CONF-861044--7

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DE87 009026

QUALITY FACTORS*

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DISCLAIMER

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ABSTRACT

The quality factor, Q, is a dimensionless modifier used in converting absorbed dose, expressed in rads (or grays), to dose equivalent, expressed in rems (or seiverts). The dose equivalent is used in radiation protection to account for the biological effectiveness of different kinds of radiation. The quality factor is related to both the linear energy transfer (LET) and relative biological effectiveness (RBE). The RBE's obtained from biological experiments depend in a complex way on the observed biological effect, the specific test organism, and the experimental conditions. Judgement is involved, therefore, in the choice of the quality factor.

Questions regarding the adequacy of current Q values for neutrons were raised first in a 1980 statement by the National Council on Radiation Protection (NCRP) and later in a 1985 statement by the International Commission on Radiological Protection (ICRP). In 1980, the NCRP alerted the technical community to possible future increases between a factor of three and ten in the Q for neutrons, and in 1985, the ICRP suggested an increase by a factor of two in Q for neutrons. Both the ICRP and NCRP are now recommending essentially the same guidance with regard to Q for neutrons: an increase by a factor of two.

The Q for neutrons is based on a large, albeit unfocused, body of experimental data. In spite of the lack of focus, the data supporting a change in the neutron quality factor are substantial. However, the proposed doubling of Q for neutrons is clouded by other issues regarding its application.

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*Research sponsored by the U.S. Department of Energy under contract DE-AC05-84OR21400 with the Martin Marietta Energy Systems, Inc.

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INTRODUCTION

Radiations differ in their biological effectiveness per unit of absorbed dose. This fact is taken into account in radiation protection by the use of the so-called dose equivalent (ICRU 1971). The dose equivalent is obtained by weighting the absorbed dose from each kind of radiation by a quality factor. The equation

$$H = QD \qquad (1)$$

shows this relationship, where H is the dose equivalent expressed in rems (or seiverts), D is the absorbed dose expressed in rads (or grays), and Q is the quality factor, which is dimensionless (ICRU 1973).

The present values of Q are related to the linear energy transfer, LET, of the radiation in question as shown in Table 1 (RBE Committee 1963). These data have been used to make detailed calculations of the dose equivalent from neutrons incident on representative phantoms of the human body (NCRP 1971). The Q values obtained in the calculations vary as a function of neutron energy and are listed in Table 2. If neutron energy data (or spectral data) are not available, then an approximate value of 10 can be used in converting a measurement of absorbed dose from neutrons to dose equivalent (NCRP 1971). This approximate value of 10 is a typical Q value for fast neutrons having energies between 0.1 and 15 MeV (Table 2).

Questions regarding the adequacy of current values of Q for neutrons were raised first in a 1980 statement by the National Council on Radiation Protection (NCRP 1980) and later in a 1985 statment by the International Commission on Radiological Protection (ICRP 1985). In 1980, the NCRP alerted the technical community to possible future increases between a factor of three and ten in the Q for neutrons, and in 1985, the ICRP issued the following recommendation with regard to Q for neutrons:

> The information now available on the relative biological effectiveness (RBE) for neutrons for a variety of cellular effects *in vitro*, and for life shortening in the mouse, is being reviewed by the Commission. The implications of this information will be considered as part of a larger review of recommendations to be undertaken by the Commission over the next four years or so. Meanwhile, in the case of neutrons, the Commission recommends an increase in Q by a factor of 2. The permitted approximation for Q for fast neutrons thus changes from 10 to 20
>
> These changes relate only to neutrons, and no other changes in Q are recommended at this time.

The above statement by the ICRP was followed by similar recommendations in draft reports by Scientific Committee 1 of the NCRP.(a) Both ICRP and NCRP are now recommending essentially the same guidance with regard to the quality factor for fast neutrons: an increase by a factor of two. The ICRP fails to give any guidance regarding the use of neutron spectral data when it is available, while the NCRP suggests that spectral data can be used with a factor of two increase uniformly applied at all neutron energies. Thus, the NCRP is also proposing a doubling of the current approximate value of 2 (or more exactly 2.3) for thermal neutrons (Table 3).

NEUTRON QUALITY FACTORS

Judgement is involved in the choice of Q which is based on literature surveys of experimentally measured values of RBE. The RBE is defined as the absorbed dose from orthovoltage x-rays divided by the absorbed dose from another radiation needed to produce the same level of biological effect (RBE Committee 1963). In general, the RBE for neutrons relative to x-rays is found to increase with decreasing dose until some maximum RBE value is reached at low doses, where the dose reponses curves for both neutrons and x-rays are presumed to be linear (i.e., proportional to dose). The most common means of establishing the maximum RBE values is to compare the slopes in the linear dose-response regions (i.e., levels of biological effect per unit of absorbed dose). In Fig. 1, for example, the number of pink-mutant events in Tradescantia stamen hairs (exposed minus control) was divided by the absorbed dose and then plotted as a function of total absorbed dose (Sparrow et al 1972). A maximum RBE value of 50 for 0.43-MeV (optimum-energy) neutrons relative to 250-kvp x-rays was established very clearly for this particluar biological endpoint. The x-ray doses were delivered acutely at dose rates of approximately 30 rad per minute (Sparrow et al 1972).

Pink-mutant events in Tradescantia stamen hairs have provided an extremely sensitive biological endpoint for investigating the effects of a variety of parameters on RBE s for neutrons (Nauman et al 1975, Underbrink et al 1976, Bond et al 1976, Underbrink et al [illegible]). This biological end-

(a)NCRP draft report NSR/RPT-SC-1/Rev 7/85, pp. 10 11, and NCRP draft report NSR/RPT-SC-1/86, pp. 17 18

point has been used to obtain quantitative data for x-rays and gamma rays over a wide range of dose rates (0.002 to 500 rad/min) and total doses (0.25 to 600 rads). For both x-rays and gamma rays, the dose-response curves are linear-quadratic: the linear component dominates below 10 rads, and there is a strong quadratic component between 10 and 100 rads. Above 100 rads, pink-mutant events saturate and decline when the total dose is delivered at high dose rates (e.g., 30 rad per minute). Hence, the effect of dose rate was studied in the strong quadratic region by selecting a total dose of 60 to 80 rads and by comparing the effect per rad as a function of dose rate (Nauman et al 1975). These studies were carried out using both 250-kvp x-rays and ^{137}Cs gamma-rays as illustrated in Fig. 2. For ^{137}Cs gamma rays, the effect per rad at a total dose of 60 to 80 rads decreases by a factor of about eight as the dose rate is reduced from 30 rad/min to 0.003 rad/min. In fact, the effect per rad at a dose rate of 0.003 rad/min or 5.2 rad/day approaches the low dose-rate limit observed in fractionated exposures to 5 rads of ^{137}Cs gamma rays (Underbrink et al 1976, 1985). It should be noted, however, that gamma rays from ^{137}Cs are less effective biologically at low doses by a factor of about two compared to 250-kvp x-rays. Thus, the maximum RBE for 0.43-MeV neutrons is about 50 relative to x-rays and 100 relative to gamma rays from either ^{137}Cs or ^{60}Co (Bond et al 1976).

The Q for neutrons is based on a large, albiet unfocused, body of experimental data on RBE. Orthovoltage x-rays are the usual reference radiation, but gamma rays from ^{137}Cs and ^{60}Co have also been widely used as reference radiations. The mixed use of reference radiations, acute vs fractionated exposures, and high vs low dose rates can easily result in factors of two or more discrepancy in the measured values of RBE for the same biological endpoint. For pink-mutant events in Tradescantia stamen hairs, the maximum RBE and the expected linear responses have been established for 0.43-MeV neutrons, 250-kvp x-rays, and ^{60}Co gamma rays (Bond et al 1976), and it seems likely that these have also been established for chromosome abberations in human lymphocytes (Edwards et al 1982, ICRU 1986). For other biological endpoints, such as life shortening and tumor induction in mice, there are indications that sufficiently low levels of effect have been observed for reliable estimation of maximum RBE values for fission-spectrum neutrons. An example of available data on mammary adenocarcinomas in female BALB/c mice is provided in Fig. 3 (Ullrich 1984,

Ullrich and Storer 1978). The ^{137}Cs gamma-ray doses of 50 to 200 rads were delivered over several days at a protracted dose rate of 8.3 rad/day or 0.006 rad/min (see Fig. 2). In a general discussion of tumor induction in mice, Fry (1981) considered that the RBE's for individual tumors have a wide range of values and difficult to average properly. The RBE values ranged from values as small as 2 or 3 to values as large as 200 or more, although most of the RBE values were less than 100 relative to gamma rays.

Sinclair (1985) has published an extensive review of virtually all of the low-dose data on RBE's for biological endpoints of special concern in radiation protection, namely carcinogensis and mutagensis. Only experiments providing data at low neutron doses were considered, and the RBE's for fission (or optimum-energy) neutrons were determined, using data from fractionated exposures to gamma rays as a reference. The results obtained for five principal endpoints from over 30 original research references are listed in the gamma-ray column of Table 4. The data in the x-ray column of Table 4 are equal to those in the gamma-ray column divided by 2. This relationship is consistent with the advice of both Sinclair (1985) and Bond (1979). The factor of 2 represents the adjustment of the data from a gamma-ray base to an orthovoltage x-ray base, the basis that is defined for measurement of RBE. It is clear from Table 4 that a Q value of 20 is more representative of the data than the current value of 10. The need to double the Q for neutrons has been the topic of considerable debate because of the conservative nature of the dose equivalent values currently being applied in neutron dosimetry for radiation protection puposes.

NEUTRON DOSE EQUIVALENT

Dose equivalent values for neutrons have been established mainly by Monte Carlo calculations which simulated neutron behavior in human tissues and determined the spatial distribution of the dose equivalent within various representative phantoms of the human body. Originally, a slab phantom with a 30-cm thickness was used to simplify the calculations (Snyder 1957). The calculations were performed for broad parallel beams of monoenergetic neutrons incident perpendicularly on one face of the slab, and the maximum dose equivalent values were adopted for use in radiation protection. More realistic calculations of the dose equivalent within the human body have used a cylindrical phantom, 60-cm

in length and 30-cm in diameter (Auxier et al 1965, Snyder 1971) and a spherical phantom, 30-cm in diameter (Chen and Chilton 1979, Shiue and Chilton 1983). Only small differences are noted in the maximum dose-equivalent values from calculations using either the spherical or cylindrical phantoms. The maximum values for broad parallel beams incident perpendicularly to the axis of the cylinder are shown as a function of neutron energy in Fig. 4 (NCRP 1971).

A major objection to the use of maximum values in neutron dosimetry is that they are non-additive and overestimate the dose equivalent at any depth in the body when applied to a broad spectrum of neutron energies (Cross and Ing 1985). For neutron energies between 100 keV and 15 MeV, the maximum dose equivalent occurs within 1 cm of the body surface (on the beam side), but for other neutrons energies, it occurs deeper within the body (i.e., 3 to 5 cm for neutron energies less than 100 keV). Hence, a quantity called the ambient dose equivalent has been recommended for use in neutron dosimetry by the International Commission on Radiation Units and Measurements (ICRU 1986). This quantity is designated as H*(10) and defined as the dose equivalent at a fixed depth of 10 mm (or 1 cm) along the radius of a 30-cm diameter sphere irradiated by a broad parallel beam of neutrons. The results of calculations by Chen and Chilton (1979) and Shiue and Chilton (1983) were averaged over the first two centimeters of depth to obtain the ambient dose-equivalent values shown in Fig. 4 (Cross and Ing 1985). The ambient values resolve the problem of non-additivity and also require only small changes in the currently used maximum values for the dose-equivalent. However, both the maximum and ambient values appear to be conservative estimates of the dose equivalent when compared to the recommendations found in ICRP Publication 26 (Sims 1985, Bartlett 1985).

In 1977, the ICRP recommended a new system for dose limitation based on an another quantity called the effective dose equivalent (ICRP 1977). The effective dose equivalent as defined in ICRP Publication 26 is obtained by weighting the dose equivalent to various body organs by a set of risk related factors (Table 1). The equation

$$H(eff) = \sum H_T w_T \qquad (2)$$

shows this relationship, where H(eff) is the effective dose equivalent, Hi is the dose equivalent to a specific organ of the body, and wi is the risk factor for that specific organ. Recently, Burger et al (1984) calculated effective dose equivalents for neutrons using slightly modified versions of the well-known MIRD phantom (Snyder et al 1969). The calculations were performed for several practical exposure conditions: a broad parallel beam of neutrons incident on the front the body (see Fig. 4), rotational neutron-field geometry (i.e., cylindrical isotropy about the vertical axis of the body), and isotropically incident neutrons. In general, the effective values of the dose equivalent are smaller than the ambient and maximum values by a factor of about two when the comparisons are made over a broad fission-neutron spectrum (Table 6). It should be noted, however, that the ambient and maximum values are not necessarily conservative at neutron energies of a couple of MeV or more (see Fig. 4).

DISCUSSION

The recent ICRP and NCRP recommendations to increase the Q for neutrons have been reviewed by an Ad Hoc Committee of the U.S. Department of Energy (DOE).[a] This ad hoc committee, as an independent review group, agreed to make its own decisions concerning the recommendations ofthe ICRP and NCRP after weighting all the information. In early delibrations, the committee expressed concern over the lack of a corresponding change in Q for protons in the original ICRP and NCRP publications, since most of the neutron dose comes from recoil protons. The NCRP is now proposing a doubling of Q for both protons and neutrons (Table 3). However, in the preface to a recent joint ICRP-ICRU Task Group Report on quality factors, one finds the following statement (ICRU 1986): "Because of the interaction between the choice of Q, the estimation of risk factors, and the choice of dose-equivalent limits, the ICRP dose not propose to alter the recommendations about Q until it has completed its current review of general recommendations. An interium recommendation on the effective (or approximate) quality factor for neutrons, based on preliminary information

(a)L. G. Faust, H. Brucker, G. D. Kerr, W. E. Lawrence, F. X. Masse, R. C. McCall, and J. E. Smathers, *Neutron Quality Factor*, Report of DOE Ad Hoc Committee (May 1986).

from the Task Group, has already been issued by the ICRP (ICRP Paris Statement, 1985)."

The DOE ad hoc committee raised three additional concerns which should be addressed in the immediate future with regard to the available data on which any change in Q must be based.

(1) The researchers contributing to the literature have used many different endpoints in measurements of the RBE. There is still no consensus as to what endpoints should be used to arrive at the best estimate of a Q value for radiation protection purposes.

(2) In many instances, the doses and dose rates used in animal experiments are too high to be applicable to routine personnel radiation protection. This whole issue deals only with normal, routine operations and not accidents (e.g., criticalities).

(3) The human data from neutron exposures is very limited. Most of the data in the literature are based on animal experiments and cell culture studies, and the extension of this data to humans has never been fully established.

In spite of the shortcomings of the current data base, the committee concluded that there was not sufficient reason to disagree with the doubling of the quality factor for neutrons as suggested by ICRP and NCRP (i.e., an increase of 2 in the current Q for neutrons based on an RBE of 20 relative to orthovoltage x-rays).

The DOE ad hoc committee also noted that improvements of the overall data base were necessary to provide better guidance with regard to further changes in Q for neutrons (as suggested by ICRP and NCRP and by Dennis and Dunster 1986). To accomplish this improvement, the committee recommended:

(1) Establishment of research goals that provide opportunities for intercomparison between different sets of biological effects data.

(2) Retrieval of original research data when possible for reanalysis by a single group to reduce individual researcher biases.

(3) Add human data bases including such human data bases as radiotherapy patients, U.S. Air Force crews, or commercial airline crews.

The neutron exposures to commercial airline crews are discussed in a recent report by Bramlitt (1985). Additional research programs to provide better guidance with regard to future changes in Q for neutrons and its application in radiation protection are discussed at length in the proceedings of a recent DOE sponsored workshop (Stapleton et al 1985).

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Table 1. Relationship between quality factor and linear energy transfer (RBE Committee 1963)

Linear energy transfer, LET (kev per micron in water)	Quality factor, Q (dimensionless)
3.5 or less	1
3.5 to 7.0	1 to 2
7.0 to 23	2 to 5
23 to 53	5 to 10
53 to 175	10 to 20
175 or more	20

Table 2. Mean quality factors for neutrons of various energies (NCRP 1971)

Neutron energy, E	Quality factor, Q
Thermal	2(•)
0.1 eV	2
1	2
10	2
0.1 keV	2
1	2
10	2.5
0.1 MeV	7.4
0.5	11
1	11
2.5	9
5	8
7	7
10	6.5
14	7.5

(•)Mean value of Q at the location of the maximum dose equivalent in a cylindrical phantom having a diameter of 30 cm and a length of 60 cm.

Table 3. Approximate values of the quality factors for various radiations(•)

Radiation	Current	Proposed
X-rays and gamma rays	1	1
Beta particles	1	1
Thermal neutrons	2	5
Fast neutrons	10	20
Protons	10	20
Alpha particles	20	20

(•)NCRP draft report [illegible]

Table 4. RBE values for fission (or optimum-energy) neutrons versus fractionated gamma rays and x-rays (Sinclair 1985)

Biological effect	Gamma rays	X-rays[a]
Mammalian tumor induction	3 to 200	1 to 100
Life shortening (in mice)[b]	15 to 45	8 to 23
Mammalian cell transformation	35 to 70	18 to 35
Cytogenetic studies	40 to 50	20 to 25
Mammalian genetic endpoints	10 to 45	5 to 23

[a]The RBE's in the x-ray column are equal to those in the gamma-ray column divided by 2. This relationship is consistent with the advice of Sinclair (1985) and Bond (1979). The factor of 2 represents the adjustment of the data from a gamma-ray base to an orthovoltage x-ray base, the basis that is defined for measurement of RBE.

[b]Life shortening in mice at low doses results from tumor induction and provides a measure for carcinogensis as a whole compared to individual tumor induction for specific sites (Sinclair 1985).

Table 5. Weighting factors, w_i, for tissues at risk (ICRP 1977)

Tissue	w_i
Gonads	0.25
Breasts	0.15
Active marrow	0.12
Lungs	0.12
Thyroid	0.03
Bone surface	0.03
Remainder[a]	0.30

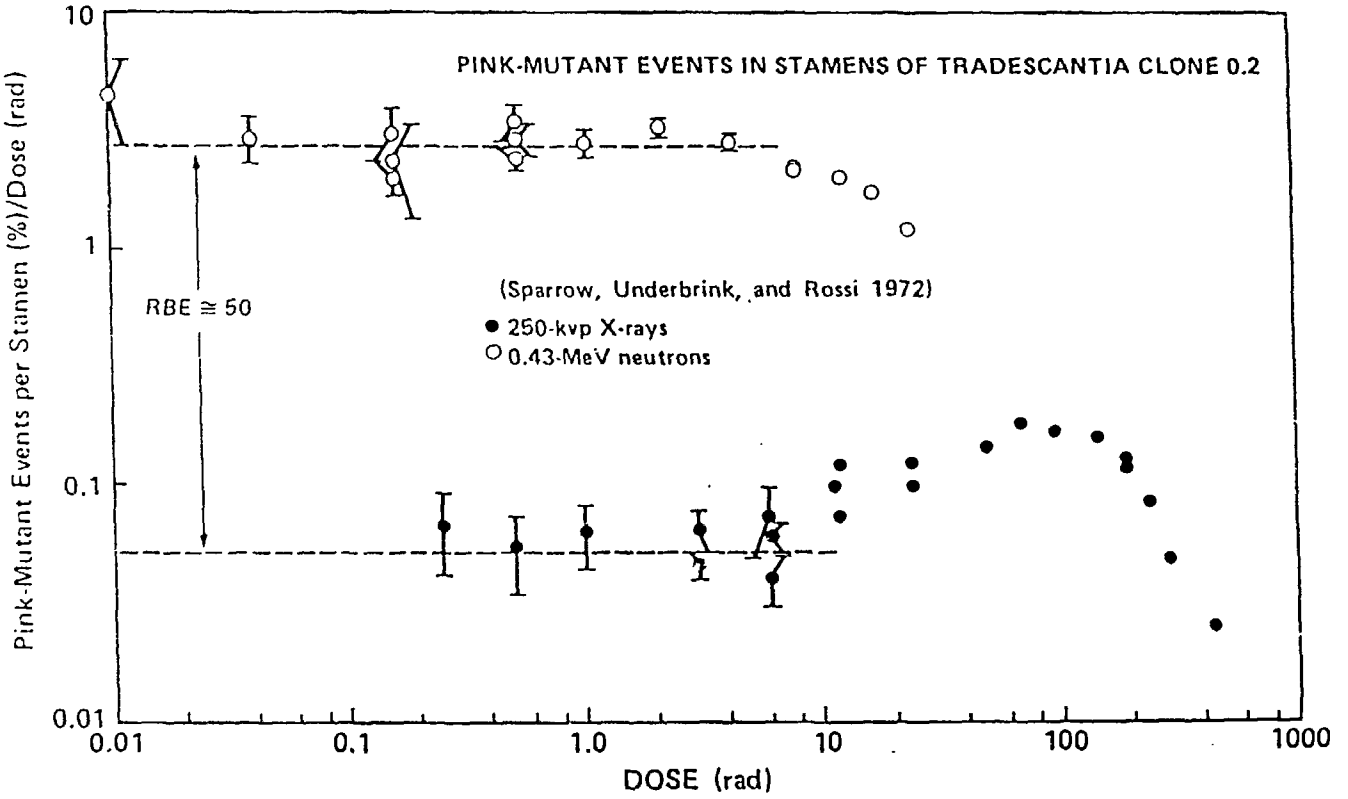
[a]Risk factors of 0.06 are applied to five additional organs with the largest dose equivalents.

Table 6. Ratios of effective dose equivalent, H(eff), to ambient dose equivalent, H*(10), for various neutron spectra and exposure conditions (Bartlett 1985)

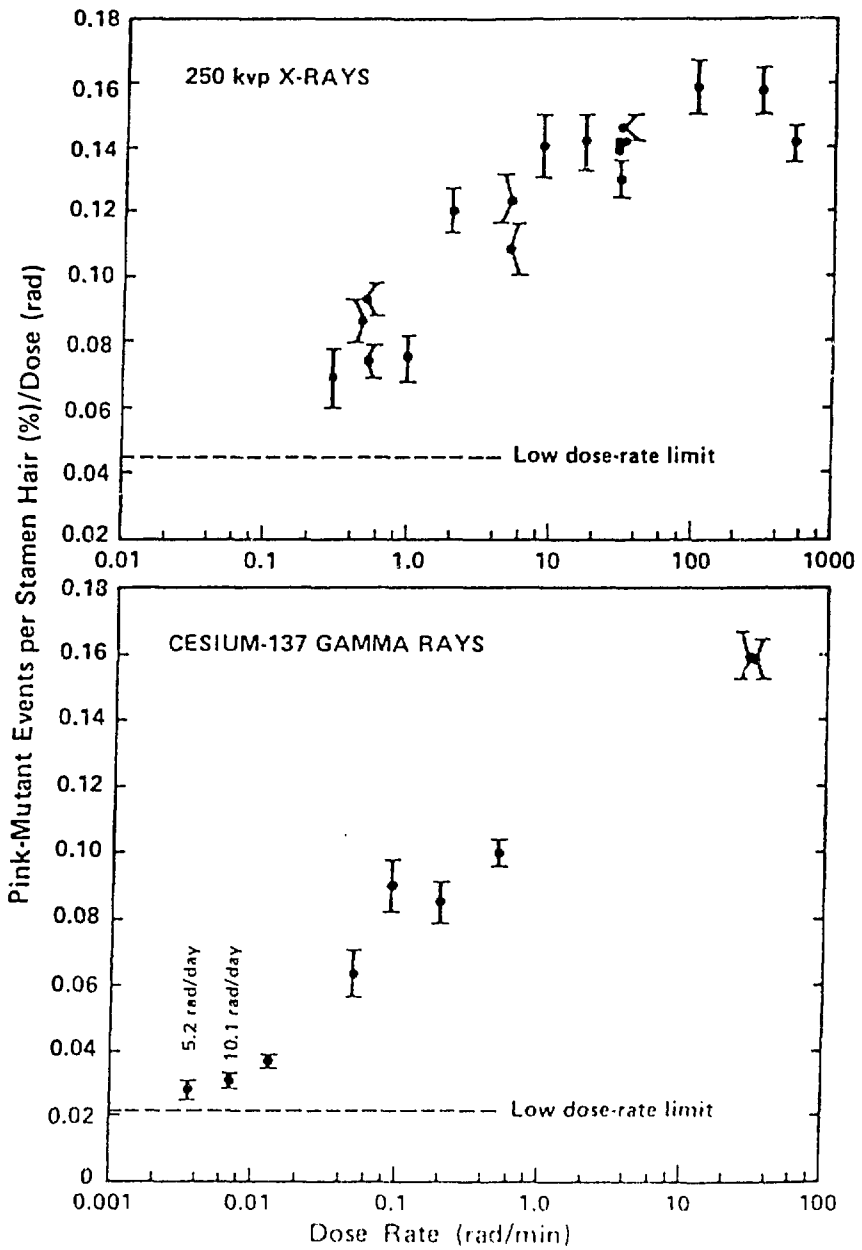
Neutron spectrum		Ratio of H(eff) to H*(10)		
		Plane beam	Rotational	Isotropic
Fission:	No shield	0.72	0.50	0.33
	10 cm D_2O	0.69	0.48	0.32
	10 cm iron	0.61	0.39	0.25
	40 cm concrete	0.70	0.49	0.32
HPRR:(a)	No shield	0.65	0.43	0.28
	12 cm lucite	0.70	0.48	0.32
	20 cm concrete	0.65	0.44	0.28
	13 cm iron	0.54	0.32	0.20
^{252}Cf:	No shield	0.73	0.51	0.34
	15 cm D_2O	0.71	0.50	0.33

(a) Health Physics Research Reactor (Sims 1985).

LIST OF FIGURES

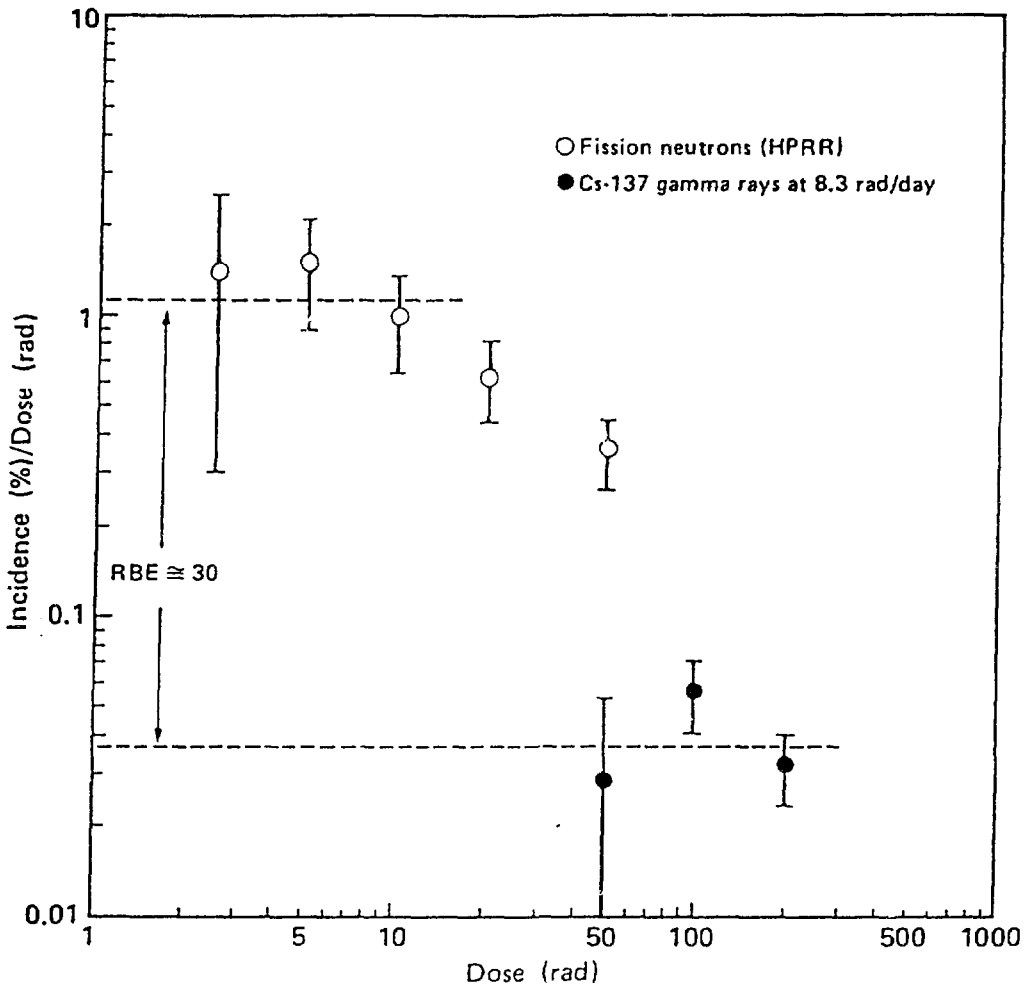

PINK-MUTANT EVENTS IN STAMENS OF TRADESCANTIA CLONE 0.2
(Sparrow, Underbrink, and Rossi 1972)
● 250-kvp X-rays
○ 0.43-MeV neutrons
RBE ≅ 50
Pink-Mutant Events per Stamen (%)/Dose (rad)
DOSE (rad)
10
1
0.1
0.01
0.01
0.1
1.0
10
100
1000

PINK-MUTANT EVENTS IN TRADESCANTIA CLONE 0.2 FROM DOSES OF 60 TO 80 RADS

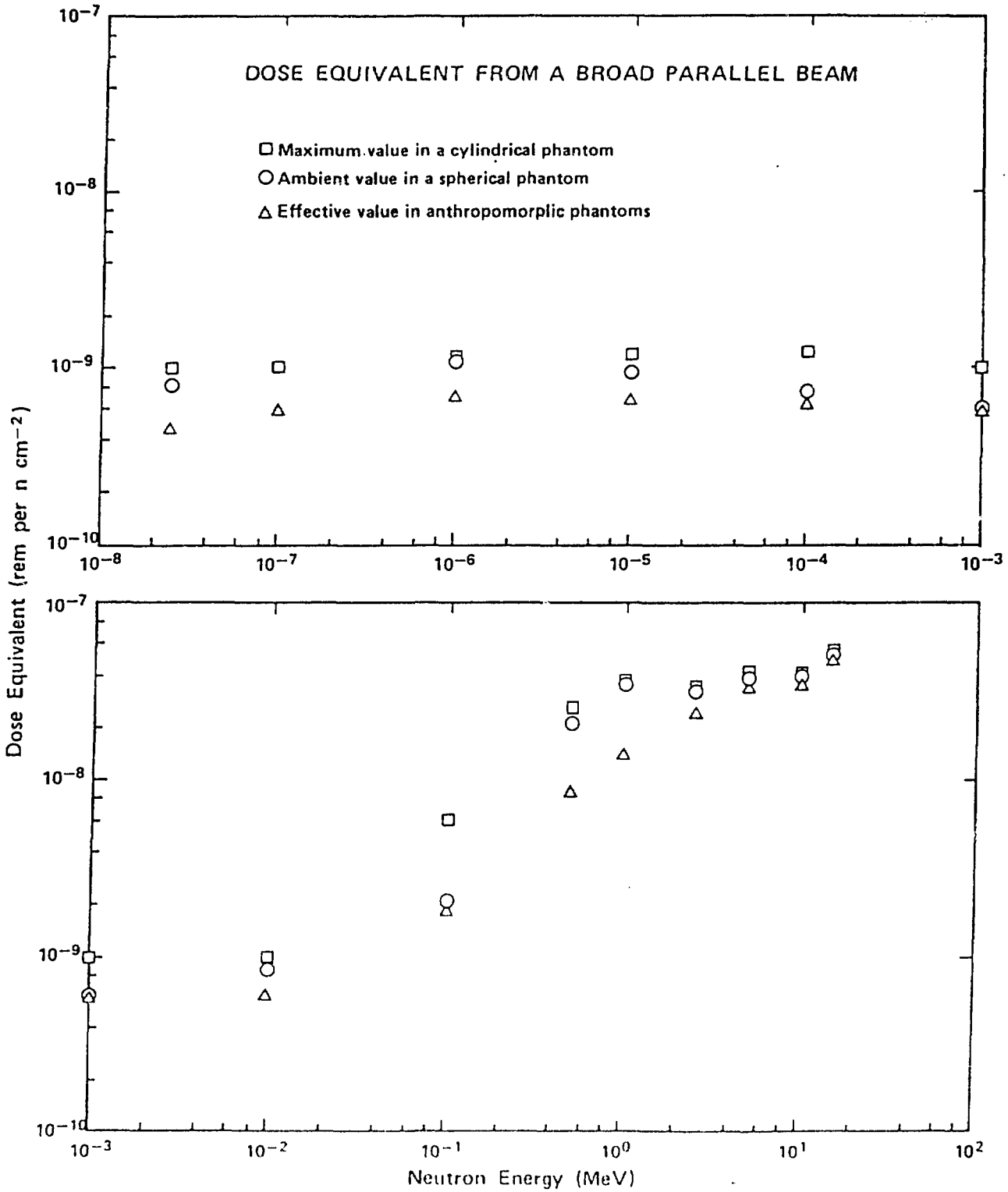


(Nauman, et al 1975, and Underbrink et al 1976)

MAMMARY ADENOCARCINOMAS IN FEMALE BALB/c MICE



(Ullrich 1984 and Ullrich and Storer 1978)


DOSE EQUIVALENT FROM A BROAD PARALLEL BEAM
□ Maximum value in a cylindrical phantom
○ Ambient value in a spherical phantom
△ Effective value in anthropomorplic phantoms
Dose Equivalent (rem per n cm⁻²)
Neutron Energy (MeV)
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10⁻⁴
10⁻⁵
10⁻⁶