Chapter 15

ENVIRONMENTAL DOSIMETRY AND RADIATION EFFECTS*

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Abstract

Specific assessment of the potential effects on wild organisms of increased radiation exposure arising from the authorized disposal of radioactive wastes to the environment requires two interrelated sets of information. First, an estimate is required of the incremental radiation exposure; and second, dose rate- response relationships are necessary to predict the potential impact of the estimated incremental exposure. Each of these aspects will be discussed in detail.

15.1. Introduction

There are no generally accepted criteria or standards for the protection of the environment (as opposed to man) from increased radiation exposure as a consequence of human activities. The ICRP does, however, accept that there is concern over environmental protection and has stated its belief that:

> " ... if man is adequately protected then other living things are also likely to be sufficiently protected." [1]

In a later set of recommendations [2], this position was developed to:

> "The Commission believes that the standard of environmental control needed to protect man to the extent currently thought desirable will ensure that other species are not put at risk. Occasionally, individual members of non-human species might be harmed, but not to the extent of endangering whole species, or creating imbalance between species."

In neither case did the Commission present evidence to support their position, nor refer to relevant review documents. There is a number of assumptions implicit within this position:

- the contaminated environment is occupied by both humans and other organisms, and similar use is made of the available resources which may be contaminated, e.g. food, water etc.;

- there are no major differences in the exposure pathways for endemic wild organisms and man i.e. the radiation exposure rates are of similar magnitude; and

- the endemic wild organisms are no more radiosensitive than man.

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In a practical situation where radioactive waste is to be disposed of into the environment, these assumptions would have to be validated by an assessment of both the likelihood and degree of radiation exposure, and the potential radiobiological response.

15.2. Dosimetry

A direct measurement of the dose rate is difficult (or impracticable) if:

- the dose rate is low (of the order of the variation in the natural background);
- the organism of interest is small and there is radionuclide accumulation above the ambient environmental concentrations;
- estimates are required of the dose rate to specific organs or tissues; and
- α- or β-particles deliver a significant fraction of the dose.

It is also clearly impossible in the preoperational phase of a disposal practice. In these circumstances, calculations must be made using appropriate models. The dosimetry models have to be simplified because it is not possible to consider all organisms, organs and tissues, and there are practical limitations on the availability of the basic data required for dose estimation e.g. the spatial and temporal variation in the distributions of the radionuclides within the organisms and in their external environment. Reasonable and valid generalisations can, however, be made so that dose rate estimates provide a close approximation to the magnitude of the environmental exposure experienced by either the most highly exposed organisms, or those considered likely to be most radiosensitive.

The development of dosimetry models requires consideration of:

- the type of radiation i.e. α- and β- particles and γ-rays;
- the relevant target e.g. the whole body, the gonad, the developing embryo, larvae etc.;
- the source of radiation i.e. external from contaminated water and sediment, and internal in tissues and organs; and
- the availability of relevant input data.

In assessments for the aquatic environment, representative organisms such as:

- fish)
) benthic and pelagic;
- crustaceans)
- molluscs) benthic; and
- birds

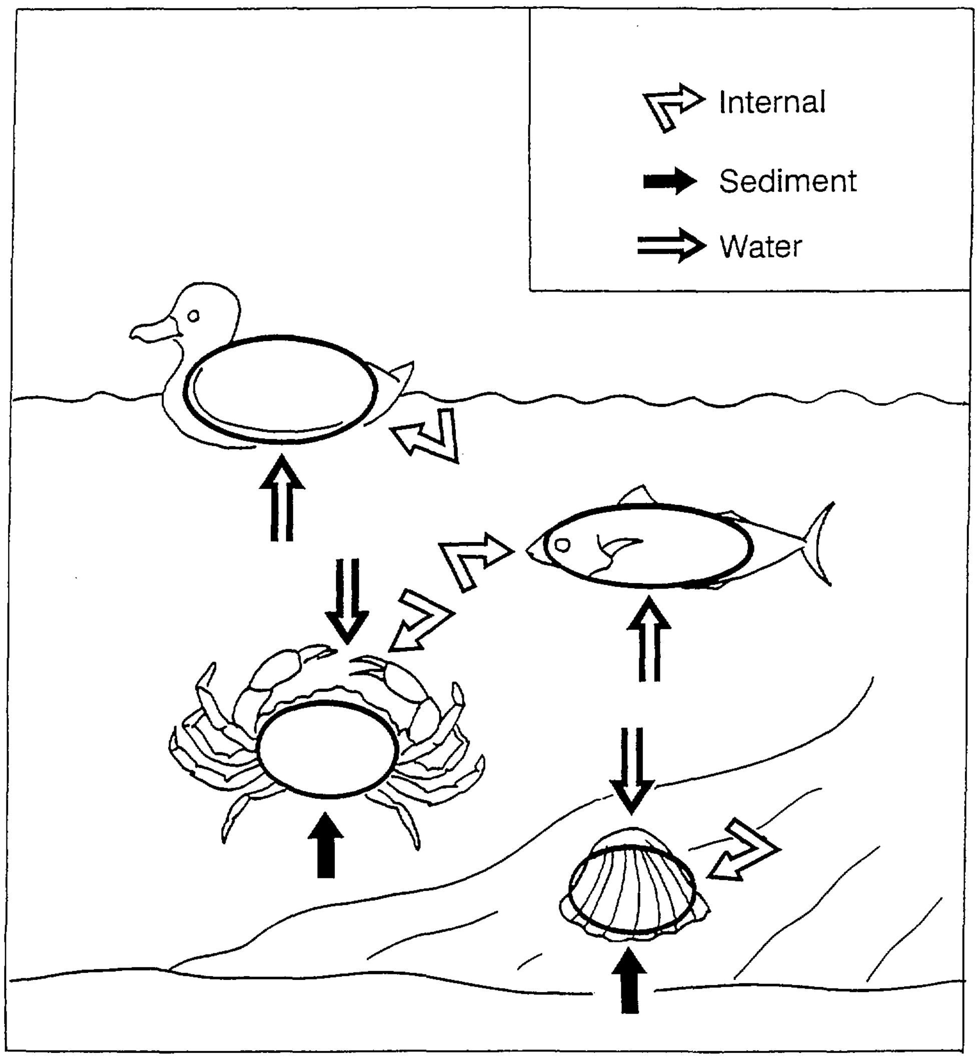

FIG. 1. Schematic diagram of the dosimetry models for some aquatic organisms.

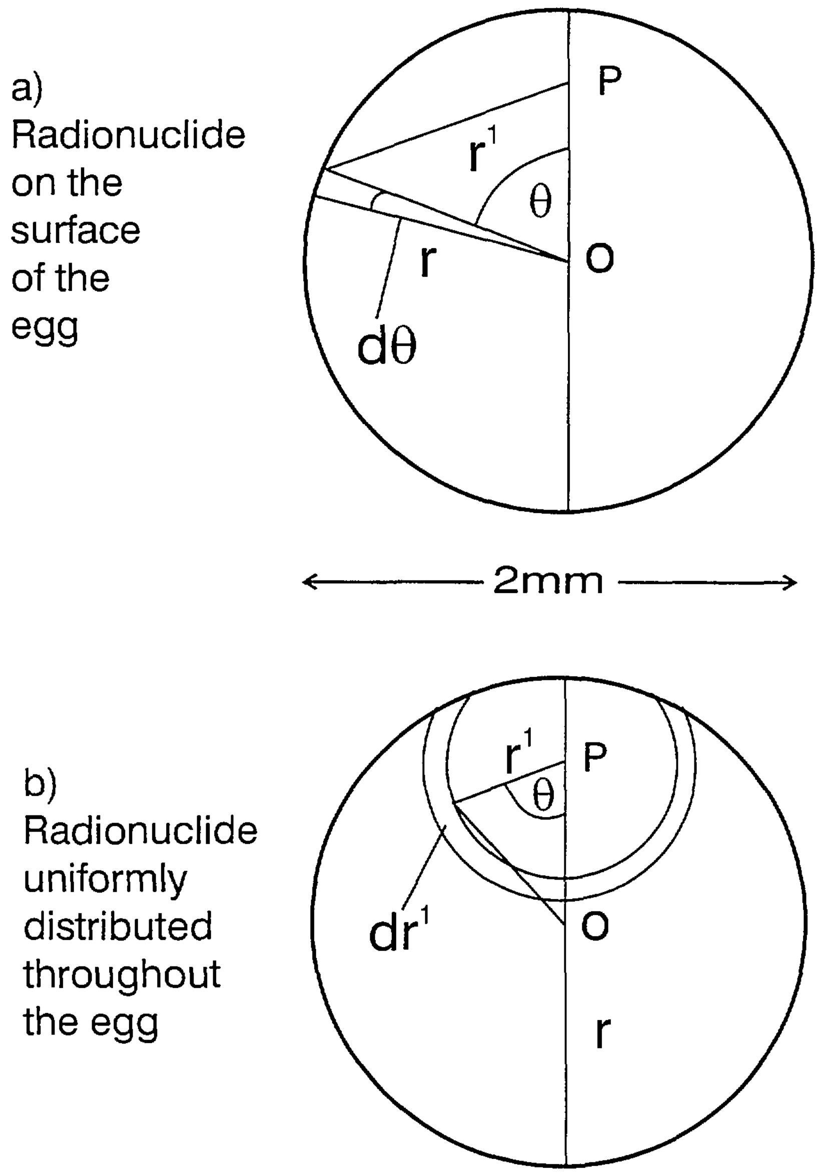

FIG. 2. Dosimetry models for fish eggs.

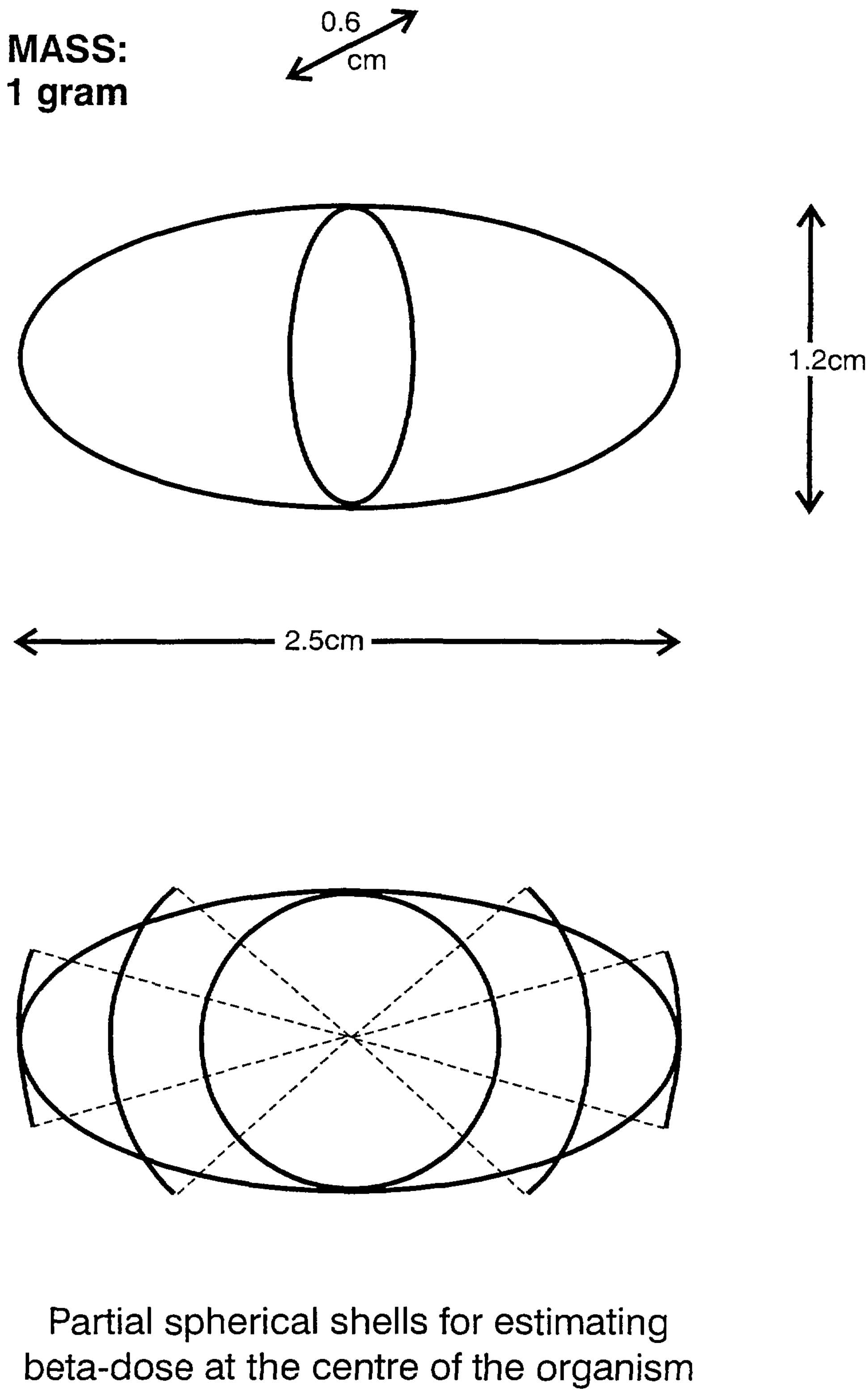

FIG. 3. The dosimetry model for a large insect or a mollusc.

have been selected for consideration, and the models have been developed from simple geometries based on ellipsoids and spheres [see Fig 1]. In the first instance, it may be assumed that there is a uniform whole body (or whole organism) distribution of the radionuclides. This assumption is reasonably valid for γ-radiation dosimetry; it is likely to be less so for β- radiation but it depends on the size of the target (organ or tissue) and the relative disposition of the β-emitting radionuclides; and it is likely to be wrong for the very short range α-particles where actual radiation exposure of the target depends upon very close proximity, if not congruence, of source and target. Because the incident radiation fields have characteristic path lengths in tissue ranging from meters for γ-rays through centimetres for β-particles down to 0.1 mm for α-particles, the dosimetric models and the information on radionuclide distributions are required on these scales if reasonably accurate estimates of dose rate are to be made. It may also be assumed that there is a uniform distribution of the radionuclides in the water and sediment.

More complex models can be developed as more data on radionuclide distributions become available or, conversely, more data have to be obtained precisely because a more complex model is required to adequately represent the real environmental situation; the developing fish egg is a relevant example (see Fig 2 from[3]). In a recent NCRP report [4], models were developed for large and small insects and larvae [Fig 3], turtles and alligators, in addition to fish, molluscs and ducks.

The nature and energy of the incident radiation determines the processes by which energy is transferred to tissue. The theoretical analysis of these processes is complex, in part due to their stochastic nature, and the resulting mathematical descriptions are not easy to apply in a dosimetric context. Simpler, empirical expressions have, therefore, been developed which describe the dose distributions as a function of distance from point sources. The dose rate, at a point, from an extended source is then obtained by integration of the point source dose distribution function over the source geometry; and if the dose (rate) is estimated at a number of points in the target, an estimate of the average dose (rate) to the tissue or organ may be obtained.

The dose distribution functions developed for aquatic organisms [3] are:
for α-particles

$$D_\alpha(r) = \frac{4.6 \times 10^{-8}}{\rho r^2} (A + B r^2) \text{ Gy h}^{-1} \text{ Bq}^{-1}$$

where ρ is the is the tissue density (g cm^{-3});
r is the distance (μm); and
A and B are parameters dependent on the α-particle emission energy (see [3], pp 44-8];

for β-particles

$$D_\beta(r) = \frac{k}{(\rho\, vr)^2} \left\{a[1-\frac{\rho vr}{c} \exp(1-\frac{\rho vr}{c})] + \rho vr \exp(1-\rho vr) \right\} \text{ Gy h}^{-1} \text{ Bq}^{-1}$$

where $[1-\frac{\rho v r}{c} \exp(1-\frac{\rho v r}{c})] = 0$ for all $r \geq \frac{c}{\rho v}$;

$$k = \frac{4.6 \times 10^{-8} \rho^2 v^3 \bar{E}_\beta n_\beta}{ac(3-e)+e} \text{ (Gyh}^{-1}\text{ Bq}^{-1}\text{)};$$

a, c and v are parameters dependent on the maximum energy of β-particle emission;
ρ is tissue density (g cm^{-3});
r is distance (cm);
$\bar{E}_\beta$ is the mean energy of β-particle emission (MeV); and
n_β is the proportion of decays giving β-particles of mean energy $\bar{E}_\beta$ MeV; (see [3], pp 47-53); and

for γ-radiation

$$D_\gamma(r) = 4.6 \times 10^{-8} \frac{\mu \bar{E}_\gamma n_\gamma}{\rho r^2} [1 - \exp(\frac{-2.3r}{r_e(0.3E_\gamma)})] \text{ Gyh}^{-1}\text{ Bq}^{-1}$$

for small organisms where scattering and absorption may be neglected and where

μ/ρ is the true mass energy absorption coefficient (cm^2 g^{-1});
r is the distance (cm);
r_e is the (0.3 E_γ) is the range of an electron with initial energy 0.3E_γ MeV (cm);
E_γ is the γ-ray emission energy; and n_γ is the proportion of decays which produce γ-rays with energy E_γ MeV (see [3], pp 54-5);

for larger organisms, where scattering and absorption must be considered:

$$D_\gamma = 5.8 \times 10^{-7} E_\gamma n_\gamma \phi \text{ Gy h}^{-1} (\text{Bq g}^{-1})^{-1}$$

where

$$\phi = \frac{\text{photon energy absorbed by target}}{\text{photon energy emitted by source}}$$

and is called the absorbed fraction; values of φ may be taken, by interpolation and extrapolation, from published tables (see[3], pp 54-5 for details).

The geometries chosen to represent certain organisms are summarised in Table I [5], and the corresponding γ-ray absorbed fractions (φ) and the β-dose rates at the centre of the organisms are shown in Figs 4 and 5.

The estimation of dose rates in a contaminated aquatic environment can be approached in a number of ways:

- hydrographic data can be used to estimate the concentrations in water from the radionuclide release, and then concentration factors (CF) and distribution coefficients

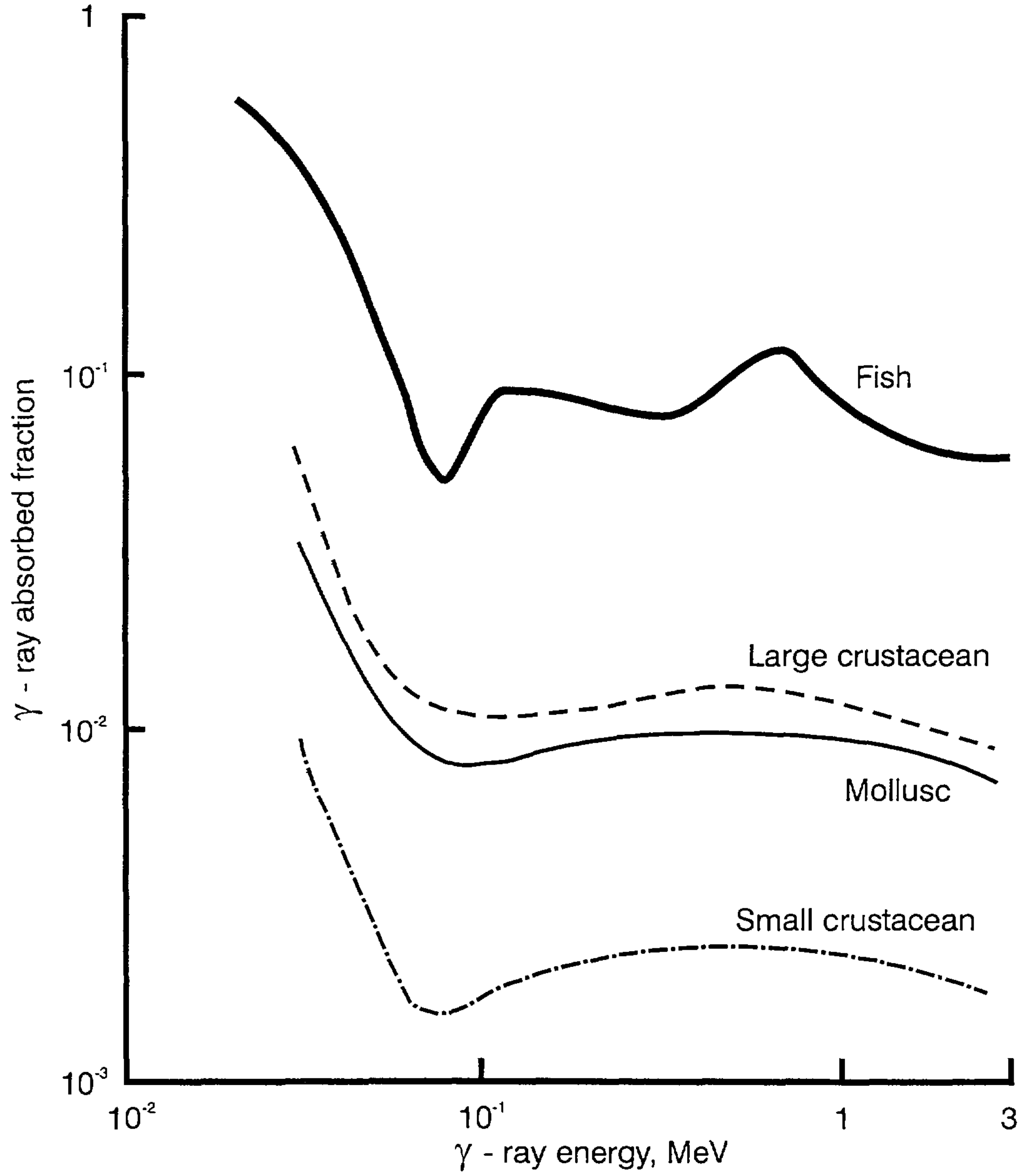

FIG. 4. γ-ray absorbed fractions for aquatic organisms for a uniform distribution of radionuclide in the body.

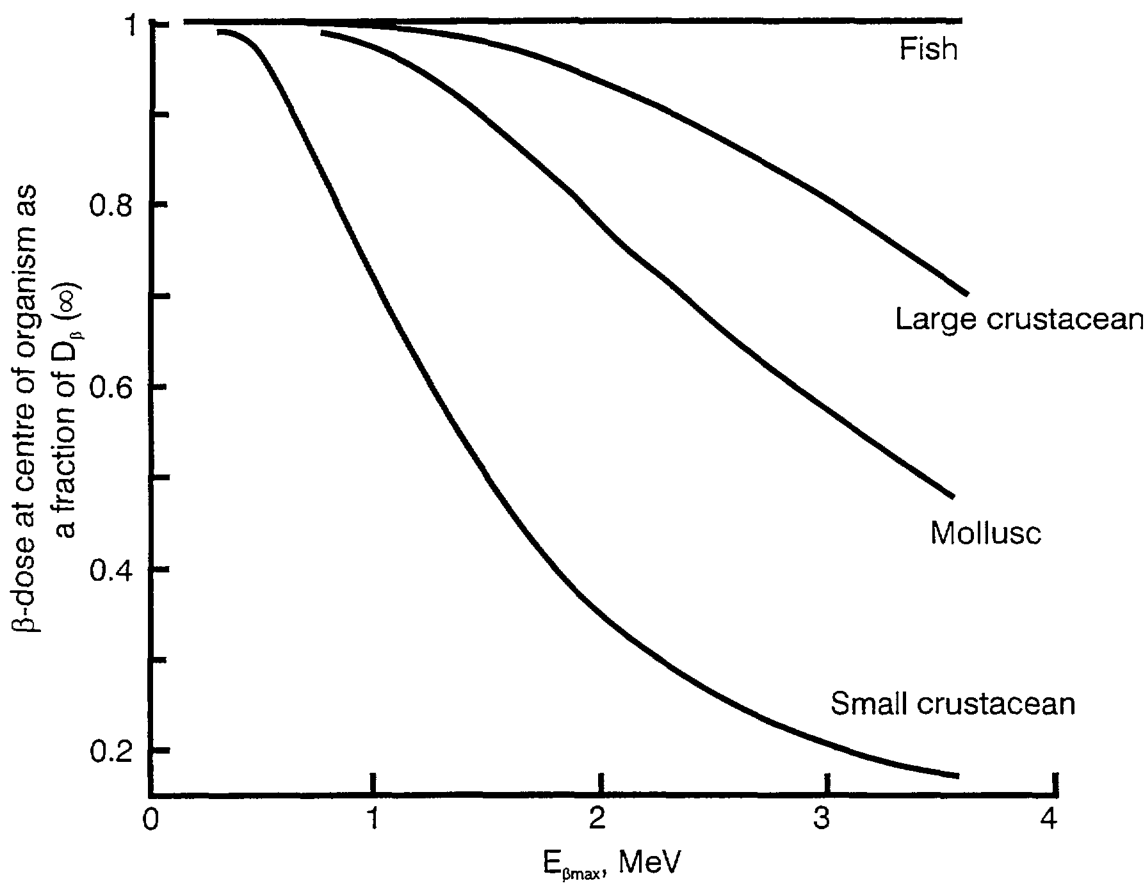

FIG. 5. β-particle dose at the centre of aquatic organisms for a uniform distribution of radionuclide in the body.

(K_D) are applied to give the radionuclide concentrations in the biota and sediments respectively. These are then the input data for the dosimetry models;

- once a release of radionuclides to the environment has commenced, the measured concentrations in water, organisms and sediment provide the input data for the dosimetry models; and

- it may be assumed that there is a maximum human radiation exposure of 1 mSv a^{-1} arising from reasonable use of the contaminated environment e.g. as a source of drinking water, fish for consumption, or for leisure activities over contaminated sediments. This implies certain limiting concentrations of the radionuclides in water, fish and sediment that can be used in the dosimetry models to estimate the maximum likely dose rates to organisms.

TABLE I. DOSE MODELS: ALL ORGANISMS ARE REPRESENTED BY ELONGATED, FLATTENED ELLIPSOIDS

Organism	Mass	Length of major axes, cm
Fish	1 kg	45 x 8.7 x 4.9
Large Crustacean	2 g	3.1 x 1.6 x 0.8
Mollusc	1 g	2.5 x 1.2 x 0.6
Small Crustacean	16 mg	0.6 x 0.3 x 0.2

Because the dose rate from contaminant radionuclides (and the natural background) is likely to include contributions from both sparsely ionizing (low linear energy transfer (LET)) photo-electrons and β-particles and densely ionizing (high LET) α-particles, the problem of specifying the biologically effective dose (rate) arises. It must be remembered (see lecture notes on radiation protection, chapter 16) that EQUIVALENT DOSE and EFFECTIVE DOSE have only been defined for use in human radiation protection; it is incorrect, therefore, to use these quantities (and the sievert unit) for environmental dosimetry. To take account of radiation quality, that is, to take account of the increased biological damage produced by the high LET α-radiation per unit absorbed dose (as compared with low LET radiation), two approaches are possible. First, the absorbed doses from the low LET and high LET components of the radiation field can be given separately. This has the advantages that each component is readily identifiable and no decision is required concerning an appropriate value for the quality factor to be applied to the high LET absorbed dose; it does, however, suffer from the disadvantage that there is not a single value representing the total biologically effective dose that can be used as a basis for an assessment of the impact on the environment of the incremental radiation exposure from the contamination. The second approach addresses this latter disadvantage by generating:

$$\text{Weighted absorbed dose} = \Sigma_i\,[\text{Quality factor for radiation } R_i \times \text{Absorbed dose from radiation } R_i]$$

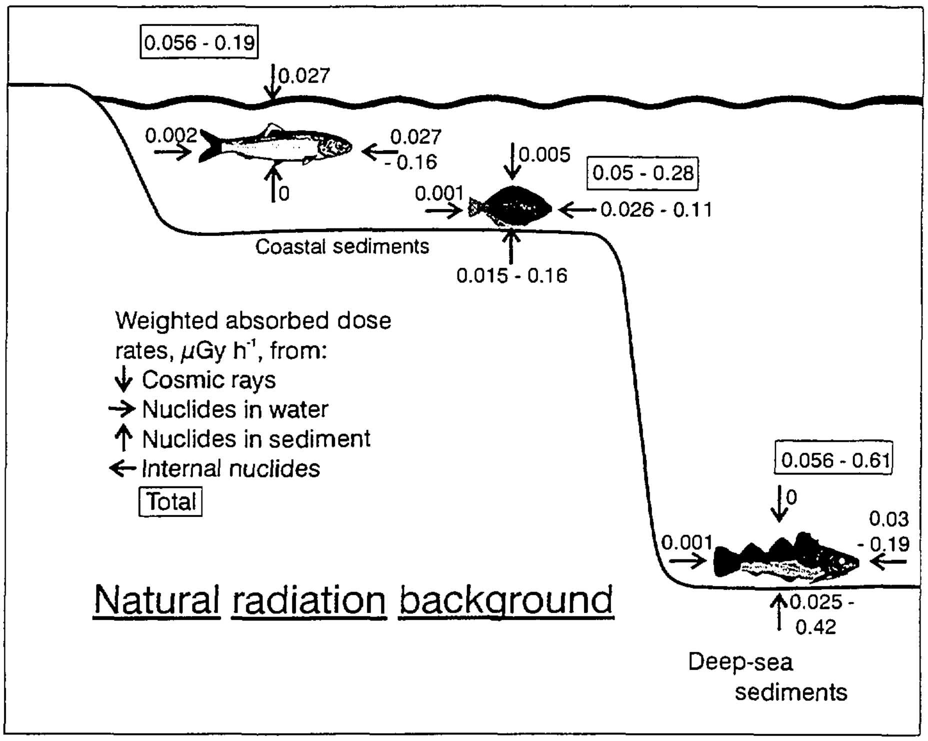

FIG. 6. Dose rates from the natural background to fish in different marine environments.

As will have become clear from the discussion above, only two radiation types require consideration: the low LET electrons and β-particles and the high LET α-particles. In the former case, the appropriate quality factor (QF) is unity; in the latter case, the appropriate QF value is 5 for the deterministic effects that are of importance (see below). The unit of the weighted absorbed dose remains the gray (Gy).

Fig 6 indicates the weighted absorbed dose rates estimated for fish occupying different niches in the sea, and Table II gives the estimated weighted absorbed dose rates experienced by the plaice *(Pleuronectes platessa)*, a bottom-living flatfish, from radionuclides discharged from Sellafield. Fig 7 shows the variation in the dose rate from the contaminated sediment, the major source of enhanced exposure for the plaice, and the approximate extent of the area where the additional exposure was greater than background. This was a situation in which confirmation of the dose estimates was considered possible with *in situ* measurements. A combined fish tag-LiF dosimeter was developed and attached to 3580 plaice which were released in the vicinity of the Sellafield effluent outfall. A total of 1053 marked fish were recaptured by normal commercial fishing operations throughout the Irish Sea over a period of 2.5 years. The dosimeters were returned to the laboratory and 92% yielded useful information. The distribution of measured dose rates is shown in Fig 8, and it can be seen that the results provide general confirmation of the original dose rate estimates [6]. Table III shows the estimated dose rates to the developing plaice embryo from contaminant radionuclides both accumulated by the developing egg and in the surrounding water [7].

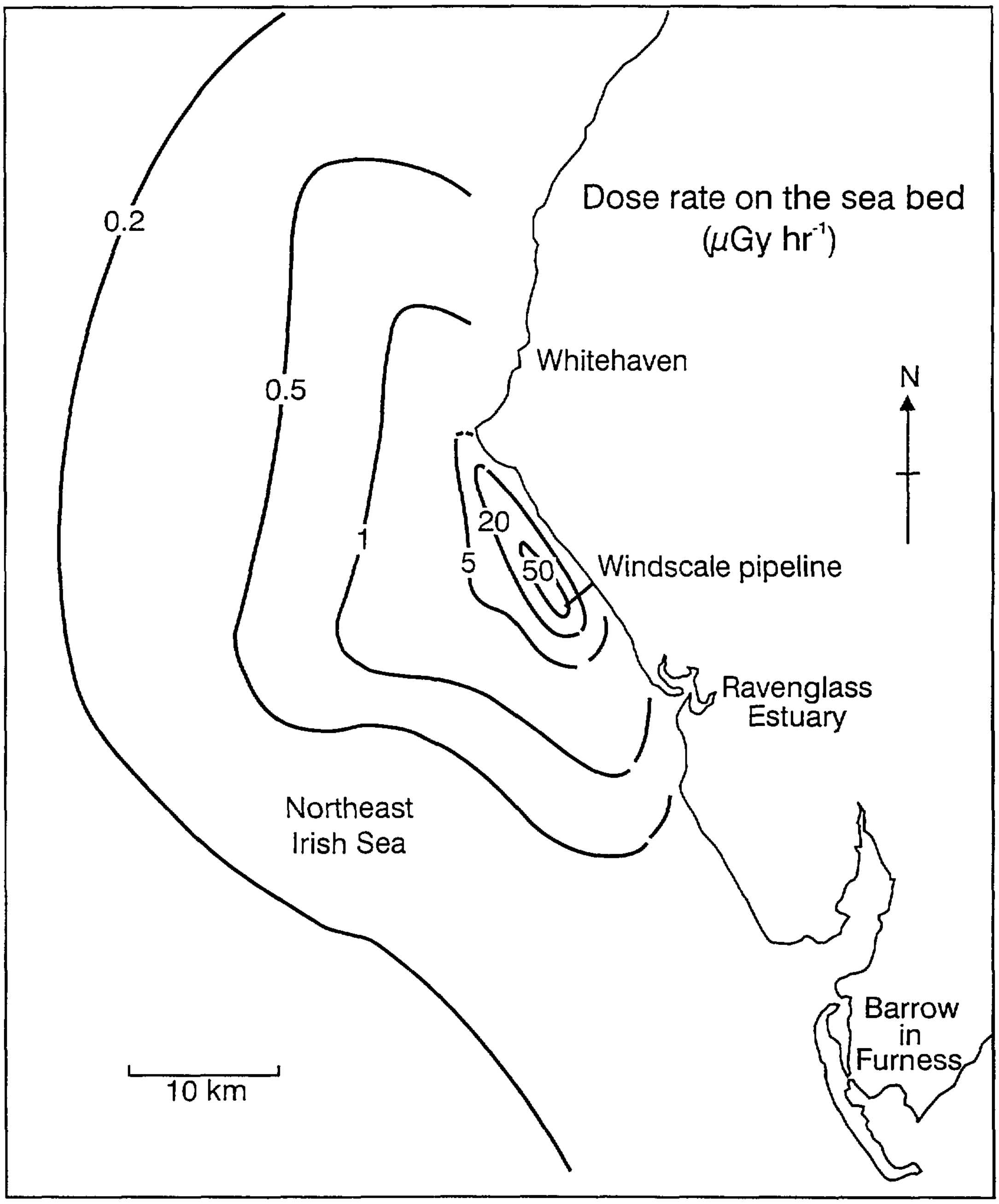

FIG. 7. Estimated dose rate on the seabed from Sellafield radionuclides accumulated by the sediment.

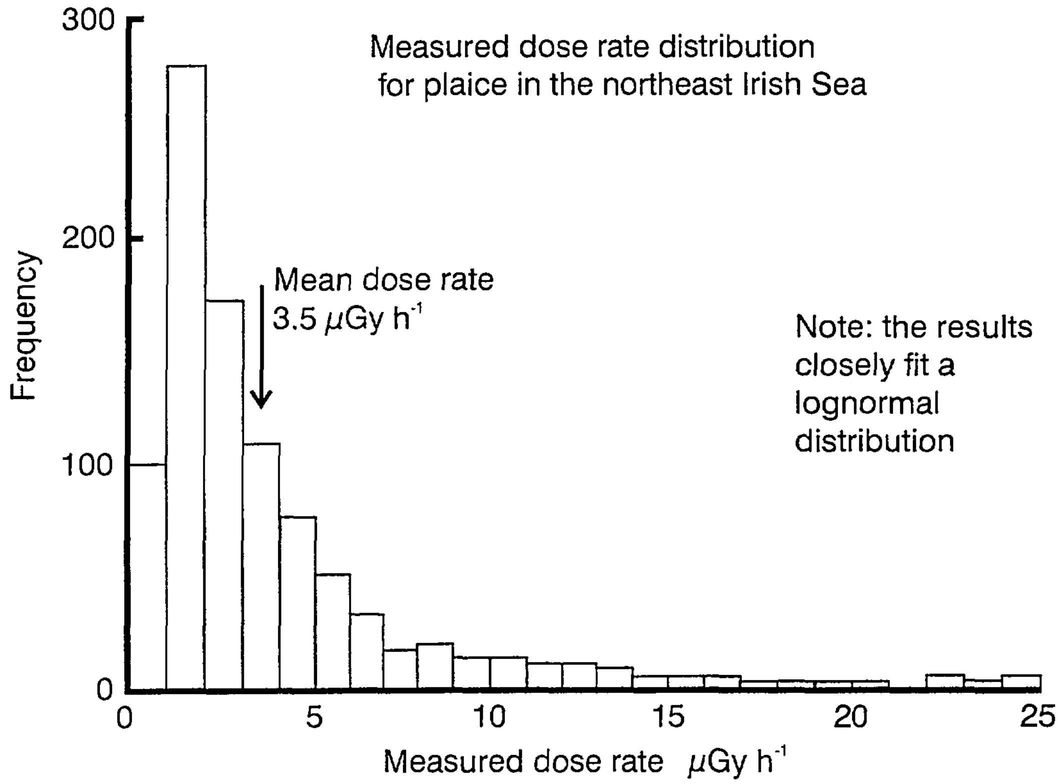

FIG. 8. Measured dose rate distribution for the plaice in the NE Irish Sea.

The significance of small dose rates to small organisms must be assessed carefully and the case of Pu-239 accumulation by plaice eggs may be considered as an example:

Pu-239 concentration in water	$= 0.04$ Bq l^{-1}
Pu-239 concentration factor for plaice eggs	$= 2$ l kg^{-1}
∴ Pu-239 concentration on plaice eggs	$= 0.08$ Bq kg^{-1}

This contamination is estimated to result in an absorbed dose rate to the developing plaice embryo of 0.001 μGy h^{-1}, or a total of 0.4 μGy over the 17 day development period.

It should be noted, however, that a single egg weighs 0.004 g;

∴ Pu-239 per egg $= 3.2 \times 10^{-7}$ Bq

i.e. there is 1 disintegration on a plaice egg every 3.1×10^{6} seconds, or 36 days. Because egg development takes 17 days, some eggs will experience the passage of one α-particle, but a majority will experience none; this shows that the estimate of the average dose rate is meaningless. In practice, Poisson statistics apply and the number of decays per egg is given by the terms of the series:

$$\exp(-0.5)\left(1 + \frac{0.5}{1!} + \frac{0.5^2}{2!} + \frac{0.5^3}{3!} + \ldots\ldots\ldots\right)$$

Thus, 76% of the eggs experience the passage of no α-particles, 19% experience 1, and 4% experience 2 passages.

TABLE II. EXPOSURE OF PLAICE IN THE NE IRISH SEA.

Source of Radiation	Dose Rate, $\mu Gy\ h^{-1}$
Internal radionuclides	0.094 - 0.10
Radionuclides in seawater	0.0005 - 0.013
Radionuclides in sediment (γ-rays only)	0.37 - 33.1
Total	0.47 - 33.2

TABLE III. ESTIMATES OF THE DOSE RATES TO DEVELOPING PLAICE EMBRYOS IN THE NE IRISH SEA, $\mu Gy\ h^{-1}$ ($x10^5$)

Nuclide	Activity on and in the egg	Activity in the water	Totals
^{144}Ce - ^{144}Pr	7	11	18
^{137}Cs	2	16	18
^{106}Ru - ^{106}Rh	5	10	15
^{90}Sr - ^{90}Y	4	11	15
^{95}Zr - ^{95}Nb	5	16	21
Total			87
^{40}K	400	300	700

TABLE IV. RADIATION EXPOSURE OF BLACK-HEADED GULLS IN THE RAVENGLASS ESTUARY

Target	absorbed dose rate, $\mu Gy\ h^{-1}$		Major source
	Low LET	High LET	
Whole Body	0.8	0.007	External γ-rays, 85%
Gut	1.2	0.6	α-emitters in food, 75%
Eggs	0.4	-	External γ-rays, 99%

The natural background from external sources is approximately 0.1 $\mu Gy\ h^{-1}$.

A final example of environmental dose estimates is given in Table IV for black-headed gulls inhabiting the estuary of the River Esk to the south of the Sellafield reprocessing plant [8].

15.3. Radiation effects

Early studies of the effects of irradiation on aquatic organisms generally employed acute exposures i.e. high doses delivered in short times that produced clear-cut, short-term effects, usually mortality. The standard measure of radiosensitivity was the estimated $LD_{50/30}$ or the dose which would kill 50% of the organisms exposed within 30 days. A summary of selected results is given in Table V and two conclusions may be drawn:

- the $LD_{50/30}$ for aquatic organisms is generally higher than that observed for mammals; and

- there are more radiosensitive endpoints than mortality of mature adults.

The first conclusion is, in fact, flawed because the $LD_{50/30}$ values do not represent equivalent endpoints for mammals and aquatic organisms. For mammals, the 30 day observation period encompasses essentially all of the short-term mortality induced by a moderate, acute radiation exposure; for poikilothermic aquatic animals, with generally lower metabolic rates, there is continuing mortality beyond 30 days and the median lethal dose declines with increasing observation time as shown for molluscs and fish in Figs 9 and 10. For aquatic organisms, the appropriate observation period would be 60-90 days to provide (lower) median lethal dose values that would be more comparable with the data for mammals. This observation reduces, but does not eliminate, the apparent differential radiosensitivity (in terms of acute mortality) between mammals and aquatic organisms. The second conclusion is more robust, and indicates that there are biological processes that are more radiosensitive and, therefore, more significant for the assessment of the potential impact of radiation on the environment.

TABLE V. SENSITIVITY OF MARINE ANIMALS TO ACUTE IRRADIATION

Organism	$LD_{50/30}$, Gy
Molluscs	370 - 1100
Crustaceans	15 - 510
But: Production of Young Amphipods reduced by 50%	6
Fish	11-56
But: Developing Plaice Eggs at Blastoderm Stage	1

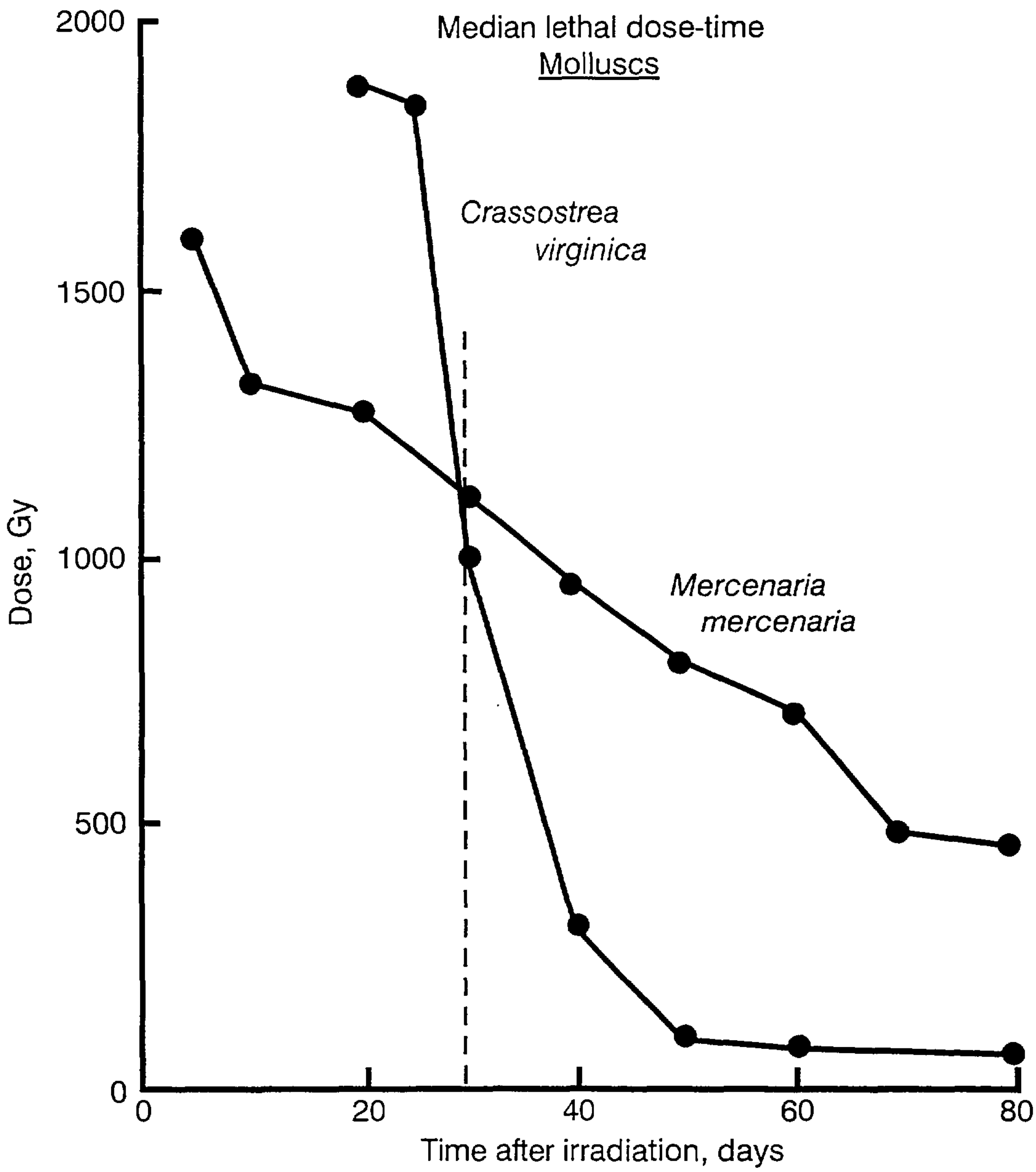

FIG. 9. Median lethal acute dose for molluscs. Adapted from J C White and J W Angelovich, Chesapeake Science, 7(1) (1966) 36-39.

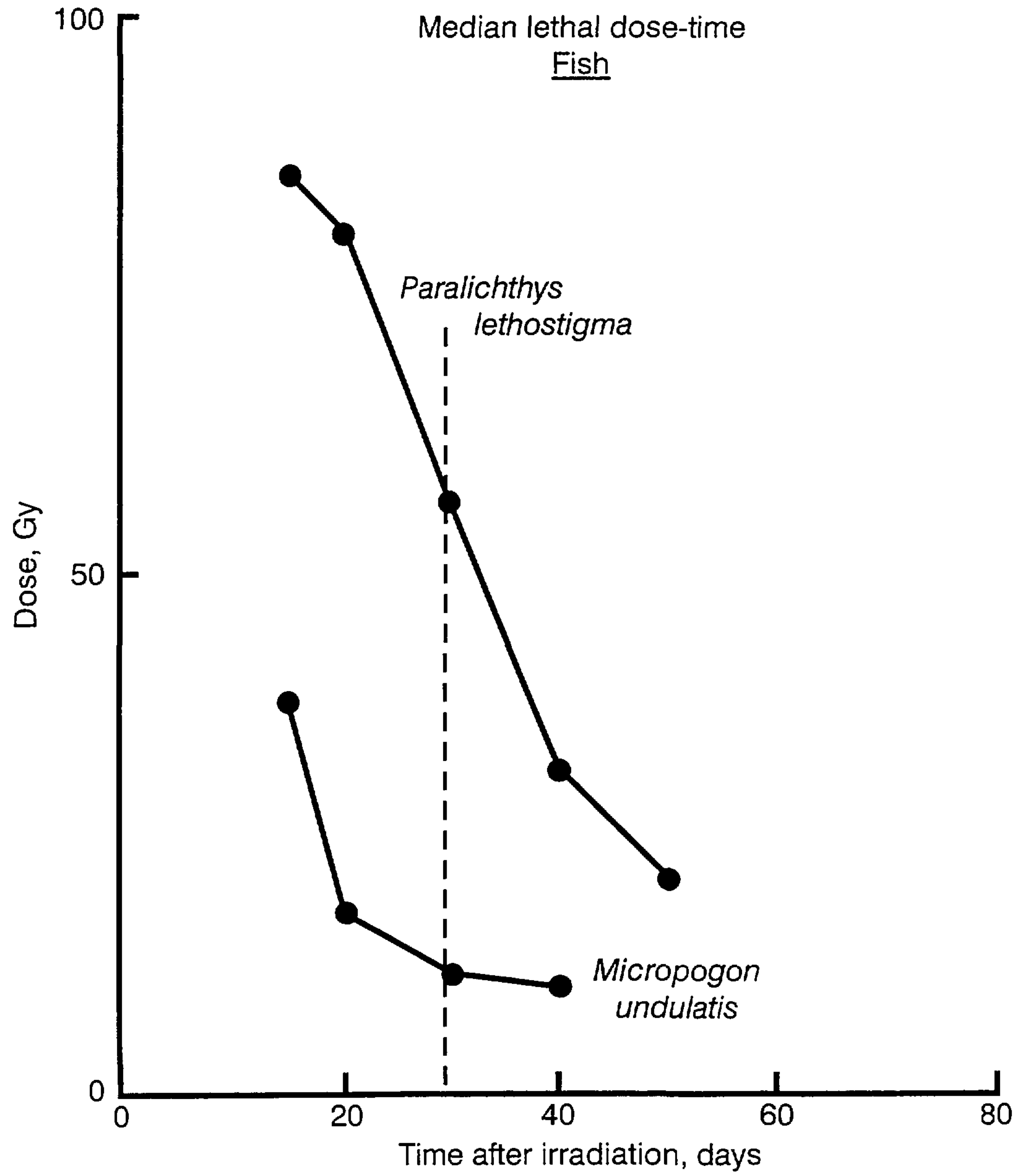

FIG. 10. Median lethal acute dose for fish. Adapted from J C White and J W Angelovich, Chesapeake Science, 7(1) (1966) 36-39.

The radiation exposures arising from a controlled, point-source release of waste radionuclides to the environment will, in general:

- be chronic, low dose rate;
- vary widely in space and time;
  and therefore,
- vary widely within populations of both mobile and sedentary organisms.

In these circumstances, the possibility of acute responses, including short-term mortality, can be discounted and more relevant endpoints are needed both as a basis for assessing potential effects and for the development of criteria to ensure protection of the environment.

In general, and in contrast with the practice in human radiological protection, it is not the individual organism that is the object of concern, but the population (appropriately defined); exceptions may be the individuals of rare, or otherwise endangered species. A relevant definition of the population depends on the problem under consideration and will be determined, in part, by the scale of interest in both space and time. A potentially useful definition is as follows:

> "A population is a biological unit for study, with a number of varying statistics - number, density, birth and death rates, sex ratio, age distribution etc. - which derives a biological meaning from the fact that some direct or indirect interactions among its members are more important than those between its members and the members of other populations (*of the same organism*)." [9].

More succinctly, a population is a self-sustaining, and relatively self-contained, unit of a particular species. In a pond, the population is likely to include all members of a given species; in streams and rivers, the population might include all members of the species upstream and down-stream of a discharge point, but not necessarily those in down-stream tributaries. The objective of protecting a population would be achieved if its ability to maintain itself, within the normal range of natural variability, in terms of:

> numbers, sex ratio, reproductive rate, death rate, age distribution etc.,

is not impaired. All of these attributes can only be defined at the population level but they are, nevertheless, integrated outcomes (but not the simple linear sum) of processes operating at the individual level,

> i.e. morbidity, mortality, fertility, fecundity, mutation rate etc.

As noted above, the processes of gametogenesis (fertility) and embryonic development (fecundity) are more radiosensitive than those leading to individual mortality. It is reasonable to conclude that there can be no effects at the population level (or at the higher community and ecosystem levels) if there are no clear radiation effects in these processes in individual organisms. These conclusions effectively define both the relevant targets for radiation dosimetry i.e. the whole body, the gonads and the developing embryo (see dosimetry section above) and the processes for which dose rate-response data are required for the assessment of potential impact. It is also important to recognize that the radiation effects in these processes are, with the exception of mutation induction, deterministic in nature.

TABLE VI. EFFECTS OF CHRONIC IRRADIATION ON THE EMBRYOS AND OFFSPRING OF THE GUPPY

Dose rate, $mGy\ h^{-1}$	Mean Brood Size	Life-Time Fecundity	Number of Live Young	Neonatal Deaths	% Survival
Controls	17.5	380	4066	15	90
1.7	13.1	220	1742	18	93
4.0	13.6	200	1661	2	90
12.6	2.3	4	21	0	100

TABLE VII. EFFECTS OF CHRONIC IRRADIATION ON TESTES WEIGHT OF *Ameca Splendens*

Dose Rate, $mGy\ h^{-1}$	Day 180	Day 280
Control	0.017	0.015
1.1	0.012	0.012
2.0	0.007	0.008
4.7	0.004	0.002

TABLE VIII. SUMMARY OF LABORATORY EXPERIMENTS ON THE EFFECTS OF CHRONIC IRRADIATION ON FISH

Fish Species	Dose Rate, $mGy\ h^{-1}$	Total Dose, Gy	Response
Guppy	1.7	35	45% Fewer young
Ameca Splendens	7.3	35	Adult mortality; few and sterile young
	7.3	16	Adult sterility
	1.1	4.8	Reduced testes weight
	0.5	6.3	Chromosome damage

From the numerous studies of the effects of radiation on aquatic organisms, it may be concluded that fish are, in general, the most radiosensitive group of the fully aquatic species; the data also show that gametogenesis and embryonic development are the most radiosensitive processes; for these processes there is also greater over-lap in the range of radiosensitivities in different phyla. Fig 11 shows the effects of chronic low-level irradiation over almost the whole of their life on the reproductive performance of the small viviparous tropical fish, *Poecilia reticulata* (the guppy), and the overall response is summarised in Table VI [10]. The effects of chronic irradiation on spermatogenesis in *Ameca splendens* (another viviparous, tropical species) is shown in Fig 12, and the data in Table VII show that the change in testes weight is a reasonably reliable indicator of radiation response at lower dose rates [11]. Recent studies [12] have shown that chronic irradiation produces a similar response in the testes of the plaice (a species with an annual gametogenic cycle as compared with continuous sperm production in the small tropical species). The results of these

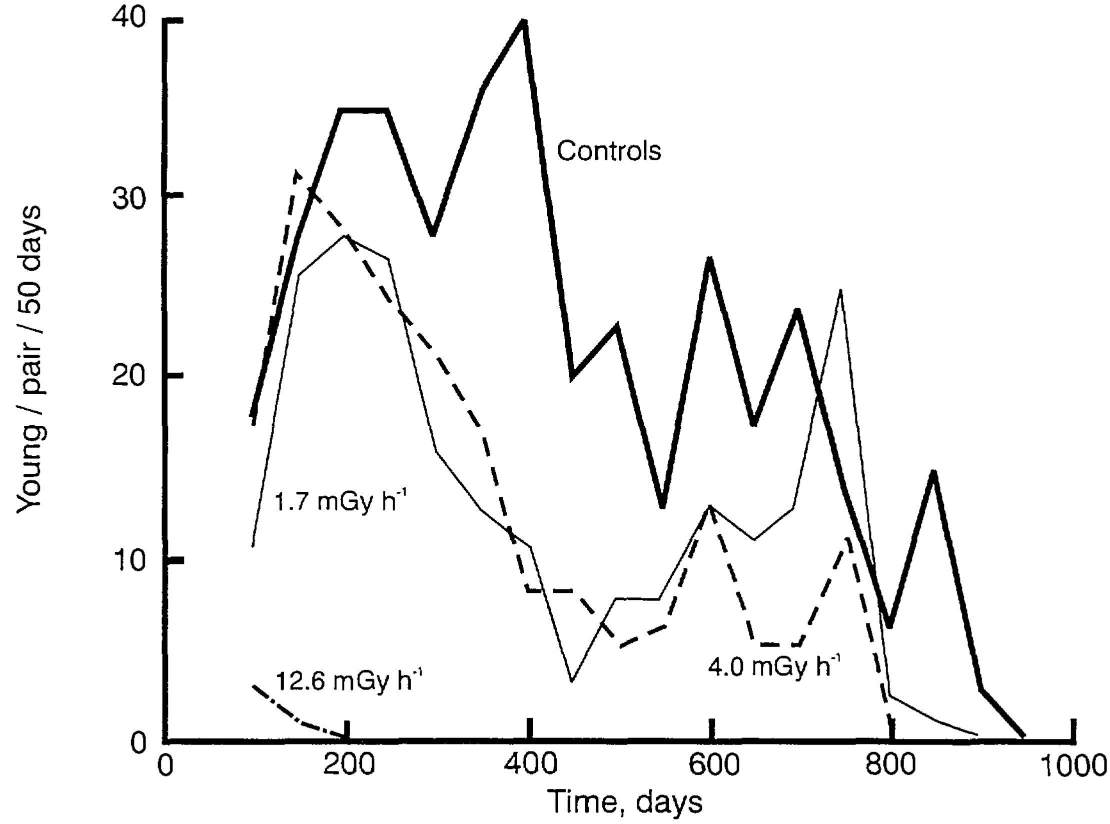

FIG. 11. The effects of life-time chronic irradiation on the offspring production of the guppy, Poecilia reticulata.

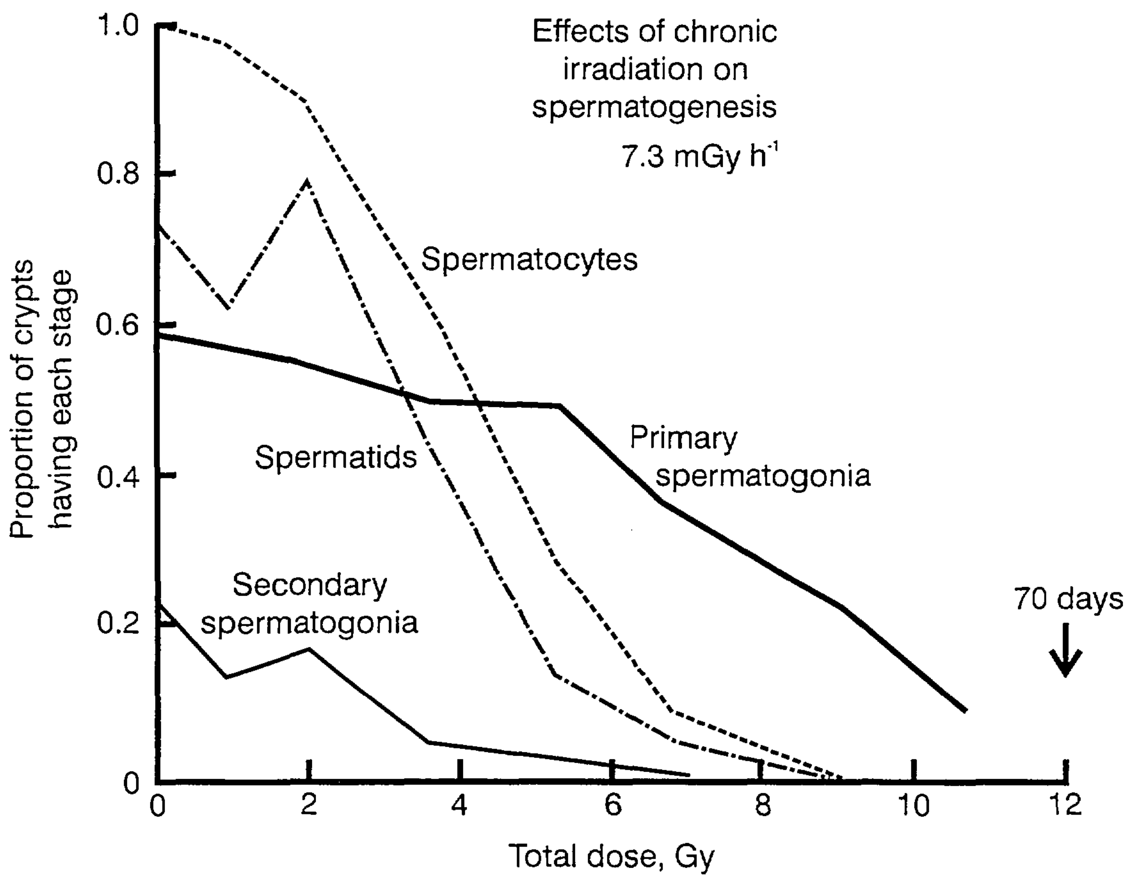

FIG. 12. The effects of chronic irradiation on spermatogenesis in the fish, Ameca splendens.

laboratory studies are summarised in Table VIII, and the environmental situation is indicated in Table IX.

TABLE IX. SUMMARY OF THE ENVIRONMENTAL SITUATION

	Dose Rate, mGy h^{-1}	Total Dose, Gy	Response
Developing Plaice Eggs		In 17 days of egg development:	
	Background: 3×10^{-5}	10^{-5}	
	Contamination: 9×10^{-7}	4×10^{-7}	No effect
Adult Plaice	Background: 1×10^{-4}	Lifetime (5 years): 4×10^{-3}	
	Contamination: Maximum 3×10^{-2}	1.3	No effects at the population level
	Average 2×10^{-3}	9×10^{-2}	

Because gametogenesis and embryonic development are of particular importance for the maintenance of the population, protection would be achieved if the most exposed individuals in the population received incremental chronic radiation exposures from the consequences of human activities (eg radioactive waste disposal) at dose rates less than those at which minor effects would be expected in these processes, i.e. the great majority of the population would experience dose rates at which there would be no detectable effects. A number of wide-ranging reviews of the available information on the effects of irradiation on aquatic organisms [4,13-18] all support the conclusion that at a dose rate of less than 0.4 mGy h^{-1} to the most highly exposed individuals in populations of aquatic organisms (and, therefore, a lower average dose rate to the population, see results in Section 15.2 above) there would be only very minor effects on gametogenesis and embryonic development and these would not be apparent in the contaminated aquatic environment as a response at the population level.

15.4 Conclusions

In all the cases that have been studied, the implementation of controls on waste discharges to limit the radiation exposure of human population groups has also limited the consequent incremental radiation dose rate to the most highly exposed wild aquatic organisms to values less than 0.4 mGy h^{-1}. It appears, therefore, that the ICRP position is likely to be correct; but it is not, however, an acceptable *a priori* assumption. An assessment of the potential impact of the radioactive waste discharge on populations of aquatic organisms should be an integral part of the pre-operational investigation of the total environmental impact of the practice.

REFERENCES

[1] International Commission on Radiation Protection. Recommendations of the ICRP, Ann. ICRP **1(3)** Pergamon Press, Oxford, (1977) 53pp. (ICRP Pubn 26).

[2] International Commission on Radiation Protection. 1990 Recommendations of the ICRP, Ann. ICRP **21(1/3)** Pergamon Press, Oxford, (1991) 201pp. (ICRP Pubn 60).

[3] International Atomic Energy Agency. Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems. Technical Report Series No. 190, IAEA, Vienna, (1979) 416pp.

[4] National Council on Radiation Protection. Effects of Ionizing Radiation on Aquatic Organisms. NCRP report No 109, NCRP, Bethesda, Maryland, (1991) 115 pp.

[5] Pentreath, R.J. and Woodhead, D.S. Towards the development of criteria for the protection of marine fauna in relation to the disposal of radioactive wastes into the sea. In: Radiation Protection in Nuclear Energy, Vol 2,. IAEA, Vienna, (1988) pp213-243.

[6] Woodhead, D.S. The radiation dose received by plaice (*Pleuronectes platessa*) from the waste discharged to the northeast Irish Sea from the fuel reprocessing plant at Windscale. Health Phys., **25** (1973)115-121.

[7] Woodhead, D.S., 1970. Assessment of the radiation dose to developing fish embryos due to the accumulation of radioactivity by the egg. Radiat. Res., **43** (1970) 582-597.

[8] Woodhead, D.S. The radiation exposure of the black-headed gull (*Larus ridibundus*) in the Ravenglass Estuary, Cumbria, UK. Sci. Tot. Environ., **58** (1986) 273-281.

[9] Bakker, K. Some general remarks on the concepts of "population" and "regulation". In: Proc. Adv. Study Inst. Dynamics and Numbers of Populations, Oosterbeek, 1970. Centre for Agricultural Publication and Documentation, Wageningen, (1971) pp565-567.

[10] Woodhead, D.S. The effects of chronic irradiation on the breeding performance of the guppy, *Poecilia reticulata* (Osteichthyes: Teleostei). Int. J. Radiat. Biol., **32** (1977)1-22.

[11] Rackham, B.D. and Woodhead, D.S. Effects of chronic γ-irradiation on the gonads of adult *Ameca splendens* (Osteichthyes: Teleostei). Int. J. Radiat. Biol. **45** (1984) 645-656.

[12] Knowles, J. F., MAFF, Lowestoft, unpublished data.

[13] International Atomic Energy Agency. Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems. Technical Report Series No. 172, IAEA, Vienna,

[14] International Atomic Energy Agency. Assessing the Impact of Deep Sea Disposal of Low-level Radioactive Waste on Living Marine Resources. Technical Report Series No. 288, IAEA, Vienna, (1988) 127pp.

[15] National Research Council of Canada. Radioactivity in the Canadian aquatic environment. NRCC report no. 19250, NRCC, Ottawa, (1983) 292pp.

[16] Blaylock, B.G. and Trabalka, J.R. Evaluating the effects of ionizing radiation on aquatic organisms. In: Advances in Radiation Biology, Vol 7, Academic Press, New York, (1978)103-152.

[17] Woodhead, D.S. Contamination due to radioactive materials. In: Marine Ecology, Vol 5, Ocean Management Part 3, John Wiley and Sons, Chichester, (1984) 1111-1287.

[18] Anderson, S.L. and Harrison, F.L. Effects of radiation on aquatic organisms and radiobiological methodologies for effects assessment. US EPA report no. 520/1-85-016, US EPA, Washington, (1988) pp.128.