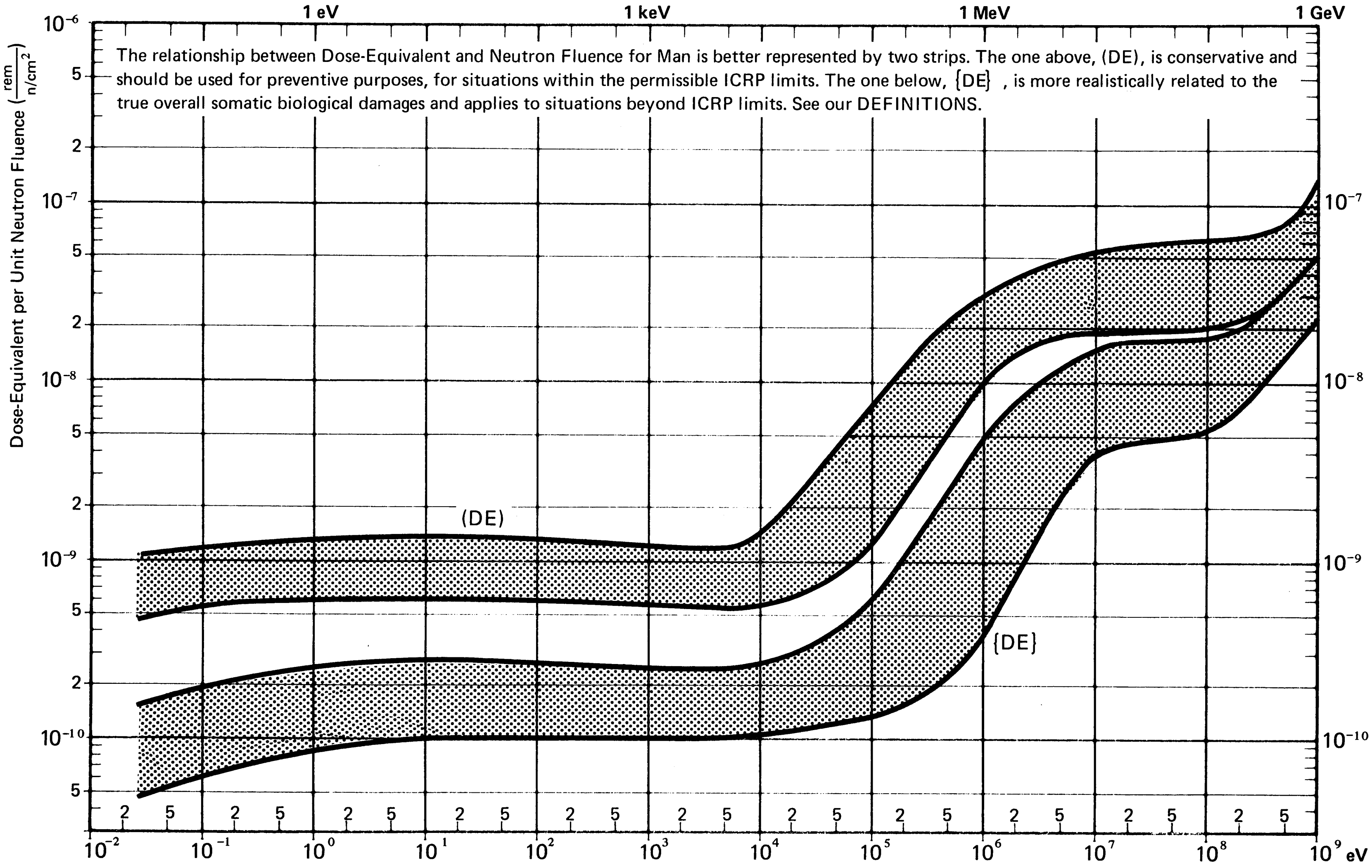


Fig. 9

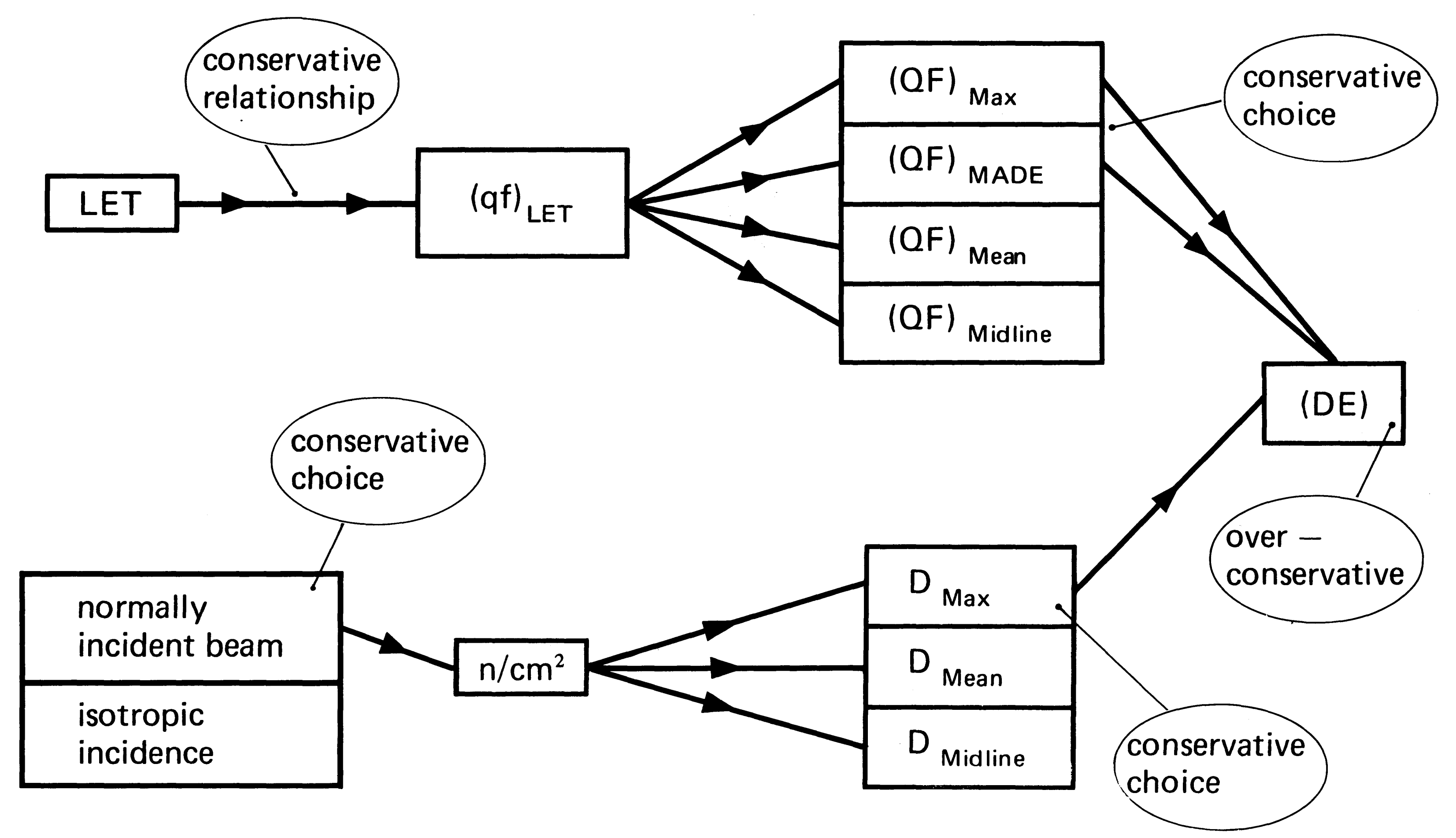
Some possibilities to relate Dose-Equivalent to Neutron Fluence for Man. All curves (except Nr. 1) refer to the cylindrical phantom irradiated normally by a broad beam of monodirectional neutrons (Fig. 2).



The relationship between Dose-Equivalent and Neutron Fluence for Man is better represented by two strips. The one above, (DE), is conservative and should be used for preventive purposes, for situations within the permissible ICRP limits. The one below, {DE} , is more realistically related to the true overall somatic biological damages and applies to situations beyond ICRP limits. See our DEFINITIONS.

Fig. 10

Fig. 11 THE MECHANISM OF OVER-CONSERVATISM



DISCUSSION

Paper : Neutron depth doses in man and corresponding quality factors - some heretical considerations

BARENDSEN: In your presentation, you derived a so-called "realistic" quality factor which, related to a dose causing death, is 50% of the exposed persons, i.e. LD 50. I think that this is not a realistic end point. I would think an exposure causing death in 10% of the exposed persons is already a severe enough dose on which to base calamity measures.

PRÊTRE: D'accord. $\{QF\} \cong$ RBE for LD_{10} est probablement une association plus raisonnable. Je l'ai d'ailleurs mentionné dans mon texte à l'endroit où $\{QF\}$ est défini. D'autre part, je ne pense pas qu'il y ait une différence très sensible entre "RBE for LD_{50}" et "RBE for LD_{10}".

HOEFERT: I would like to see that the quantity dose-equivalent and the unit rem are reserved for chronic irradiations in radiation protection. In this field, we have already enough difficulties to understand what the dose-equivalent is and I do not want to enter into a discussion on this problem.

In cases of acute irradiations one should perform an investigation in the following order:

i) determine the total energy imported (integral dose) to the person in question,

ii) study the distribution of dose in the body and possibly critical organs,

iii) try to apply a value for the RBE (it should not be named quality factor) if this is known and meaningful.

PRÊTRE: Il y a certainement plusieurs possibilités de marquer la différence entre d'une part les grandeurs utilisées à des buts préventifs et relatives à des irradiations peu importantes, et d'autre part les grandeurs réalistes destinées à décrire les effets précoces d'une irradiation aiguë. L'important, c'est que l'on marque cette différence d'une façon ou d'une autre. Je n'ai pas la prétention de donner ici la solution définitive, mais j'espère avoir au moins soulevé le problème.

Ce qu'il faut éviter, c'est que des gens utilisent des concepts ICRP tels que DE et QF dans des domaines où ils ne sont pas applicables; je citerai par exemple la protection civile ou les domaines militaires.

NEARY: I should like to make the comment that the quality factor, OF, of ICRP is intended to relate to the dose-equivalent in a particular tissue or organ. The limited evidence at present available suggests that the values of OF at various LET's are not particularly over-conservative, at least in the region up to 100 keV/μ, though they may well be at higher LET's. In practice, the more important contribution to the conservativeness comes from the technical limitations of monitoring, that is, the virtual impossibility of making the sufficiently detailed dose-measurements throughout an exposed person which would be needed for the more realastic assessment of hazard.

NACHTIGALL: Herr Prêtre, Sie schlagen vor, die Neutronendosimetrie vom Überkonservativismus zu befreien, indem eine neue QF-LET-Beziehung eingeführt wird. Ich glaube, dass wir mit diesem Konzept Schwierigkeiten haben werden. Aber ein Teil des Überkonservativismus kann mit Hilfe neuer Fluenz-Äquivalentdosis-Konversionsfaktoren abgebaut werden. Die heutigen Konversionsfaktoren basieren auf den alten Rechnungen von Snyder und Neufeld. Zugrunde liegt als Phantom eine 30 cm dicke, seitlich unendlich ausgedehnte Scheibe aus TE-Material. Inzwischen gibt es neue Rechnungen für zylindrische, elliptische oder kugelförmige Phantome. Das führt bereits zu niedrigeren Konversionsfaktoren. Wenn man sich bei einer Neuberechnung auf das in der neuen ICRU-Publication 11 vorgeschlagene Kugelphantom von 30 cm Durchmesser einigen würde und statt parallelen Neutroneneinfalls isotropen Einfall zugrunde legen würde, wäre ein grosser Teil des Überkonservativismus abgebaut.

PRÊTRE: Oui, c'est la partie physique du conservatisme que l'on peut réduire ainsi. Mais la partie biologique est nettement plus importante, et il y aurait plus à faire de ce côté là. J'aimerais aussi faire remarquer que le choix d'un mannequin plus ou moins anthropomorphique ne modifie pas fortement les facteurs permettant de convertir la fluence en équivalent de dose.

HOFERT: (After the remark of Heinzelmann and Nachtigall on phantoms).

The discussion on phantoms seems to me to be of a rather academic interest. As an operational health physicist I am ready to accept any fluence-to-dose-equivalent conversion factors for neutrons under two conditions, namely that:

i) ICRP should tell me that they are relevant to the radiation risk and subsequently endorse them.

ii) There should exist a simple device based on the above conversion factors which allows for a rapid determination of dose-equivalent in daily routine work.

BAARLI: I saw from your slides that you suggested a QF for high-energy radiation of about four. I think we have at the present time very little evidence to make a particular proposal at these energies and we should be careful to propose any figures which need to be proved to be correct.

Further, we are also dependent upon using instruments in an easy and simpler way to estimate the risk. Under these circumstances, we are willing to trade accuracy against easiness, but we have to assure ourselves that we do not underestimate the risk.

Regarding the real situation, I would like to stress what Hoefert said: we would like to go back to use the basic concepts and not base the estimate entirely on assumed QF.