SOURCES AND EFFECTS OF IONIZING RADIATION

United Nations Scientific Committee on the Effects of Atomic Radiation

UNSCAR 1996 Report to the General Assembly, with Scientific Annex

UNITED NATIONS
New York, 1996
NOTE


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Scientific Annex
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1. During the last few years the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) has undertaken a broad review of the sources and effects of ionizing radiation. The results of this work have been issued in a series of publications: the UNSCEAR 1993 Report with nine scientific annexes, the UNSCEAR 1994 Report with two scientific annexes and the present UNSCEAR 1996 Report with one scientific annex, "Effects of radiation on the environment". These three publications form a series of reports entitled Sources and Effects of Ionizing Radiation, which together inform the General Assembly and the scientific and world community of the Committee's latest findings and evaluations.

2. The scientific annex of this report was developed over several annual sessions and completed at the forty-fifth session of the Committee, at which L. Pinillos Ashton (Peru), A. Kaul (Germany) and L.-E. Holm (Sweden) served as Chairman, Vice-Chairman and Rapporteur, respectively. The names of members of delegations who attended the sessions during which this report was considered are listed in the Appendix. The Committee wishes to acknowledge the assistance of a small group of scientists in the preparation of the scientific annex: D. Woodhead, (principal consultant) R.M. Alexakhin, B.G. Bennett and A. Bouville, who conducted the reviews of the scientific literature and who made the preliminary evaluations on which the final assessment of the Committee is based.

3. The Committee considers in this report the effects of ionizing radiation on plants and animals in the environment. These effects have not previously been addressed directly by the Committee. The emphasis of past assessments has been on determining the effects of radiation on human health. With the increasing interest around the world in nurturing the environment and concerns about possible detrimental effects of radiation, the time is appropriate for the Committee to provide a summary of the effects of radiation on the environment. The information for this summary has been drawn from reported observations in natural and contaminated environments, from experimental studies and from the Committee's own assessments of radiobiological effects. The intention is to provide countries, national and international organizations and the scientific community with information that can be used in a constructive manner to identify areas for further research and to evaluate ways to reduce the effects of radiation on the environment.

1/ The United Nations Scientific Committee on the Effects of Atomic Radiation was established by the General Assembly at its tenth session, in 1955. Its terms of reference are set out in resolution 913 (X) of 3 December 1955. The Committee was originally composed of the following Member States: Argentina, Australia, Belgium, Brazil, Canada, Czechoslovakia, Egypt, France, India, Japan, Mexico, Sweden, the Union of Soviet Socialist Republics, the United Kingdom of Great Britain and Northern Ireland and the United States of America. The membership was subsequently enlarged by the General Assembly in its resolution 3154 C (XXXVIII) of 14 December 1973 to include the Federal Republic of Germany, Indonesia, Peru, Poland and the Sudan. By resolution 41/62 B of 3 December 1986, the General Assembly increased the membership of the Committee to a maximum of 21 members and invited China to become a member.
with a reference text on the effects of radiation on plants and animals in all sectors of the environment.

4. All living organisms have developed and survive in environments subject to a natural radiation background. Global fallout from nuclear weapons tests in the second half of this century has made minor additions to this background. Also, increments in radiation exposures of a more local or regional nature have arisen because of emissions to the atmosphere, water bodies and the ground from the operation of nuclear power facilities, from industrial, medical and defence-related operations and from some accidents. Generally, there have been no apparent effects in plants and animals from these radiation exposures. Following severe accidents, however, damage has been observed in individual organisms and populations.

5. There is a wide range of sensitivities of plants and animals to ionizing radiation. In general, mammals are the most sensitive of the animal species, followed by birds, fish, reptiles and insects. The range of sensitivities of plants overlaps that of animals. Reproductive capacity, which is particularly important for the maintenance of the population, appears to be the most radiosensitive population attribute. For natural plant and animal communities, there is little evidence that dose rates of 0.1 milligray per hour (i.e. about 1.000 times greater than the natural background) to a small proportion of the individuals (and therefore, lower average dose rate to the remaining organisms) would have any detrimental effects at the population level.

6. The Committee is proceeding with a new programme of work to evaluate further the sources and effects of ionizing radiation. Recent data on radiation exposures in countries worldwide are being collected in order to determine representative values and ranges of such exposures in human population groups. New information from radiobiological and epidemiological studies is being reviewed, which should improve understanding of the effects of radiation and the underlying risks. During the 41 years of work of the Committee, considerable knowledge has been acquired of radiation sources and of the inevitable and circumstantial exposures that are a part of human life. An understanding of the underlying mechanisms of radiation interactions will improve the assessments of radiation risks. The Committee will continue to direct its efforts towards a broader understanding of ionizing radiation sources and effects.

7. Following established practice, the Report to the General Assembly does not include the scientific annex. The UNSCEAR 1996 Report, Sources and Effects of Ionizing Radiation, with the scientific annex "Effects of radiation on the environment", will be issued as a United Nations sales publication in order to achieve wide distribution of the findings for the benefit of the international scientific community.

Appendix

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* At the thirty-eighth and thirty-ninth sessions: Federal Republic of Germany.
* At the thirty-eighth, thirty-ninth and fortieth sessions: Union of Soviet Socialist Republics.
* At the thirty-eighth, thirty-ninth, fortieth and forty-first sessions: Czechoslovakia.
Scientific Annex
ANNEX

Effects of radiation on the environment

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INTRODUCTION

1. The effects of radiation on plant and animal communities have not so far been specifically addressed by the Committee. Living organisms have primarily been considered as part of the environment in which radionuclides become dispersed and as resources which, when contaminated, may contribute to human exposures. For example, some plants and animals are elements of food-chains and represent pathways for the transfer of radionuclides to man and an eventual source of internal exposure. Like man, however, other organisms are themselves exposed to internal irradiation from accumulated radionuclides and to external exposure from contamination of both the living and inanimate components of their environment.

2. In the absence of reports of obvious deleterious effects in other organisms from environmental radiation, either natural or from controlled releases of man-made radionuclides, it has generally been accepted that priority should be given to evaluating the potential consequences for man, who is among the most radiosensitive mammalian species, and to providing a sound basis for protecting human health. This position has, however, been questioned recently [D4, T1], and it has been shown that there is at least one situation, namely in deep-sea sediments, an environment very remote from man, where the above accepted priority could be incorrect [13]. It should also be noted that detrimental effects on the environment have been observed in localized areas as a consequence of plants and animals having received short-term, very high radiation doses following major accidental releases of radionuclides, e.g. in areas affected by the southeastern Urals accident of 1957 and the Chernobyl accident of 1986.

3. In response to such concerns, and to demonstrate explicitly that full account can be, and is being, taken of the potential effects of radiation on the environment, reports have been prepared that consider a number of specific situations, e.g. fresh-water and terrestrial environments [14, M5, N1], the deep ocean [13] and coastal waters [W9]. In view of these many activities, it would seem to be an appropriate time for the Committee to make an independent review of the situation and summarize the present state of knowledge of the impact of ionizing radiation on plant and animal populations in natural and contaminated environments. Such a summary would, of necessity, draw upon the previous, more limited reviews and studies, but it should adopt the widest possible scope and, in particular, should utilize the results of the Committee’s own earlier summaries of the radiobiological work carried out over the last 50 years. It is not, however, the intention of the Committee to make any judgement on particular environmental situations.

4. The presence of cosmic radiation and natural and artificial radionuclides in the environment implies a
consequential radiation exposure of the indigenous populations of organisms and, as is the case for man, it is to be expected that the probability of adverse effects would be greater where exposures are higher than the range of the natural background radiation dose rate. There is, however, a fundamental difference in the viewpoint adopted for the evaluation of the risk. For man, ethical considerations make the individual the principal object of protection, and in practice this means that the incremental risk to the individual arising from increased radiation exposure must be constrained below some level which society judges to be acceptable; this level of risk, although small, is not zero [18]. Although man displays an enormous range of attitudes towards the other species that share this planet (consider, for example, a population of mosquitoes at one extreme and an individual giant panda at the other), for the vast majority of organisms it is the population that is considered to be important, and protection of each population from increased risk from radiation might be the appropriate objective: exceptions might be populations of small size (rare species) or those reproducing slowly (long generation times and/or low fecundity), for which it might be more appropriate to target protective measures at the level of the individual organism. Thus, depending on whether it is the individual or the population that is of interest, there are likely to be differences in the responses that are significant for the assessment of potential or actual impact. Nevertheless, it is self-evident that there cannot be any effect at the population level (or at the higher levels of community and ecosystem) if there are no effects in the individual organisms constituting the different populations. It is not the case, however, that detectable radiation-induced effects in some members of a population would necessarily have any significant consequences for the population as a whole.

5. In considering impact assessment, it is also necessary to note that natural populations of organisms exist in a state of dynamic equilibrium within their communities and environments and that ionizing radiation is but one of the stresses that may influence this equilibrium. The incremental radiation exposure from human activities cannot, therefore, be considered in isolation from other sources of stress, both natural (e.g. climate, altitude, volcanic activity) and of human origin (e.g. synthetic chemical toxins, oil discharges, exploitation for food or sport, habitat destruction). When, as is not uncommon, ionizing radiation and chemicals, both from human activities, are acting together on a population, there arises the difficult problem of correctly attributing any observed response to a specific cause.

6. The objective of this Annex is to summarize and review information on:

(a) the radiation exposures (actual or potential) received by organisms in their natural habitats from the natural radiation background, from radionuclides released to the environment in a controlled manner from industrial activities and from radionuclides released as a consequence of accidents; and

(b) the responses to acute and chronic irradiation of plants and animals, both as individuals and as populations;

It is not the purpose of this Annex to predict the impact of specific incremental radiation exposures arising from human activities on populations of wild organisms, but with the information base provided, national and international bodies may be able to select appropriate criteria for the radiological protection of natural populations, communities and ecosystems.

I. DOSIMETRY FOR ENVIRONMENTAL EXPOSURES

A. METHODS OF DOSE ESTIMATION

7. Accurate estimation or determination of the dose rate and the integrated dose to organisms is essential for assessing the potential or actual impact of contaminant radionuclides in the environment. This simple statement conceals a multitude of difficulties that prevent the easy achievement of that estimation. In certain very restricted circumstances it has been possible to use thermoluminescent dosimeters to obtain direct estimates of the radiation exposure, but such techniques are of limited general applicability. Direct measurements are especially difficult if the dose rate is low, if the organism is small, if the dose rate to a specific organ or tissue is required or if alpha or beta particles are a major source of exposure. For mobile species of wild organisms there is the additional difficulty of recapturing sufficient dosimeter-marked animals to determine the range of dose rates and doses experienced by the population.

8. Although there is usually little need for high precision in the quantification of the radiation exposure of organisms in the environment, it is nevertheless necessary to distinguish between the various dosimetric quantities and to indicate their interrelationships. In the case of a photon field in air, that is, for laboratory studies employing either x rays or gamma rays from sealed sources and for field studies with large gamma-ray sources, it has been common practice to determine the exposure in free air. The conversion of these data to estimates of the absorbed dose in the relevant targets is
complex because of the assumptions that are necessary concerning the uniformity of the photon field, the presence of full secondary electron equilibrium and the absence of photon scattering.

9. When the now obsolete units roentgen and rad were employed to quantify the irradiation of organisms by photons, it was usual to equate the numerical value of the exposure in free air to the absorbed dose in the organisms (see, for example, [S1]). This approximation may be adequate, provided that the organism is sufficiently small for absorption and multiple scattering to be neglected but large compared with the range of secondary electrons.

10. A more accurate and more general numerical relation can be based on the air kerma, \( K_a \), which is given by

\[
K_a = a X
\]

(1)

where \( X \) is the exposure in C kg\(^{-1}\) and \( a \) is the conversion factor applicable for most photon energies between 0.1 and 4 MeV. 3.385 Gy per C kg\(^{-1}\). It may be noted that the form of this relation (and those given below) applies equally to the time derivatives.

11. In the case of radiation equilibrium, \( D_{org} \) the absorbed dose in an organism, is numerically equal to \( K_{org} \) the tissue kerma at the same point. Then,

\[
D_{org} = K_{org} = s K_a
\]

(2)

where \( s \) is the ratio of the mass energy absorption coefficients of the tissue of the organism and the air (taken to be 1.10 for photon energies in the range 0.1-4 MeV). Thus,

\[
D_{org} = s a X
\]

(3)

The product of \( s \) and \( a \), which ICRU designates as the factor \( f \) [11], relates the absorbed dose at a specified point in the medium to the exposure at that point. It has the value 37.0 Gy per C kg\(^{-1}\) for muscle tissue and 37.5 Gy per C kg\(^{-1}\) for water [11].

12. For organs and tissues at some depth in larger organisms, the effect of geometry is taken into account by introducing the factor \( g \):

\[
D_{org} = s g K_a
\]

(4)

where \( K_a \) is the air kerma in free air. For example, an average value of 0.7 has been assumed for \( s g \) to estimate the absorbed dose in the gonads of human beings: this is an average value for males and females to be applied in both outdoor and indoor exposure conditions [U2]. Because the value of \( s \) is taken to be 1.10, it may be inferred that \( g \) has a value of 0.64. Values of \( s g \) have also been given for small mammals [Z1]. Again, assuming \( s = 1.10 \), the values of \( g \) are 0.89 for the mouse, 0.87 for the rat, 0.81 for the monkey and 0.70 for the dog in conditions of bilateral exposure with \(^{60}\)Co gamma rays. These values give a qualitative indication of the effect of animal size on the midline absorbed dose in the organism for a constant air kerma but are applicable only for the specific situation described.

13. Even in the relatively straightforward situations considered above, simplifications have been made, e.g. by averaging over photon energy for the parameters \( a \), \( f \) and \( s \). In a natural environment, where the assumptions of photon field uniformity, secondary electron equilibrium and no photon scattering are unlikely to be valid and the radionuclide distribution is certain to be inhomogeneous, simple derivation of the absorbed dose from an estimation of the exposure is not possible.

14. In these circumstances it is necessary to employ dosimetric models to estimate the radiation exposure. These can be developed to take account of the radiation type; the specific geometry of the target, e.g. the whole body, the gonads, the developing embryo or the plant meristem and the source of exposure, e.g. radionuclides accumulated in body tissues, adsorbed onto the body surface or distributed in the underlying soil. Clearly, it is not possible to consider all organisms, and there are limitations on the basic data that can be made available as input for the models. e.g. the spatial and temporal distributions of the radionuclides both within the organism and in the external environment. Additional sources of complexity arise from the behaviour of mobile organisms in modifying the exposure from external sources and, particularly for some aquatic organisms and many insects, from the occupation of different environmental niches at different stages of the life cycle. Thus the models must be simplified and generalized without losing the realism essential for the valid estimation of dose.

15. A dosimetric model is essentially a mathematical construction that allows the energy deposition in a defined target to be estimated from a given radionuclide (source) distribution. The model is often derived using theoretical or empirical functions that describe the distribution of dose about a point source [B11 B12 L5 W7]. The dose at a point in the target is then obtained by integrating the point source dose distribution function over the defined radionuclide source, either internal or external. This procedure is frequently simplified by using simple geometries (spheres, ellipsoids etc.) of appropriate size to represent the target and by assuming that the radionuclide distribution is uniform (over a surface or through a volume) or that it varies in a way that can be described by a simple mathematical expression (e.g. an exponential decline in radionuclide concentration with depth in soil or sediment).
16. Another approach that has been employed for gamma radiation is to use the known cross-sections for photon absorption and scattering in Monte Carlo calculations to determine the absorbed fraction, defined as

\[ \phi = \frac{\text{Photon energy absorbed in target}}{\text{Photon energy emitted by the source}} \]  

for a variety of source and target geometries [B13. E3]. These data can be used, either directly or with interpolation (or, to a lesser extent, extrapolation), for geometries that can represent targets of environmental concern [N1. O4].

17. In principle, these procedures can be adapted for use with terrestrial and aquatic organisms from both the plant and animal kingdoms and for both internal and external sources of radiation. In practice, the use has been more limited.

18. The presence of an alpha-particle component in the total absorbed dose rate to a tissue in a plant or animal raises the question of how to take account of the probably greater effectiveness of this radiation type (quality of radiation) in producing biological damage. Such considerations have been very critically examined for the purposes of human radiological protection, where each component of the absorbed dose to a tissue or organ is weighted according to the radiation quality [18]. It seems reasonable to apply a similar approach to radiation dosimetry for organisms other than man. In practice, however, there are circumstances that alter the detailed application of the approach, in particular, the choice of the radiation weighting factors and the descriptive terms employed. In the human case, the major concern has been with the induction of stochastic effects (principally cancer) at low doses and dose rates. For alpha radiation, experimental determinations of relative biological effectiveness (RBE) lead to a recommended radiation weighting factor of 20 for the purpose of human radiation protection. In the case of wild organisms, however, it is likely to be deterministic effects that are of greatest significance, and for alpha radiation the experimental data for animals indicate that a lower weighting factor, perhaps 5, would be more appropriate; the weighting factors for beta and gamma radiation would remain unity. It has been assumed that these weighting factors would also apply for effects in plants, although there are no definitive experimental data. It should be pointed out that the various equivalent dose quantities, and the name of the unit, sievert (Sv), are specific to human radiation protection. In the absence of corresponding dosimetric concepts and quantities developed for application to non-human organisms, in this report the absorbed doses from low-linear energy transfer (LET) radiations (beta particles, x rays and gamma rays) and from high-LET radiation (alpha particles) are assessed and specified separately.

The absorbed doses retain the unit joule per kilogramme (J kg\(^{-1}\)) and the unit name gray (Gy).

**B. DOSE CALCULATIONS**

1. **Plants**

19. In the case of plants, the absorbed dose from photons is generally not equal to air kerma (see paragraph 8), and there is a complex relation between the radiation field and the absorbed dose that depends not only on the relative mass energy absorption coefficients of air and the plant material but also on the relative stopping powers for electrons. For beta particles, electron scattering, as well relative stopping power, is involved. In approximate calculations it may be adequate to assume that the ratios of the coefficients and stopping powers are unity and to neglect scattering. It may also be assumed that there is radiation equilibrium in air, i.e., that the absorbed dose, \(D\), is equal to the kerma, \(K\).

20. With these simplifications Jacobi and Paretzke [11] considered methods of calculating doses to plants, specifically for leaves of trees and pine needles, from exposure to natural and artificial sources of radiation. The dose rate to the plant material, \(D_{p,\text{ext}}\), has external and internal components. For the external component, the relationship between the absorbed dose rate to the plant and the air kerma rate is

\[ \dot{D}_{p,\text{ext}} = s g \dot{K}_s \]  

The factor \(s\) is taken to be unity. The geometry factor \(g\) equals one for gamma rays and higher energy beta particles but drops to zero for low energy beta particles unable to penetrate the leaf cuticle to the cell growth layer, at a depth of around 0.1 mm. If the radiation exposure results from radionuclides in air, the dose rate may be expressed in terms of the radionuclide concentration in air:

\[ \dot{D}_{p,\text{ext}} = s g w E C_i / \rho_i \]  

where \(w\) is the disintegration fraction, \(E\) is the energy per disintegration (1 MeV = \(1.602 \times 10^{13}\) J), \(C_i\) is the concentration of the radionuclide in air (Bq m\(^{-3}\)) and \(\rho_i\) is the density of air (may be taken to be 1.3 kg m\(^{-3}\)). The cumulative doses to plant components may be estimated from assumed mean lifetimes for leaves of 0.5 years and needles of 7 years [11].

21. For estimating internal dose rates in plants, the relevant equation is

\[ \dot{D}_{p,\text{int}} = \phi w E C_p / \rho_p \]
where \( \phi \) is the absorbed fraction of the energy released through disintegrations, \( C_p \) is the concentration of the radionuclide in the plant material (Bq m\(^{-3}\)) and \( p \) is the density of the plant material (taken to be 800 kg m\(^{-3}\)). Because of the small dimensions of leaves and needles, the factor \( \phi \) is small for gamma radiation and higher energy beta particles and increases to unity as the beta energy declines and for alpha particles.

22. There are two points to be noted about this approach: first, the calculation of the dose rate from the external source takes no account of the possibility of self-shielding and is thus likely to be an overestimate; and secondly, the expression for the dose rate from the internal source does not include the contribution from contamination in other parts of the same plant and will thus tend to underestimate the dose rate.

(a) Natural sources

23. For natural tritium and \(^{14}\)C produced in the atmosphere through the interactions of cosmic rays, the doses to terrestrial plants are, owing to the very short ranges of the beta particles, almost entirely from internal sources. The concentrations of the radionuclides in plant tissue may be estimated from environmental data. The natural concentration of tritium in surface waters is about 0.4 Bq kg\(^{-1}\) [U44]. For average concentrations of water in leaves and pine needles of 70% and 50%, respectively [J11], and assuming the dry matter is cellulose equivalent (6% hydrogen by weight), the estimated tritium contents are 0.35 Bq kg\(^{-1}\) (leaves) and 0.31 Bq kg\(^{-1}\) (pine needles). The activity of \(^{14}\)C in terrestrial biological material is 230 Bq kg\(^{-1}\) carbon. Again assuming that the plant dry matter is cellulose equivalent (44% carbon by weight), the \(^{14}\)C concentrations are 31 Bq kg\(^{-1}\) (leaves) and 51 Bq kg\(^{-1}\) (pine needles). These concentrations of cosmogenic radionuclides correspond to absorbed dose rates of about 10\(^{4}\) μGy h\(^{-1}\) to both leaves and pine needles from tritium and 0.0009 μGy h\(^{-1}\) and 0.0016 μGy h\(^{-1}\) to leaves and pine needles, respectively, from \(^{14}\)C. It is fairly straightforward to estimate the dose rates for these natural, global and atmospheric sources of tritium and \(^{14}\)C, because the resultant distributions are, more or less, in dynamic equilibrium throughout the biosphere.

24. There are, however, many data on the concentrations of tritium and \(^{14}\)C in environmental materials that demonstrate, through the presence of different specific concentrations (activity amount per unit mass of the element) in different compartments, time-dependent transport processes. Some of them have been demonstrated, for example, in monitoring and modelling the time-dependence of tritium in air, soil and vegetation at the Savannah River fuel reprocessing plant in the United States [M20]. General features of tritium in plants have been considered in a review by Belot [B16]. The formation and behaviour of organically bound tritium in plants has been determined and compared with that of tritiated water in plant systems, e.g. [D19, 16]. These aspects, which give rise to an overall variation by a factor of up to 10 in specific concentration, complicate the more simplified view of tritium in the environment, which considers that it occurs only in the form of tritiated water and that equilibrium specific concentrations prevail. Similar considerations, although of lesser degree (overall variation in specific concentration by a factor of up to 4 [B31]) arise from more detailed analyses of \(^{14}\)C behaviour. Thus, assessments of the impact of additional sources of these two radionuclides in the environment, often very localized in nature and often involving releases to compartments other than the atmosphere, e.g. surface waters and landfill, need to take account of the time-dependent pathways for radionuclide redistribution, the chemical forms and transformations and the potential influence of source-dependent factors on nuclide accumulations in plants.

25. Potassium-40 is both an internal and an external source of radiation exposure to plants. The external component may be considered using the general approach discussed in paragraphs 8-12. The internal dose depends on the potassium content of the plant, which is 0.1%-0.5% of the fresh weight in leaves and needles. The atom ratio of the potassium isotopes, \(^{40}\)K/\(^{40}\)K\(_{\text{e}}\), is 1.2 \(\times 10^{-4}\), giving a specific concentration of 32 Bq g\(^{-1}\) potassium and a \(^{40}\)K concentration in fresh plant tissues in the range 32-160 Bq kg\(^{-1}\). Because of the relatively high beta energy of \(^{40}\)K, the absorbed fraction, \( \phi \), may be no more than 0.1-0.15 [J11]. In roots, trunks and branches of trees, the value of \( \phi \) would be more nearly equal to one. With these assumptions, the \(^{40}\)K in plant tissue could deliver a dose rate in the range 0.001-0.006 μGy h\(^{-1}\).

26. The concentrations of radon, \(^{222}\)Rn, in surface air are quite variable. Time-averaged concentrations in normal areas may be in the range 2-30 Bq m\(^{-3}\). With less vertical air exchange in forests, the radon concentrations may be expected to be higher than over open land for the same rate of radon exhalation from the ground. For the noble gases, the radionuclide concentration in plant material is given by

\[
C_r = LC_i
\]

where \( L \) is the dimensionless solubility coefficient. The value of \( L \) depends on temperature and is approximately 0.5 for radon in leaves and needles at 15°C [J11]. In soil in the root zone, the radon concentrations may be higher by a factor of about 1,000 than in open air [J11].

27. The average concentration of \(^{222}\)Rn in groundwater varies widely, depending on the composition of the soil.
and the bedrock. For soil with an average $^{226}$Ra content
of 40 Bq kg$^{-1}$ [U2] the average radon concentration in
soil water would be about 60 Bq kg$^{-1}$ [U3]. Much higher
values have been measured in deep groundwater in
certain areas, for example, 8,000 Bq kg$^{-1}$ in granitic
areas of Maine in the United States [H4] and
50,000 Bq kg$^{-1}$ in Finland [J2]. Lewis and McDonnell
[L6] found that the main route of accumulation of $^{222}$Rn
into plants was through mass flow with water uptake by
the roots. Although the subsequent loss was not related
to transpiration. The data indicate that the $^{222}$Rn is lost
faster than the water, resulting in a lower $^{222}$Rn
concentration in water in the aerial tissues of plants than
in groundwater. This is consistent with the data of
Kirchmann and Berino [K8], who showed that less than
10% of the $^{222}$Rn produced from the in situ decay of
$^{226}$Ra was retained by pea plants. Thus there is likely
to be a significant $^{222}$Rn concentration gradient in the plant
water, from a high value (close to the groundwater
concentration) in the roots to a value lower by a factor
of as much as 10 in the leaves. Assuming that the radon
content in plant water in the leaves is one tenth that in
groundwater (i.e. 6 Bq kg$^{-1}$ on average), that the
fractional water content of the plant is 0.8 and that the
short-lived decay radionuclides are at equilibrium, then
the absorbed dose rate from this source is approximately
0.06 μGy h$^{-1}$, of which 95% is from high-LET alpha
radiation. This is within the range 0.005-0.54 μGy h$^{-1}$
suggested by Jacobi and Paretzke [J1]. It is clear that the
absorbed dose rate to the root meristem tissue could be
substantially greater. Because the data cited above relate
to small plants [K8, L6], it is possible that the dose rate
to trees, for a given concentration of $^{222}$Rn in
groundwater, could be greater, owing to the longer
residence time of the $^{222}$Rn in the plant.

28. The radon decay products $^{210}$Pb and $^{210}$Po also
contribute to the dose to plant components. While $^{210}$Pb
may be taken up by the plant through roots and leaves,
it occurs predominantly as deposited surface contamination
[J1]. Average concentrations of $^{210}$Pb in leaves and
needles are 10 and 5 Bq kg$^{-1}$, respectively [J1], and a
$^{210}$Po/$^{210}$Pb activity ratio of 0.8 may be applied to derive
$^{210}$Po concentrations.

29. The factors for estimating doses to leaves and
needles of trees from natural radionuclides in the plant
material, as derived by Jacobi and Paretzke [J1], are
presented in Table 1. They provide a basis for estimating
the radiation dose rate received by trees from natural
background sources. The results are summarized in
Table 2. Four additional assumptions are made in
deriving these values:

(a) the absorbed dose rate from the ionizing
component of cosmic radiation is 0.032 μGy h$^{-1}$ at
sea level [U2];
(b) the absorbed dose rate from the neutron com-
ponent of cosmic radiation is 0.0004 μGy h$^{-1}$ [U2];
(c) the absorbed dose rates for the long-lived $^{238}$U and
$^{232}$Th series radionuclides are as given in [J1];
(d) the average content of $^{222}$Rn in forest air is
10 Bq m$^{-3}$, with concentrations ranging up to
50 Bq m$^{-3}$. The dose factor (0.00066 μGy h$^{-1}$ per
Bq m$^{-3}$ for the beta/gamma component) is taken
from [J1]. For $^{222}$Rn in air, only the external beta/gamma
dose from short-lived decay products is of significance.
The remainder of the dose from $^{222}$Rn comes from the $^{222}$Rn
dissolved in groundwater and taken up by the roots into the
plant.

30. It is apparent from Table 2 that the greatest part of
the dose rate, and its potential variation, arises from the
$^{222}$Rn dissolved in the groundwater and taken up by the
roots. Other sources of variability, such as the range of
$^{40}$K contents in the plant material and the increase in
cosmic radiation exposure with altitude [U2], are of
minor consequence. Small herbaceous plants experience
an additional exposure from the beta radiation from $^{40}$K,
$^{238}$U series and $^{232}$Th series radionuclides in the soil.
For the range of concentrations given in [U2] and assuming
equilibrium in the two decay chains, the maximum
additional exposure from these sources could be 0.1, 0.1
and 0.05 μGy h$^{-1}$, respectively; the actual exposure is,
however, likely to be much less, owing to geometrical
factors.

31. Point source distribution functions have been
used to estimate the absorbed dose rate to phytoplankton
in both fresh and marine waters from natural
radionuclides [I2, W9]. The results are summarized in
Table 3. For both fresh-water and marine phytoplankton,
the greatest part of the natural background dose rate is
delivered by alpha particles; in the former case by $^{222}$Rn
and its decay products in the surrounding water and in the latter case by $^{238}$U and $^{232}$U
and by $^{228}$Th plus its decay products accumulated in the
organisms. As has been noted in another context [H5],
low values for the estimated absorbed dose rate to small
organisms must be interpreted with care. For example,
the low total radionuclide content in any individual
phytoplankton cell and the discrete nature of the
radiation emission process mean that many cells will
pass through a number of divisions without experienc-
ing any dose; conversely, a cell in which a radionuclide
decay does occur will experience a relatively higher
dose. In these circumstances, macroscopic dosimetry
principles, which average the absorbed radiation energy
over a relatively large mass (1 g or greater), are very
unlikely to be appropriate.

(b) Artificial sources

32. The factors for estimating doses to the leaves and
needles of trees from artificial radionuclides of noble
gases in air, as derived by Jacobi and Paretzke [J1], are
summarized in Table 4. They can be used to indicate absorbed doses to the leaves and needles of trees using the normalized discharges to the atmosphere from nuclear reactors given in e.g. ([U2]). It is assumed that the average integrated activity concentrations at 1 km from the source for dispersion in all directions can be estimated by a simple approximation [U5], the value being \(3 \times 10^7\) Bq s m\(^{-3}\) per Bq. No allowance has been made for radioactive decay during the transit time from emission to target. The results are given in Table 5. The values of normalized dose may be multiplied by the annual electrical energy generated (e.g. 0.5 or 1 GWe) to obtain estimates of the annual dose for a typical reactor.

33. The potential impacts of releases of tritium and \(^{14}\)C can be assessed in a similar manner, with the additional assumptions [C5] that at 1 km from a nuclear power plant these radionuclides have become uniformly incorporated into the background atmospheric water vapour (3 g m\(^{-3}\)) and carbon dioxide (0.046% by weight), respectively, and that the corresponding specific concentrations are also appropriate for tree leaves and needles. Using the assumptions of hydrogen and carbon contents of leaves and needles given in paragraph 23, the normalized absorbed dose rates may be estimated. The resulting values are, however, likely to be overestimates, because the specific concentrations in the terrestrial compartments will probably be less than those in the atmosphere. The extent of the overestimation will depend on the relative sizes of the hydrogen and carbon pools in the different compartments, the net rates of exchange between them and the histories of the discharges; it will, therefore, be site-specific.

34. The absorbed dose rates to fresh-water and marine phytoplankton from contaminant artificial radionuclides have been assessed using point source dose distribution functions [I2, W9]; the results are summarized in Table 3. The caveat in paragraph 31 concerning the interpretation of low absorbed dose rates to small organisms is equally applicable here.

35. Absorbed dose rates to aquatic macrophytes have been estimated by a number of authors [K4, M5, N3] using a generally conservative model based on radiation absorbed fractions in a 30 cm diameter sphere. Using derived values for the environmental concentrations arising from discharges in liquid effluents at 16 nuclear power station sites, Kaye [K4] estimated the dose rates from internal sources in the range 0.009-20 \(\mu\)Gy h\(^{-1}\), mainly from isotopes of caesium. Myers [M5] estimated the dose rates from a variety of radionuclides for individual concentrations in water used either as drinking water (intake \(2\) l d\(^{-1}\)) or as a source of fish for human consumption (0.1 kg d\(^{-1}\)), with either pathway leading to an effective dose equivalent of 1 mSv a\(^{-1}\). In both cases the estimated absorbed dose rates to aquatic plants were as high as 1,000 \(\mu\)Gy h\(^{-1}\), with the highest values being due to the alpha-emitting radionuclides. These figures are theoretical and reflect the limited use of resources (water and fish) by humans rather than potentially realistic doses to aquatic organisms.

36. Neither of the above authors [K4, M5] considered exposure from external sources, and it is likely that the overestimation of the dose rate from gamma radiation within the plants (implicit in the model) would be partially compensated by this absence of an estimate for the contribution from gamma-ray sources in the water and sediment. Although the model probably does not overestimate the absorbed dose rate from alpha radiation from internal sources, for which complete absorption is a reasonable assumption, a number of considerations suggest that the dose-rate estimates should nonetheless be treated with caution:

(a) the large surface area per unit weight of aquatic macrophytes almost certainly means that the observed concentration factors represent absorbed as well as metabolically incorporated radionuclides;
(b) the dose factors for certain of the radionuclides [N3] include contributions from both short- and long-lived decay products where appropriate, but for the latter the derived concentrations in water are based on an extremely conservative model, in that there are no loss processes operating in the water column over a 30-year period; and
(c) on the basis of the information given concerning the model and its parameters [N3], the dose-rate factors for the alpha-emitting radionuclides appear to be too high by a factor of up to 10.

These considerations lead to the conclusion that the dose rates are likely to be overestimates.

37. A technical report published by IAEA [I4] also provides estimates of the dose rates to terrestrial plants from deposited radionuclides following discharges to the atmosphere. The model PATHWAY [W10], developed to estimate doses to man, was used to derive the equilibrium concentrations of radionuclides in plants (and animals. see below) for the limiting case that man, while living on the land, breathing the air over it and eating food produced from it, would receive an annual effective dose of 1 mSv. To estimate the dose to the plant from internal sources, it was assumed that the energy of alpha and beta particles would be totally absorbed (except \(^{22}\)P, which would be 50% absorbed) and that 10% of the emitted gamma-ray energy would contribute to the dose. An additional degree of conservatism was provided by using estimates of the radionuclide concentrations in plant tissue on a dry weight basis, which are 5-10 times higher than on a wet weight basis, to calculate the absorbed dose rates to living (wet) plant tissue. The results are given in Table 6.
38. Spirin [S23] developed a dosimetric model to estimate radiation doses to agricultural crops from radionuclides in the soil. The air plus the plant material is represented as a homogeneous medium of uniform density (intermediate between the densities of air and of plant material) that attenuates the radiation field, developed by integrating a point source isotropic dose function over the (plane) source in the soil. This provides a dose distribution through the depth of the plant layer. Redistribution of the radionuclides from the surface of the soil into a 20 cm deep layer reduces the estimated beta dose by a factor of 30 and the gamma dose by a factor of 3. It was concluded that the dose from external alpha emitter contamination would be negligible compared with that from radionuclides taken up by the plants. In the latter case, the alpha radiation is assumed to be completely absorbed in the critical tissue (the apical meristem or leading shoot), in which the radionuclide concentration was related to that in the soil by a simple uptake factor. For equal degrees of soil contamination (1 Bq m\(^{-3}\) mixed to 20 cm depth) the calculations showed that alpha radiation, e.g. from \(^{239}\)Np, could be a much more significant source of exposure than beta and gamma radiation from \(^{90}\)Sr, \(^{90}\)Y or \(^{137}\)Cs [S23].

2. Animals

39. There appear to have been fewer estimates of the potential exposure of truly terrestrial animals than of animals occupying semi- and fully aquatic niches. This is probably a reflection of the greater use that has been made of aquatic systems for waste discharge.

(a) Natural sources

40. Estimation of the natural exposure of terrestrial animals appears to have attracted little attention, probably because it is implicitly assumed that the magnitude (and range) of the exposure will be little different from that of the exposure of man. This is likely to be a reasonable assumption, given that man coexists with animals throughout the terrestrial environment and that even situations leading to enhanced exposure, e.g. arctic food-chains [H3] or the occupation of burrows (enhanced radon exposure) seem to have parallels in the case of man. There can also, however, be significant differences. Animals living above ground in the open are likely to receive a lower alpha radiation dose to the lungs, because the concentration of radon and short-lived progeny will, on average, be lower by a factor of 5 than the concentration experienced by the local human population indoors. Animals living below ground receive, in addition to the increased lung dose from radon and its short-lived progeny, an increased dose from terrestrial gamma radiation; for small animals, the beta component from the external sources would also need to be taken into account.

41. In areas of human habitation with normal soil concentrations of \(^{40}\)K, \(^{238}\)U and \(^{232}\)Th, the mean external gamma-ray dose rate in air has been estimated to be 0.057 \(\mu\)Gy h\(^{-1}\) [U2]. For animals living most of their life underground in those areas, it may be assumed that the incident gamma radiation field has \(3\pi\) geometry (approximately), yielding a mean gamma dose rate in air of about 0.09 \(\mu\)Gy h\(^{-1}\): if a mean burrow occupancy factor of 0.9 is assumed, the annual dose to small animals is about 0.7 mGy.

42. The alpha dose to rodent species inhabiting burrows from \(^{222}\)Rn and its short-lived progeny arises from two sources: the radon and decay products in the inhaled air and the uptake of radon into soft tissue. For both sources, estimates are required of the radionuclide concentrations in burrow air. The equilibrium radon concentration in soil air, \(C_{\text{SA}}(\text{Rn},z)\), at a depth of \(z\) metres is given by:

\[
C_{\text{SA}}(\text{Rn},z) = \frac{f \cdot C_g(\text{Ra}) \cdot \rho}{\varepsilon} - 1 - e^{-\frac{\sqrt{\text{Rn}/D_\varepsilon}}{\lambda_{\text{Rn}}}} \quad (10)
\]

(equation 14, Annex D [U5]), where \(f\) is the radon emanation fraction, taken to be 0.2; \(C_g(\text{Ra})\) is the mass concentration of \(^{222}\)Ra in the soil, taken to be equal to the representative \(^{238}\)U concentration, 40 Bq kg\(^{-1}\); \(\rho\) is the bulk density of soil, taken to be 1,600 kg m\(^{-3}\); \(\varepsilon\) is the soil porosity, taken to be 0.25; \(\lambda_{\text{Rn}}\) is the decay constant of \(^{222}\)Rn, 2.1 \(10^4\) s\(^{-1}\); and \(D_\varepsilon\) is the effective diffusion constant for radon in bulk soil, taken to be 5 \(10^7\) m\(^2\) s\(^{-1}\). All parameter values have been taken from the UNSCEAR 1993 Report (paragraph 83, Annex A) [U2]. The derived estimate for the \(^{222}\)Rn concentration in burrow air at a depth of 0.2 m is 1.7 \(10^6\) Bq m\(^{-3}\). This will be a maximum value because equation (10) does not take account of the influence of advective flows. Owing to adsorption of the short-lived progeny to soil particles, their concentrations in burrow air will be lower than that of the parent radon by a factor in the range 10-100 [J3].

43. The dose rate from \(^{222}\)Rn taken up into soft tissue can be estimated on the assumption that the mean solubility coefficient for radon is about 0.4 \(10^3\) Bq kg\(^{-1}\) tissue per Bq m\(^{-3}\) in air and that the short-lived decay products are in equilibrium with the \(^{222}\)Rn in tissue. This approach yields a dose factor of about \(5 \cdot 10^4\) \(\mu\)Gy h\(^{-1}\) per Bq m\(^{-3}\) of \(^{222}\)Rn in air. For the estimated \(^{222}\)Rn concentration in burrow air of 1.7 \(10^6\) Bq m\(^{-3}\), the absorbed dose rate to lung tissue (and probably other soft tissues, including the gonads, in small animals) is about 0.085 \(\mu\)Gy h\(^{-1}\). The dose rate to the alveoli of the rodent lung from \(^{222}\)Rn (1.7 \(10^4\) Bq m\(^{-3}\)) and its decay products (170-1,700 Bq m\(^{-3}\)) in inhaled air can be estimated to be 0.25 \(\mu\)Gy h\(^{-1}\) using the model developed by Drew and Eisenbud [D11].
44. Rodents inhabiting an area of enhanced natural background, the Morro do Ferro, Minas Gerais, Brazil, were marked with fluorocarb dosimeters and retracted after about five weeks. The absorbed dose rates from external sources over this period were in the range 1.5-7.6 μGy h⁻¹. The concentrations of 226Th, 228Ra and 228Ra were determined in bone, leading to an estimate of 0.16 μGy h⁻¹ for the average absorbed dose rate [D10]. The concentrations of 220Rn and 222Rn in the burrows of the animals were high and very variable. An extensive laboratory study of the deposition of the daughter products in the lungs after inhalation allowed the development of a dosimetric model giving estimates of 180 and 29 μGy h⁻¹ for the absorbed dose rates at the surfaces of the trachea and alveoli, respectively; the maximum values could be greater by a factor of 4 [D11]. Studies have been carried out in areas of Russia where the gamma dose rate from external sources reaches 80 μGy h⁻¹ [M1]. If the internal dose to soft tissues from 222Rn absorbed through the lungs and from its short-lived decay products varies with the external dose rate in the same way as indicated by the calculations in the preceding paragraph, it may be concluded that the absorbed dose rates to the soft tissues of rodents inhabiting burrows in these high natural background areas of Russia could reach as much as 100 μGy h⁻¹.

45. The transfer of the natural radionuclides 210Pb and 210Po along a lichen-caribou-wolf food chain has been studied in northern Canada and estimates made of the absorbed dose rates in a variety of tissues. In caribou, there appeared to be no discrimination in uptake between 210Pb and 210Po, and for concentration ratios less than unity, there was no biomagnification from lichen to caribou. The 210Po/210Pb activity ratio was less than unity in bone and greater than unity in all other tissues measured (except the foetus), and with a weighted average value of about 0.9 for the whole body, it was concluded that the greater part of the 210Po body burden was derived from 210Pb decay in bone and translocation of the 210Po to soft tissue. The highest absorbed dose rates, 0.7-1.1 μGy h⁻¹, were estimated for the liver; but perhaps of greater significance in the context of this review, the absorbed dose rate in the testes was estimated to be 0.05 μGy h⁻¹. The wolf appeared to discriminate against 210Pb relative to 210Po and to gain the greater part of its 210Po body burden directly from food intake, although with concentration ratios less than unity, there was no biomagnification from caribou to wolf. Again, the highest absorbed dose rates, 0.4-1.2 μGy h⁻¹, were estimated for the liver, with values in the range 0.02-0.04 μGy h⁻¹ in the testes [T25, T26]. The greater part of all the radiation dose was delivered by high-LET alpha particles from 210Po.

46. The methods for estimating the doses to aquatic organisms are more completely developed than those for estimating doses to terrestrial organisms [12, 13, W7]. This is due more to the growing need in recent years to specifically consider the impact of radioactive waste disposal on natural populations in aquatic environments [13, N1, P5] than to any intrinsic differences in the problems posed. The models are based on point source dose distribution functions or absorbed fractions, as appropriate, and simplifications are made to the extent dictated by the data available for input to the model. Estimates of radiation doses from natural background are summarized in Table 3 for fish and molluscs. More detailed data for these and other aquatic organisms are given in [12, 13, P5, W8, W9]. but the information in Table 3 is quite representative.

47. Two points may be made about the data presented in Table 3. First, the radiation exposure of the molluscs is generally greater than that of the fish, because the benthic (bottom-living) molluscs is exposed to radiation from the sediments and the pelagic (surface water) fish is not. More importantly, the dose rate from internal sources is greater for the molluscs because most of the available data on radionuclide accumulation (concentration factors) are for filter-feeding detritivores. The fine particles making up the food scavenge radionuclides efficiently from the water, thus leading to higher body burdens of the radionuclides. Secondly, the absorbed dose rates from internal exposures to natural radiation sources are relatively high due to the high-LET contribution from 210Po. Indeed, for certain pelagic oceanic organisms, the absorbed dose rates in particular tissues from this source can be very high, e.g. up to 150 μGy h⁻¹ in the hepatopancreas and 4 μGy h⁻¹ in the testes of a small mid-water shrimp [C7, H6] and 30 μGy h⁻¹ in the intestine and 1 μGy h⁻¹ in the gonads of a sardine [C8].

(b) Artificial sources

48. Coughtrey [C5] estimated dose rates to the soil fauna, as exemplified by the earthworm, from the deposition into woodland of iodine, strontium and caesium radionuclides released to the atmosphere from a pressurized water reactor at a distance of 300 m. The radionuclide concentrations in the surface soil were estimated from a dispersion calculation and an assumed deposition rate. The consequent accumulations of the radionuclides by the earthworm were estimated using concentration factors. The dose rates were calculated on the following assumptions: for the external sources, that the dose rate from both beta and gamma radiation was that to the soil, which was effectively infinite in extent; and for the internal source that only the beta component was significant and that it was totally absorbed. A different approach was adopted for 4H and 4C releases, which were assumed to equilibrate with the atmospheric water vapour and carbon dioxide, respectively. The resulting concentrations of 4H per gram hydrogen and
\(^{14}\)C per gram carbon in the plume were assumed to apply to the earthworm. This is likely to be a conservative assumption, since it neglects the input of uncontaminated water (as rain from outside the plume) and the diluting effect of the large organic carbon pool in living plants and the soil humus; an estimate of the degree of conservatism would require detailed modelling of the particular situation (see also the next paragraph). The total dose rate to the earthworm for the predicted operating conditions of the power plant was 0.01 \(\mu\)Gy h\(^{-1}\), and since the greatest part of this was due to \(^{14}\)C, it is certain to be an overestimate; if the station was operated such that the effective dose rate to man reached 1 mSv a\(^{-1}\), then the estimated dose rate to the earthworm would be 5.7 \(\mu\)Gy h\(^{-1}\).

49. As was the case for plants (paragraph 24), the dose from tritium should consider tritium in body water and organically bound tritium in tissues. The relative amount of the two components depends on the source of the tritium, i.e. either tritiated drinking water or organically bound tritium in food (with food type also having an influence [K21]) [L12, L13, P16, P17, R11, T27]. Although the assumption of a constant concentration of tritium (as Bq kg\(^{-1}\) hydrogen) in the biosphere could be questioned, it is difficult to see how more specific data could be translated to the environmental context to generate improved estimates of radiation doses from contaminant tritium. A more detailed model of the behaviour of tritium in the vicinity of the input, including the dynamic processes along food-chains, would be required. Similar considerations probably also apply to \(^{14}\)C.

50. Soil fauna are also potentially at risk from the release of waste radionuclides from shallow landfill repositories. Coughtrey [CS] considered the case in which radionuclides were accumulated by bank soil from stream water draining a trench disposal site. The total dose rates to the soil organisms were estimated to be 18 \(\mu\)Gy h\(^{-1}\) from low-LET radiation and 14 \(\mu\)Gy h\(^{-1}\) from alpha radiation.

51. The \textsc{Pathway} model [W10] has been used to estimate radionuclide concentrations in surface-living animals from aerial deposition [14]. The domestic sheep used as a model terrestrial animal, and it was assumed that the predicted radionuclide concentrations, except for \(^{137}\)Cs, would be typical of wild animals. For \(^{137}\)Cs, the estimated tissue concentrations generated by the model were increased by a factor of 10 to take account of the known influences of either carnivorous behaviour or the consumption of certain plants on the accumulation of this radionuclide by different wild animals. The predicted concentrations in sheep muscle were assumed to apply to the gonads for all radionuclides except \(^{89}\)Sr, for which the muscle value was increased fourfold to give the concentration in the gonads. The dosimetry model assumed total absorption of the alpha and beta radiation in the gonads and a 30% absorption of the gamma energy. The results for the absorbed dose rates from these internal sources, given in Table 6, correspond to the limiting case of humans receiving 1 mSv a\(^{-1}\) from occupation of the same environment.

52. Kozmin et al. [K9] developed models to estimate the radiation exposure of farm animals following accidental releases of radionuclides to the atmosphere. The radiation exposure pathways considered were external exposure from the plume, inhalation from the contaminated ground-level air, contaminated pasture (external and internal source), contaminated soil (external and internal source) and contaminated livestock barns (external). In practice, it is the internal exposure following ingestion that is of particular significance. Compartment models were developed to predict the radionuclide distributions within the animals and the consequent radiation exposures. Cumulative dose estimates for sheep, pigs and cattle are presented in Table 7 for acute and chronic exposures to \(^{131}\)I (thyroid). \(^{89}\)Sr-\(^{90}\)Y (bone) and \(^{137}\)Cs (muscle).

53. Models based on point source dose distribution functions or absorbed fractions, as appropriate, have been used to estimate the absorbed dose rates to pelagic fish and benthic molluscs from contaminant radionuclides. The results are summarized in Table 3, where it can be seen that, as was the case for the natural sources and for the same reasons, the exposure of benthic molluscs is greater than that of pelagic fish (see paragraph 47).

54. The dose rates to fresh-water fish have also been estimated for the situation in which humans receive the limiting effective dose rate of 1 mSv a\(^{-1}\) from the combined exposure pathways of drinking water (2 l d\(^{-1}\), fish consumption (0.1 kg d\(^{-1}\)) and external exposure from contaminated sediments (occupancy 2,000 h a\(^{-1}\)) [N1]. The results for a selection of radionuclides in the liquid effluents are given in Table 6. These data are consistent with those from the controlled waste discharge from the Magnox nuclear power station into Lake Trawsfynydd in northern Wales, where the total absorbed dose rate to fresh-water fish from all sources was estimated to be 0.08-0.3 \(\mu\)Gy h\(^{-1}\) (0.7-2.6 mGy a\(^{-1}\)) [W8] when the effective dose rate to the human critical group was estimated to be no greater than 0.25 mSv a\(^{-1}\) [M7].

55. For a benthic fish (the plaice, \textit{Pleuronectes platessa}) in the northeastern Irish Sea, the estimated dose rates from contaminant radionuclides accumulated in the seabed from the waste discharges from the Windscale (now Sellafield) nuclear fuel reprocessing plant were sufficiently large (up to 50 \(\mu\)Gy h\(^{-1}\)) to attempt direct measurements. Small thermoluminescent
dosimeters were developed that could be attached to the fish, and 3,580 fish were marked with a combined tag/dosimeter and released in the vicinity of the waste outfall. In a period of 2.5 years, 1,053 fish were re-captured, and the dosimeters on 969 of them yielded useful results. After allowing for the mobility of the fish, the data essentially confirmed (within a factor of 2) the estimates of radiation exposure calculated on the basis of a simple model using the measured distributions of the radionuclides in the sediments [W8, W9]. Small thermoluminescent dosimeters have also been used to obtain an estimate of 4 μGy h\(^{-1}\) for the absorbed dose rate to periphyton 24 km downstream from the point of discharge, the Hanford plant, into the Columbia River [L7].

C. COMPARISONS OF ENVIRONMENTAL EXPOSURES

56. At present, data on radiation exposures of wild organisms from both natural background and contaminant radionuclides are incomplete, the more so in some areas than others. The aquatic environment is probably the most thoroughly studied environment to date [I2, I3, I9, N1, N3, W9], but even for it, substantial generalizations have had to be made, particularly in respect of the range of organisms that can reasonably be considered [I3]. As has been emphasized [I3, I9], the limiting factor is not the development of an appropriate dosimetric model for a particular organism but the acquisition of essential input data on the temporal and spatial distributions of the radionuclides both external to and within the organism. Although dynamic models have been employed to describe the dispersion and dilution of radionuclides in a water body, the accompanying re-concentration transfers to sediments and biological tissues are almost always modelled as equilibrium processes, i.e., simple distribution coefficients and (whole-body) concentration factors are used. This largely neglects the temporal variation in dose rate due to short-term fluctuations in the discharge rate, to differing stages in the life cycle, to behaviour and to short-term environmental processes (e.g., seasonality) etc. As a consequence, while the estimated absorbed dose rate might be a reasonable indication of the general magnitude of the environmental value, it does not provide a very secure basis for evaluating total doses over time. Such reservations apply with equal validity to the more limited data that have been developed for releases to the atmosphere [C5, I4], for shallow landfill sites [C5, I4] and for a deep repository [M5]. It is, nevertheless, possible to draw some general conclusions.

57. As is the case for man [U2], naturally occurring alpha-emitting radionuclides appear to be the most significant sources of background radiation exposure for the majority of wild organisms. In the terrestrial environment the main source is radon and its short-lived decay products. The estimated range of absorbed dose rate to the leaves and needles of trees from this source is 0.005-0.5 μGy h\(^{-1}\). Given the apparent significance of this source of exposure, it would be useful if the radon content of plant tissues could be determined by direct measurement rather than by inference from concentrations in groundwater. Studies of the uptake of \(^{40}\)K into plants from potassium-rich soils would also be worthwhile, because plants do not have the same regulatory mechanisms for potassium content as animals. For terrestrial animals in areas where the soil has the normal concentrations of uranium and thorium, the highest radiation exposures will be experienced by burrow dwellers. In this case, the absorbed dose rate from external sources is about 0.09 μGy h\(^{-1}\), that from radon (and from its short-lived decay products) accumulated in soft tissue is about 0.085 μGy h\(^{-1}\) and that to the lungs from radon and its decay products in the burrow air is about 0.25 μGy h\(^{-1}\). Exceptionally, in areas of uranium or thorium mineralization, the natural background absorbed dose rates could be higher by a factor of as much as 1.000. In aquatic environments, \(^{210}\)Po is the major contributor, with absorbed dose rates of up to several microgray per hour to the gonads of marine animals. The recognition that alpha particles (short-range, high-LET radiation) are the principal source of background radiation exposure underlines the need for (a) detailed knowledge of the distribution of the radionuclides in relation to potential targets as well as realistic models for the estimation of absorbed dose rates and (b) the selection of a radiation weighting factor appropriate to the biological effect of concern.

58. Discharges of tritium, \(^{14}\)C and noble gas radionuclides to the atmosphere during normal operation of a reactor do not appear to be an important additional source of exposure to plants, because the increment is likely to be much less than the variability (and uncertainty) in the estimate of the natural exposure. Discharges to the atmosphere of other radionuclides could be more significant, and in the limiting situation for humans (1 mSv a\(^{-1}\)), it appears that some plants and animals in the vicinity of the reactor might experience dose rates up to a few tens of microgray per hour; in practice, the actual discharges during normal operation (and, hence, the dose rates) are likely to be much lower.

59. For discharges to aquatic environments both the estimates of dose rates based on measurements of concentrations of radionuclides in contaminated environments and the estimates inferred for the limiting situation of 1 mSv a\(^{-1}\) to man are much greater than the estimates of the natural background exposure (see Table 3). The organisms might receive dose rates up to 60 μGy h\(^{-1}\) (500 mGy a\(^{-1}\)), and in one case an absorbed dose rate of 5,700 μGy h\(^{-1}\) (50 Gy a\(^{-1}\)) was estimated for aquatic macrophytes [M5].
60. Accident situations are by nature quite different, particularly in their potential to produce high dose rates and doses in the environment. As the actual exposure regime obviously depends on the quantities of specific radionuclides released, the initial dispersal and deposition patterns and their redistribution over time in the environment, it is difficult to generalize. Following the accident at the Chernobyl nuclear reactor, large quantities of short-lived radionuclides were released, leading to high dose rates in the local area. Total doses up to 100 Gy were delivered to trees (and, by inference, to most other organisms in the locality) over a period of a few days [K3]. This radiation regime may be characterized as "acute", in that the doses were delivered in times that were shorter than, or comparable to, the times taken for severe damage to become apparent. During this initial, acute phase the dose rate declined rapidly as the very short-lived radionuclides decayed. The release following the accident in 1957 in the southeastern Urals was dominated by $^{144}$Ce-$^{144}$Pr (approximately 66%; $T_{1/2} = 285$ d) and $^{90}$Zr-$^{90}$Nb (approximately 25%; $T_{1/2} = 65$ d). In that case, the dose rates in the local area were also relatively high ($> 4,000$ $\mu$Gy h$^{-1}$) but declined more slowly, such that high total doses causing severe effects (including mortality) could still be accumulated from essentially chronic exposure. Close to the release point, total doses up to 2,000 Gy were experienced [T17]. In the longer term, the exposure regime for the Chernobyl release has been dominated by $^{137}$Cs ($T_{1/2} = 30$ a) and $^{90}$Sr ($T_{1/2} = 28.6$ a) and that for the southeastern Urals accident area by $^{90}$Sr: in both cases, the exposures are chronic and moderately high, with responses other than mortality becoming significant. Further experience derived from the study of exposures and effects from these accidents is presented in Section III.D.

61. Dose rates to plants and animals in the environment from naturally occurring or contaminant radionuclides may be estimated from basic dosimetric relationships. The accuracies of the estimates are generally limited by uncertainties in knowing the concentrations of radionuclides that prevail in the media surrounding the organism and that accumulate within the organism. Based on reasonable assumptions, dose factors have been derived for a number of radionuclides, and these have been applied to estimate dose rates in various environments. It is recognized that the simplifications often implied in these assumptions lead to overestimated dose rates.

62. In areas of normal background, the absorbed dose rates to terrestrial plants are 0.07-0.8 $\mu$Gy h$^{-1}$ (0.6-7 mGy a$^{-1}$), mainly from $^{222}$Rn taken up from the groundwater. Absorbed dose rates to aquatic plants would normally be at the lower end of this range. Absorbed dose rates to terrestrial animals are highest for those inhabiting underground burrows; in this case the rough estimates are 0.25 $\mu$Gy h$^{-1}$ in the lungs from $^{222}$Rn and its decay products and about 0.09 $\mu$Gy h$^{-1}$ each from absorbed radon in tissue and external exposure. In areas of uranium or thorium mineralization, the absorbed dose rates could be higher by a factor of as much as 1,000. In aquatic environments, $^{210}$Po is a major contributor to dose, with absorbed dose rates to the gonads of some marine animals reaching several microgray per hour.

63. Radioactive waste discharges to the atmosphere to landfills or to aquatic systems from man-made practices entail increased radiation exposures of wild organisms. The incremental radiation exposures are chronic (i.e., continuing) at absorbed dose rates of generally no more than 100 $\mu$Gy h$^{-1}$ but very exceptionally several thousand microgray per hour. These additional radiation exposures are greater than the normal range of natural radiation background but are generally within the extreme range of background when the exceptional cases of areas of uranium and thorium mineralization are included. Given that waste discharges are point sources and that releases normally become dispersed and diluted (account is taken of reaccumulation processes in developing the database of distributions and concentrations of radionuclides used as input to the dosimetric models), these dose rates are likely to apply to only a small proportion of the individuals in any population; the average dose rate to the population will probably be much lower (see, for example, [W8, W9]).

64. Detailed information on the responses of organisms to radiation exposures at absorbed dose rates up to 1,000 $\mu$Gy h$^{-1}$ is required to make an assessment of potential environmental impact. Responses to acute irradiation or to short-term exposures at higher dose rates can also provide useful information, particularly about the relative sensitivities of different species and classes of organism and of the different life stages of a species. Information on the sensitivity of individual plants and animals to radiation exposure and the possible effects on populations and communities of organisms is presented in Chapters II and III.
II. EFFECTS OF RADIATION ON PLANTS AND ANIMALS

65. The effects of ionizing radiation on plants and animals began to be studied immediately following the discovery of X rays and radioactivity (see, for example, [A13, T24]). Since 1945, when the first nuclear detonations were conducted, there has been widespread concern about the impact of environmental radiation exposures and interest in the environmental behaviour of radioactive materials, as of result of which many studies, using a wide variety of plant and animal species, have been performed [A1, B1, C3, I5, P3].

66. The responses of organisms to radiation exposure are many and varied and may become manifest at all levels of organization, from the individual biomolecule to the ecosystem. The significance of a given response depends on the criterion of damage adopted, and it should not be concluded that a response at one level of organization will necessarily produce a consequential, detectable response at a higher level. It has been noted (paragraph 4) that for humans it is the risk of harm to the individual that must be minimized but that for the great majority of all other species it is the population that is valued and for whose protection appropriate radiation exposure controls could be implemented.

67. In the widest sense, a population may be defined as all members of a particular species. However, radiation fields arising from radioactive waste discharges generally show large spatial variability, not least because of the discrete nature of the input, and many members of a population may not receive any significant exposure from a particular source. The natural distributions of most species are inhomogeneous ("patchy") in response to the variable occurrence of the ranges of physical, chemical and biological conditions within which, in combination, the individuals of the species are able to survive, i.e. species are geographically restricted. Thus, it is probable that a more limited, and relevant, definition of a population could be developed for the purposes of environmental impact assessment.

68. In a similar context [14] the following definition, developed for use in population ecology, has been suggested as a useful basis for discussion and progress: "A population is a biological unit for study, with a number of varying statistics (e.g. number, density, birth rate, death rate, sex ratio, age distribution), and 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 members of other populations [B14]." Such a population would be (or could be) a self-sustaining unit, independent of other, geographically separate populations of the same species. Protection of this population would require that increased radiation exposure did not significantly affect those attributes (i.e. those mentioned in the definition) on which the population depends for maintenance within the normal dynamic range of variation dictated by the interactions of natural physical, chemical and biological factors.

69. These attributes, which can be defined only for populations of organisms and which may be taken to be indicators of their health, are, nevertheless, integrations of properties that relate to individuals (in no sense is this meant to imply simple addition) (see, for example, [M8]). It may be concluded, therefore, that there can be no response to radiation at the population level (or, indeed, at any higher level of organization) without there being some clearly detectable effect in individual organisms (or at lower levels of organization). This clearly implies that the protection of the population (as the ultimate objective) may be achieved by restricting the exposure of individual organisms to the extent that there are no significant radiation effects on those processes that are necessary for the maintenance of the population. It is therefore necessary to consider the available information on the effects of radiation (mainly at chronic low dose rates) on the relevant processes in individual organisms, to consider how these responses might translate to an impact on the population, and to examine the results of studies of population responses to deliberate experimental irradiation or in environments contaminated by controlled or accidental releases.

70. Examination of the population attributes (paragraph 68) indicates that the individual responses to radiation exposure that are likely to be significant at the population level are mortality (affecting age distribution, death rate and density), fertility (birth rate), fecundity (birth rate, age distribution, number, density) and the induction of mutations (birth rate, death rate). The response of these individual functions to radiation exposure can be traced to events at the cellular level in specific tissues or organs. An extended summary discussion of the processes involved was given in the UNSCEAR 1982 Report ([U5], Annex 1, "Non-stochastic effects of irradiation"). There is a substantial body of evidence indicating that the most radiosensitive sites are associated with the cell nucleus, specifically on the chromosomes, and, to a lesser extent, implying the additional involvement of damage to intracellular membranes. The end result is that the cells lose their reproductive potential. For most cell types, at moderate doses, death occurs when the cell attempts to divide; death does not, however, always occur at the first post-exposure division; at doses of a few gray, several division cycles may be successfully completed before it eventually occurs. It is also well known that radiosensitivity varies within the cell cycle, with the greatest sensitivities being apparent at mitosis and the
commencement of DNA synthesis [U5]. It follows that the greatest radiosensitivity is likely to be found in cell systems undergoing rapid cell division for either renewal (e.g. spermatogonia) or growth (e.g. plant meristems and the developing embryo); these examples clearly underlie the processes in individual organisms that are important for maintenance of the population.

71. Fractionation, or protraction, of exposure to low-LET radiation increases the total dose required to produce a given degree of damage. At low dose rates, e.g., those that arise from the controlled discharge of radioactive effluents into the environment, the factors responsible for mitigating the response are the repair of sublethal damage, the repair of potentially lethal damage, the replacement of killed cells through proliferation of survivors, and other slow repair processes not related to cell repopulation [U5]. Although it is clear that repair, in the general sense, is possible, the existence and extent of residual injury is less clear. While such an outcome may be demonstrated for moderate, acute doses, it is not possible to extrapolate these results to predict the likely response to low-level exposures extending over a significant fraction of the lifetime of an organism. However, given that genetic mutations may be passed from generation to generation, it is reasonable to suppose that somatic mutations individually consistent with cell survival can occur and accumulate over time until the combined impact reduces cell viability.

72. In addition to the intrinsic factors already mentioned as affecting radiosensitivity, account should also be taken of the extrinsic factors in a contaminated environment, such as season (rapid growth of plants in spring, lower metabolic activity in hibernating animals) and temperature (metabolism in poikilotherms). The response of an organism to increased radiation exposure is also likely to be modified if it is under stress from other sources, e.g., if there are non-radioactive contaminants in the environment or if it is at the limit of the normal biogeographical range for the species. It has been shown, for example, that exposure to DDT increases the retention of 137Cs in rats; thus, in addition to the potential stress from pesticide exposure and its possible interaction with radiation, there is also a DDT-dependent increase in the radiation dose rate from internal sources [U13].

A. TERRESTRIAL PLANTS

73. Radiation injury in plants expresses itself as abnormal shape or appearance, reduced growth or yield, loss of reproductive capacity, wilting and, at high exposures, death [S7]. Acute lethal doses to higher plants range from 10 to about 1,000 Gy (approximate mean absorbed doses averaged over the whole plant).

At the extremes of radiation sensitivity are plants such as mosses, lichens and unicellular species, which are highly resistant, and woody species, which are the most sensitive. In 12 species of woody plants assessed 10-14 months after exposure, the lethal doses were 8-96 Gy [S12]. The pine tree is the most sensitive, experiencing severe mortality following short-term absorbed doses of about 10 Gy [W11]. Growth is severely inhibited at 50%-60% of the lethal dose. Floral inhibition is observed at 40%-50% of the lethal dose and failure to set seed at 25%-35%. Thus, the capacity of the plant population to maintain itself can be damaged at acute doses lower than those required to cause mortality. Below 10% of the lethal dose, effects are not so apparent, and the plant maintains a normal appearance. These general observations from several herbaceous plant species are illustrated in Figure I [S8]. Another general relationship is that the dose that reduces survival by 10% (LD10) is roughly equivalent to the dose that reduces the yield by 50% (YD50) [S7].

74. Because there is interest in the morphological changes produced by tissue damage and repair (rather than by mutation) that may be observed at contaminated sites, it is worthwhile mentioning the changes of this kind that have been observed in the laboratory. Leaves of plants formed during irradiation may show abnormalities such as dwarfing, asymmetrical development and distorted venation as well as changes in texture and thickening, which occurs at dose rates above 2.4 Gy d⁻¹ in Antirrhinum sp., an annual flowering plant (the total dose was not given, but for a late spring-early summer growing season of 150 days, it could be up to 360 Gy) [S9]. Older leaves formed prior to irradiation are little changed by exposures, except in respect of texture: they commonly become dry, stiff, coarse and thickened [S9]. Effects in flowers include additional and abnormal buds and inflorescences at dose rates of 0.20-0.24 Gy d⁻¹ for 56 days (total dose 11-13 Gy). At a higher dose rate of 0.34 Gy d⁻¹ (19 Gy), vegetative rather than floral production was favoured and modified leaves occurred in floral positions [S9]. The needle length of pine trees becomes progressively shorter as acute exposures are increased above 0.5 Gy. Needle length is 10% of the control at 3 Gy in growing plants and at 4.5 Gy in dormant plants [S10].

75. The sensitivity of plants to external x radiation or gamma radiation varies over a wide range and depends on both the stage of individual development and the phylogenetic category of the particular species. A comparative analysis [S45] of the radiosensitivity of higher plants in terms of the median lethal dose has shown that the range of variation exceeds two orders of magnitude in both the dormant seed phase (from 5 Gy in Picea abies to 2.000 Gy in Raphanus sativus, of 99 species studied) and the vegetative phase (from 4 Gy in Pseudotsuga douglaxsi to 580 Gy in Capsella bursa-
pastoris, of 64 species studied). Within a species, the radiation sensitivity (in terms of LD₉₀) may vary by a factor of more than 20 between different stages of development: the dry seed is most resistant and the gametogenic cells at meiotic prophase (the stage prior to the reduction division, when the duplicated chromosomes become visible in cell preparations) are most sensitive. Overall, the data suggest a close relationship between radiosensitivity and phylogenetic position [S45]. The more primitive species in the Gymnospermae are the most radiosensitive and show a relatively narrow range of LD₉₀ (5-63 Gy for dormant seeds and 4.6-16 Gy for the vegetative phase). The more advanced groups show generally greater radiosensitivity but also greater variability, viz. the Monocotyledon class (10-350 Gy for dormant seeds and 9.6-52 Gy for the vegetative phase) and the evolutionary advanced Dicotyledon class (30-2,000 Gy and 4.8-580 Gy, respectively). It may be noted that a similar trend is apparent within individual families; thus the radiosensitivity of the more primitive Vicia faba (50 Gy and 9.8 Gy, respectively) is about 25 times greater than that of the more advanced and specialized Trifolium repens (1,250 Gy and 243 Gy, respectively) [S45].

76. Because phylogenetic development in higher plants is accompanied by the elimination of redundant hereditary information and a reduction in genome size [S45], it can be suggested that there should be some relationship between radiosensitivity and cell nucleus parameters. Sparrow and Miksche [S46] investigated the dependence of the tolerance of higher plants to chronic irradiation on cell nuclear volume and DNA content. Linear relationships were developed [S47] that could be used to predict radiosensitivity; Figure II shows the dependence of acute lethal dose on interphase chromosome volume for woody and herbaceous species of angiosperms [S12]. Experimental studies with 28 species demonstrated good agreement between the predicted radiosensitivity and that measured in the field, although it was accepted that significant variability could be introduced by the specific conditions of irradiation and uncontrolled environmental factors [S48].

1. Cultivated and pasture crops

77. Most studies of the effects of radiation on agricultural plants utilize the dose required to reduce the yield by 50% or 100% (YD₉₀ or YD₁₀₀) as the measure of radiation response [S7]. The major cereal crops show the highest radiosensitivity when the ears (seed heads) are developing (YD₉₀ = 4.1-16 Gy); rice is an exception (YD₉₀ = 75 Gy). At other stages of development the YD₉₀ is 20-60 Gy, with rice again being an exception at 160 Gy [F6]. A specific feature of the response of cereals at early stages of development is an increased production of shoots caused by damage to apical meristems and a loss of apical dominance; by producing an increased numbers of ears, this may somewhat compensate for the loss of grain per ear [F6]. Legumes have YD₉₀ in the range 2.6-40 Gy for the vegetative stage and 1-4 Gy for flowering stages. Root crops are less sensitive, with YD₉₀ ranging from 14 Gy for onions to 90 Gy for radishes. Miscellaneous crops, in order of increasing resistance, are lettuce, pineapple, strawberry, squash, spinach, cabbage and tomato, which have YD₉₀ of 45-120 Gy [S7]. Oil seed crops are moderately insensitive, with YD₉₀ of 120-160 Gy [F6]. Pasture and forage crops, where the yield is related to vegetative mass rather than seed production, show the lowest sensitivities (YD₉₀ = 150-230 Gy) [S7].

78. A number of factors have been shown to modify the radiation responses of crop plants. Adverse weather conditions (an increase in temperature and a reduction in relative humidity) after acute irradiation of spring wheat reduced the YD₉₀ by a factor of 4; this effect was dependent on the cultivar studied. Substantial differences have been found between cultivars of spring wheat (172 varieties) in their growth after seed irradiation. Depending on the age of the plants at irradiation, the YD₉₀ can vary ninefold, with the lowest radiosensitivity observed at the time when the multiple apical meristems are produced [F6].

79. The irradiation of seeds with acute doses up to 10 Gy stimulated early emergence in flax and early growth in spring wheat and barley under laboratory conditions. Field trials with irradiated wheat seed showed, however, that any hormetic effect was not consistently translated to an increase in grain yield [S24]. Substantial variations in hormetic responses were found both within and between cultivars and species. and an early stimulation of growth in response to irradiation did not necessarily yield benefits at harvest, mainly because other environmental variables had a much greater influence [S25, S26].

80. As a consequence of the observed relationships between radiosensitivity and nuclear and chromosomal parameters (paragraph 76 [S12, S46, S47, S48]), cultivars of the same species having similar nuclear volumes at interphase would be expected to display similar radiosensitivities. However, a comparative analysis of 172 cultivars of hexaploid wheat [S45] has revealed a 2.5-fold variation in the radiosensitivity of the seeds as indicated by changes in morphometric characters in the seedlings. It was shown that increased radiosensitivity correlated with the degree of biochemical polymorphism, i.e. the differentiation of the genome, in the cultivars [S45].

81. An investigation of the combined effects of irradiation and exposure to lead or cadmium salts on the induction of cytogenetic damage in the leaf meristem of spring barley has demonstrated statistically significant
interactive responses, primarily at low doses of the agents [G11]. Taken together with other data [U5], these results, which indicate non-linear biological responses to combined exposures to contaminants, emphasize the importance of taking account of multiple factors when assessing the potential impact of radiation on the environment.

2. Forest trees

82. Studies have been made of the effects of short-term (16-18 days) acute exposures of pine trees (in a mixed birch-pine forest) in the spring and the autumn. After the autumn exposure the LD₉₀ declined from 50 GY after two years to 30 GY after five years, when the expression of the acute radiation damage was essentially complete. After the spring exposure the trees showed greater radiosensitivity, with the LD₉₀ after two years being 30 GY (greater by a factor of 1.7) [K5]. It was noted that suppression of normal growth at the main and all lateral shoots was a more sensitive indicator of damage than tree mortality [K5], and an absorbed dose of 15 GY in the spring has been found to be 100% lethal within one year for cell proliferation in the apical meristem and for the processes of needle formation [S14]. The developing radiation response of pine trees following radiation exposure in the autumn has been covered in more detail by Karaban et al. [K6] (they also give data for birch trees, which show lower radiosensitivity). Although pine trees appear to be more resistant to acute radiation exposure in the autumn, when the period over which radiation mortality is expressed is extended to six years after irradiation, the LD₉₀ declines, approaching that shown by trees irradiated in the spring [M10].

83. In the first year following acute irradiation of pine trees in the spring, photosynthetic activity was reduced at all doses greater than 5 GY in a dose-dependent fashion. Together with the loss of needles and growth points (apical and lateral meristems), this reduction decreased primary productivity. Although the photosynthetic rate recovered to above control values in the second year for doses below 25 GY and in the third year for doses below 50 GY, this was insufficient to counterbalance the continuing loss of needles, and the overall productivity of the pine stands continued to decline. An acute exposure of 12.5 GY depresses the net rate of photosynthesis in Pinus taeda and Pinus elliottii saplings in the period 4-20 days after irradiation and also depresses the rate of CO₂ evolution by stems [H18]. Birch trees show greater radioresistance [S27]. Using common end-points as indicators of damage, it has been shown that the responses of birch trees to a combination of acute irradiation (0-30 GY) and sulphur dioxide exposure (7 mg m⁻³) exceeded by a factor of 1.5 the sum of the responses to each of the factors separately, i.e. there was a synergistic interaction. It was concluded that a complex mechanism underlay the combined response, because the final outcome depended on the order in which the two factors were applied and was not simply proportional to radiation dose [S16].

84. The maintenance of reproductive viability is necessary for the continued survival of the population and is certainly required for recovery if some radiation mortality occurs. The exposure of pine trees to doses in the range 0.3-22 GY over 16 days in the autumn, when the early stages of pollen (the male gamete) formation takes place, has been shown to produce damage [T11]. In the spring following exposure, vegetative growth and the production of male cones occurred in trees that had received less than 12 GY; in the following year all the experimental trees (in which doses had been up to 22 GY) were productive. At doses greater than 3 GY there was a substantial reduction in the fertility and viability of the pollen produced; viability recovered in the second year, and in the third year neither pollen fertility nor viability differed from control values at any dose studied (<22 GY). At doses exceeding 0.7 GY, morphological changes in the male cones, particularly in terms of size and pollen production rate, persisted into the second year, but by the third year recovery to control values was apparent at doses up to 12 GY [T11]. From these data it cannot be determined whether radiation-induced changes in either male fertility or mortality would be limiting for a pine tree population.

85. In seeds of the ash tree (Fraxinus americana, a deciduous tree) water content was shown to significantly affect sensitivity to acute gamma irradiation. Seeds with a 3.4% water content showed a dose-dependent reduction in germination at doses greater than 100 GY; storage of the irradiated seed for three years. or irradiation of three-year-old seed, further reduced germination rates but did not materially affect the pattern of dose dependence. The survival of the germinated seed to the production of seedlings was very low at 100 GY and zero at higher doses. Raising the water content of the seeds to 40% increased the germination rate at all doses up to 400 GY and substantially increased survival at doses up to 200 GY. The reason given for this lower radiosensitivity was that the lifetime of the radiation-induced free radicals in moistened seeds is shorter than in dry seeds [H7]. More than 50% of one-year-old ash seedlings survived all doses up to 114 GY when irradiated in the dormant state (late autumn), but exposure in the spring (at bud break) produced over 70% mortality at doses greater than 56 GY. Over the next few years, the seedlings irradiated in the dormant state grew faster than those irradiated in the spring at all doses greater than 24 GY, a dose at which the survival was also unaffected [H7].

86. Within a forest, the development and vigour of trees of a given species and age will vary owing to, for
example, light interception (crowding and/or shading by dominant individuals), exposure to wind and soil quality. For disadvantaged pine trees, these factors cause reduced height and poorly developed crowns. The less vigorous trees show greater radiosensitivity over three years following short-term (eight days) acute exposures up to 25 Gy; at 50 Gy there is no difference in the overall cumulative response [S15]. It has also been noted that acute radiation exposure renders pine trees more susceptible to attack by xylophagous (wood-eating) insects [S17]. These results have been confirmed by observations made after the Chernobyl accident, which found that poorly developed and less vigorous pine trees experienced the highest mortality [K22]. Such findings emphasize the importance of regarding radiation exposure as only one of the stresses likely to be experienced by plants.

87. Of course, a pine-birch forest does not consist only of pine and birch trees. In addition to other tree species, there is a herbaceous understorey component of the plant community adapted to the conditions of light intensity, moisture, exposure to wind etc. that prevail under the upper canopy formed by the leafy crowns of the pines and birches. Short-term acute exposure of this community in the autumn did not, in the following year, lead to the loss of any of the 188 herbaceous species present, nor was there any substantial change in species content [S18]. There were, however, delays (in eight species) and advances (in three) in the normal, seasonal developmental progression of some of the plants at absorbed doses in the range 30-50 Gy. In the same dose range, morphological variation from normal was noted in 16 species. These effects had disappeared by the second season after exposure. At doses greater than 100 Gy, and particularly in the second season after exposure, there were increases in the relative biomass and the relative number of species in the experimental plots. This response was ascribed to the increased illumination of the forest floor following the radiation-induced loss of the sensitive upper canopy (the pine trees) and is thus indirect rather than direct [S18]. In the first two years following acute exposure, the light and precipitation penetrating to the forest floor were not much different than in the control areas. By the fourth year there were well-defined, dose-dependent increases in light penetration (up to sixfold) and precipitation (up to twofold) owing to the loss of pine foliage and, at the highest doses, the loss of trees, causing an increase in grass biomass up to 3.5 times that in the control area. In the longer term, the extension of the grass ground cover in the irradiated area is expected to delay the recovery of the coniferous component of the forest by suppressing seed germination and seedling survival [S28].

88. These data on the response of a pine-birch forest community have been incorporated into a model to examine the long-term consequences of acute radiation exposure [S19]. An exposure of 25 Gy (less than the LD₉₀ for pine trees) substantially reduces both the number and productivity of the pines to minimum values at 15 years and 5 years, respectively, with slow recovery thereafter. The birch trees, being more radio-resistant, benefit from the reduced competition, and their number and productivity increase, although not enough to balance the loss of the pines. It was predicted that complete recovery to the pre-irradiation state would require more than 50 years following an acute exposure of 25 Gy [S19]. Such a result is not surprising, since it might be expected that a period longer than the average lifetime of the trees would be necessary to regain the stable climax state.

89. The outcome of these studies of the acute radiation response of the pine-birch forest is broadly comparable with the results of experiments on other plant communities, which were reviewed by [4, W3].

90. The protraction of radiation exposures increases the total doses required to kill plants: for 11 woody species, the LD₉₀ increased by a factor of 4.3 between the first and eighth years of continuous exposure [S13]. Gymnosperms (including the pine species), with a three-year LD₉₀ of 46 Gy (5.200 μGy h⁻¹), remained much more radiosensitive than angiosperms, for which the three-year LD₉₀ was 330 Gy (38,000 μGy h⁻¹) (see also [14]). The LD₉₀ for Pinus rigida increased to 74 Gy after 10 years of exposure (average dose rate of 1,250 μGy h⁻¹) [S29], and that for Abies balsamea increased to 110 Gy after 11 years of exposure (average dose rate of 1,500 μGy h⁻¹) and was still increasing [D12]. The numbers of balsam fir saplings in irradiated plots was, however, greater than in control plots at dose rates up to 250 μGy h⁻¹ over 11 years [D12]. After 11 years of radiation exposure, the LD₉₀ for plantation black ash (Fraxinus nigra) specimens planted as two-year-old saplings had increased to more than 900 Gy at a dose rate greater than 10,000 μGy h⁻¹. All naturally growing saplings of black ash were killed within five years at exposures of approximately 10,000 μGy h⁻¹, but two older specimens were surviving after 11 years at dose rates of 11,000 and 4,400 μGy h⁻¹; a green ash (Fraxinus pennsylvanica) was also surviving after 11 years at a dose rate of 5,900 μGy h⁻¹ [D13]. Changes in canopy cover owing to mortality confirm the relative radiosensitivities of gymnosperms and angiosperms after 10 years of chronic irradiation [4A].

91. In mature trees, needle growth is reduced by exposures over 3-4 years at dose rates greater than 3,000 μGy h⁻¹ to Abies balsamea [D12] and over 10 years at dose rates greater than 600 μGy h⁻¹ to Pinus rigida [S29]. For one-year-old saplings of Pinus sylvestris, needle length was substantially reduced at 7,000 μGy h⁻¹ over a single growing season but was increased marginally relative to the controls at lower
ANNEX: EFFECTS OF RADIATION ON THE ENVIRONMENT

dose rates (<78 μGy h\(^{-1}\)); stem length was reduced at all
dose rates, and significantly so at 7,000 µGy h\(^{-1}\) [S30].
Two-year-old seedlings of *Pinus banksiana* showed
reduced stem growth at dose rates greater than
3,700 µGy h\(^{-1}\) over the growing season [A5]. Above
500 µGy h\(^{-1}\), the percentage of dead buds on *Abies balsamea*
increased rapidly after five years of chronic
exposure [D12]. Trunk growth in mature specimens of
*Pinus rigida* can be reduced by dose rates in the range
400-2,000 µGy h\(^{-1}\) over 9 years [W16] and at dose rates
above 1,700 µGy h\(^{-1}\) over 10 years [S29]. The radiation
response can be intensified by poor growing conditions
[S29, W16] or mitigated in trees with large healthy
crowns free of competition [W16]. The cambium layer
appears not to be terminally damaged by the irradiation
[S29]. Net photosynthesis and CO\(_2\) exchange in *Pinus
rigida* are poor indicators of damage from chronic
irradiation at dose rates less than 12,000 µGy h\(^{-1}\) [B20].

92. Chronic irradiation over a nine-year period
reduced the number of mature seeds in *Pinus rigida*
cones to 10% of the control values at a dose rate of
about 1,500 µGy h\(^{-1}\); no cones with mature seed were
found at nine-year accumulated doses greater than
74 Gy [S29]. White spruce ( *Picea glauca*) pollen has
been found to have an acute LD\(_{50}\) between 60 and
90 Gy for seed yield and quality [R6].

3. Shrub species

93. Radiation effects in shrub species can be illus-
trated by the results of two experiments, one short-term
and the other longer term. In the short-term experiment,
estimated beta doses from simulated fallout (K-Y-
contaminated particles) to the developing flower buds
of *Viguiera porteri* (approximate doses of 30 and 60 Gy
at two experimental sites) induced a significant (2.5-
fold and 3.6-fold, respectively) increase in aberrant
flowers (extra petals, fasciated flowers, incomplete
flowers) relative to control plants. Flowers with addi-
tional petals, which constituted 81% of the aberrant
forms, produced 38% fewer seeds than normal controls,
with no significant differences between the values for
the two exposures. Seeds from flowers receiving 51 Gy
showed a delay in the initiation of germination and a
38% reduction in germination rate; the plants from all
irradiated seeds were, however, apparently normal [M11].

94. After seven years of chronic exposure, 31 shrub
species growing naturally in a mixed boreal forest
showed 50% mortality at dose rates ranging from 800 to
over 60,000 µGy h\(^{-1}\); for another 24 species, individuals
were surviving at the upper end of the range 10-
14,000 µGy h\(^{-1}\) but in only three cases had single
individuals died at higher dose rates during the term
of irradiation. Where sufficient data were available to
estimate it, the 50% lethal dose rate decreased with
irradiation time but for four species appeared to have
reached stable long-term survival values of 10,000
µGy h\(^{-1}\) (*Alnus rugosa*) and 15,000 µGy h\(^{-1}\) (*Corylus
cornuta, Vaccinium angustifolium* and *Vaccinium
myrtilloides*). Differences in radiosensitivity could be
related to some extent with growth habit. e.g.,
average mature height, vegetative growth from shielded
roots, deciduous or evergreen. Regardless of
radiosensitivity, somatic effects were seen in most
species, and those that carried aerial buds through the
dormant season showed the greatest number of effects
on leaves, flowers and branches [D14]. The capacity to
regenerate from rhizomes shielded below ground and
from the bases of damaged stems at ground level,
growth habits that contribute to the relatively high
apparent resistance to chronic irradiation in *Gaylussacia
baccata* and *Vaccinium ovatum*, appear to derive from
adaptations that improve survival in response to a natural
stress. namely, forest fires following lightning strikes
[B21].

4. Herb communities

95. The predominant effect of chronic irradiation of
herb communities is to reduce species numbers
(diversity) as the dose rate increases. caused by the loss
of more radiosensitive taxa [F7, F8, W12]. The
threshold for change was less than 20,000 µGy h\(^{-1}\) for
old field communities [W12], and the dose rate to
produce a 50% reduction in the diversity of a plains
short grass community declined with extended exposure
to about 1,000 µGy h\(^{-1}\) [F8]. Nevertheless, a winter rye-
weed community showed little change in composition
below 40,000 µGy h\(^{-1}\), although the rye standing crop
was reduced at dose rates down to 10,000 µGy h\(^{-1}\)
and the production of fertile rye seed was reduced at dose
rates above 1,000 µGy h\(^{-1}\) [H9]. Although a number of
herb species, one of which was *Erigeron canadensis*,
survived at dose rates up to 130,000 µGy h\(^{-1}\), the
reproductive potential was damaged above 20,000
µGy h\(^{-1}\) [W17]. In the longer term. chronic irradiation
slows the rate of successional change [F7], which may
depend, more than usually, on the adventitious arrival
of viable seed from outside the irradiated area [W12].
Overall, however, herbaceous plants appear to be
somewhat less radiosensitive than shrubs.

5. Lichens

96. The diversity of lichen communities was reduced
by chronic irradiation at a dose rate of 1.1 Gy h\(^{-1}\) over
one year. To survive at all at this dose rate (over
9,000 Gy a\(^{-1}\)) attests to the radioresistance of the lichen
species. An apparent threshold dose rate of 125,000
µGy h\(^{-1}\) was found for effects on the composition of
lichen communities, although relative densities were
changed at lower dose rates. Crustose forms were more
resistant than either foliose or foliose forms. However,
these two less resistant forms grew more vigorously in
areas where the dose-rate range was 26,000-96,000 μGy h⁻¹ than in the control areas, although this may have been an indirect response to irradiation. caused by the collarette loss of the canopy as trees died off at these dose rates. The total density of lichens also declined with increasing dose rate, that is, the more radioreistant species did not colonize the areas vacated by the more radiosensitive species, but this may be a consequence of an observation period that was too short relative to the slow growth rates of these organisms [B22, W17].

6. Fungi

97. The appearance of the fruiting bodies of macrofungi in an irradiated forest appeared to depend more on the availability of an adequately nutritional substrate than on the radiation dose rate. After an eight-year exposure, mushrooms appeared at dose rates up to 100,000 μGy h⁻¹, puffballs at dose rates up to 325,000 μGy h⁻¹ and slime moulds at dose rates up to 770,000 μGy h⁻¹. These values are likely to be overestimates of the actual tolerances, as the fruiting bodies evolve from vegetative organisms, which are shielded to a greater or lesser extent below ground [H10].

7. Indirect effects

98. A number of indirect effects of radiation exposures may become apparent in plant communities. In white oaks subjected to chronic gamma irradiation there is a dose-rate-dependent gradient of damage in the form of delayed bud burst and an extended period of leafing-out, during which process the leaves are softer and of a yellowish hue, making them attractive to aphid parasites. High densities of aphids were observed in some years (1963 and 1969) but not in others; these densities were, moreover, significantly greater on trees at dose rates greater than 4,000 μGy h⁻¹ than on trees at lower dose rates. It was concluded that other factors, primarily meteorological, governed the presence and distribution of overwintering aphids capable of colonizing the weakened host plants [H11]. Insect damage did not, however, contribute to the loss of canopy cover in an irradiated boreal forest [D15].

99. The induction of direct damage in plants by long-term chronic irradiation is likely to have indirect effects on the local environment that may then interact with the radiation stress. Loss of vegetation and canopy cover have been shown to affect evapotranspiration in an irradiated oak-pine forest. Close to the radiation source, where virtually all the vegetation had been destroyed after 1.5 years of exposure at dose rates above 65,000 μGy h⁻¹, the cumulative evapotranspiration was about 85% of that in undamaged forest. The rates of evapotranspiration in the first half of the growing season increased as the dose rate (and damage) decreased but became independent of irradiation during a drought in the second half of the season. The lowest dose rate at which there was a clear reduction in cumulative evapotranspiration was 4,800 μGy h⁻¹, at which point the tree canopy had been reduced by 50% but the shrub layer had remained almost undamaged [R7]. A chronic irradiation dose-rate gradient has also been shown to have significant effects on litter fall and total organic matter content of the soil. Even 12 years of exposure were not sufficient for these changes to reach a stable equilibrium. At that time, the total annual litter fall declined continuously at dose rates above 1,500 μGy h⁻¹, as did the standing crop of litter. The effect of this reduced organic input was apparent in the humus standing crop, which showed depletion, relative to control areas. At all dose rates above 1,500 μGy h⁻¹, there was, however, a noticeable secondary maximum in the humus standing crop at a dose rate of 10,000 μGy h⁻¹, corresponding to a zone where a relatively radioreistant sedge (Carex pennsylvanica) had become established [A6].

100. The devastated area close to the radiation source in the chronically irradiated oak-pine forest would be a site where normal successional colonization would be expected were it not for the continuing radiation exposure. It has been shown that there is a significant input of wind-borne seed of adventive herbs, which are typical colonizers of disturbed areas [W18], and many of these are sufficiently radioreistant to germinate and produce young plants that can grow to maturity in the high-exposure zone. The capacity of these plants to repopulate the disturbed area through reproduction was limited, however, by two factors. First, the radiation exposure severely reduced the normally prolific seed production: secondly, rabbits selectively grazed the plants that were conspicuous in the otherwise barren area. In combination, these factors retarded the rate of recolonization, and the more successful species were present as a few small clumps. These species were generally of normally small stature and thus more likely to receive adventitious shielding from standing and fallen dead trees or they were perennials with the advantage of shielded sub-surface buds. It was this latter characteristic that, together with relative radioreistance, favoured a species normally present at low density in the forest. The sedge (Carex pennsylvanica) spread vegetatively and vigorously from the few original individuals and seemed likely to dominate the successional pattern to the exclusion of the hardy herbs [W19].

8. Summary

101. Acute lethal radiation doses in plants have been noted to range from 10 to 1,000 Gy. For some forms of lower plants (mosses, lichen) the upper range of the acute lethal dose may be higher by an order of magni-
tude. In general, larger plants are more radiosensitive than smaller plants, with radiosensitivity decreasing in the order coniferous trees, deciduous trees, shrubs, herbaceous plants, lichen and fungi [W20, W21]. Non-
lethal effects are noted at lower doses, for example severe growth inhibition is noted at 40%-50% of the lethal dose and failure to set seed at 25%-35% of the lethal dose. At doses less than 10% of the lethal dose, effects are less apparent, and plants maintain a normal appearance.

102. A range of sensitivities to radiation exposure is exhibited by the components of plants. Ranging from dry seed (least sensitive) to apical meristems (most sensitive). Various crop plants show different reductions in yield following radiation exposures, with further modification caused by external factors (temperature, humidity). Young plants and plants disadvantaged by growing conditions may show increased radiosensitivity.

103. Plant species are also variably tolerant to chronic radiation exposures. In the more sensitive pine species, dose rates above 3,000 µGy h⁻¹ over 3-4 years reduce needle growth; in one-year-old saplings, needle length was substantially reduced at 7,000 µGy h⁻¹ over a single growing season. Trunk growth was reduced in mature pine trees by dose rates in the range 400-2,000 µGy h⁻¹ over nine years. Delayed bud burst and an extended period of leafing-out was demonstrated in white oaks exposed to chronic gamma radiation. At dose rates greater than 4,000 µGy h⁻¹ the trees were more susceptible to aphid infestation.

104. With effects of chronic radiation of the most sensitive plants evident at 1,000-3,000 µGy h⁻¹ and some specific changes noted at 400-2,000 µGy h⁻¹, it is suggested that chronic dose rates of less than 400 µGy h⁻¹ (10 mGy d⁻¹) should have only slight effects in sensitive plants but would be unlikely to produce any significant deleterious effects in the wider range of plants present in natural plant communities.

B. TERRESTRIAL ANIMALS

1. Mammals

(a) Mortality

105. Radiation effects in mammals have been extensively studied in radiobiological experiments using laboratory animals (mice, rats, dogs and monkeys) and domestic livestock (pigs, sheep, goats, burros and cattle) [B8, B9]. Except in the case of exposure at unusually high doses, radiation damage or lethality in mammals is due to disturbances in the haematopoietic system and the gastro-intestinal mucosa. These cell self-renewal systems contain stem cells, differentiating cells and functional end cells, with the stem cells being the most radiosensitive and thus the predominant influence on the radiation response. Symptoms become apparent when end cells are not replaced.

106. Mammals die from damage to the gastrointestinal tract within the first 10 days following exposure to relatively high radiation doses (midline doses of 10-50 Gy) ([U3]. Annex G. "Early effects in man of high doses of radiation"). The intestinal symptoms (diminished food and water intake, diarrhoea, loss of fluids and electrolytes, decreased intestinal absorption etc.) are a consequence of cell depletion in the intestinal lining due to damage to the survival and proliferative capacity of the crypt stem cells; the normal continuous flow of mature replacement cells from the crypts to the villi is interrupted. The time course of events is almost independent of dose in the range 10-50 Gy but differs widely between species. The differences in radiosensitivity between species result from the complex interactions of the sensitivities of the crypt stem cells and their rates of maturation and progression from the crypts to the villi. Approximate LD₅₀ₐ for the gastrointestinal syndrome are as follows: mouse, 12 Gy; rat, 11 Gy; rhesus monkey, 9 Gy; and dog, 8 Gy [Y3]. The values were determined for particular strains of these species, and wide variations are known to occur. However, the approximate species differences (due to the complexities noted above) might arise from variations in intestinal morphology that have to do with adaptations to particular diets, i.e. herbivory, omnivory and carnivory [V3].

107. Mammals die from bone marrow failure (the haematopoietic syndrome) within weeks following whole-body radiation exposures giving midline doses of 1.6-10 Gy. The ultimate cause of death in different species is granulocytopenia, thrombocytopenia or lymphocytopenia [U3]. These conditions are again the result of complex interactions of differential radiosensitivities and cell cycle and maturation kinetics (including stem cell survival) in the various cell lineages. Nevertheless, there is an apparent inverse relationship between the LD₅₀ₐ and the weight of the animal [U3], and approximate values are 6-10 Gy for small mammals and 1.6-2.5 Gy for larger ones [B8]. For domesticated animals (cattle, sheep, goats, pigs, burros and horses) the LD₅₀ lies in the range 1.2-3.9 Gy (midline dose) [K10]. In addition to the variation in LD₅₀ₐ, the rate of change of survival with dose also varies between species (Figure III). With some evidence that at lower sublethal doses there might be less variation between species. There has been considerable effort (e.g. [B10]) to reanalyse experimental results to quantify more exactly species-relevant LD₅₀. There are, however, many differences in response between separate strains of the same species, dosimetric uncertainties and differences in conditions of maintenance.
and care of the animals before and after exposures that can affect response. All species are markedly influenced by the presence of pathogenic bacteria in the animal, which reduces survival times and, thus, LD$_{95}$. The LD$_{95}$ for mice housed in a germ-free system has been found to be about 2 Gy higher than that for mice housed in a conventional system [L4].

108. Protraction of a given total exposure generally reduces the extent of injury, as it allows two distinct processes to intervene. First, sublethal damage is repairable at the cellular level, which is particularly important for exposures to low-LET radiation. Secondly, cell proliferation can replace lethally damaged cells and maintain the cell population at a new level, which is determined by the dynamic interaction between the dose rate and the rate of cell death and by the total reserve proliferative capacity.

109. At reduced dose rates (protraction of a given total dose) of low-LET radiation, all species show a gradual increase in LD$_{95}$; higher total doses are tolerated. This changing response has been attributed to the increasingly effective influence of cellular repair of sublethal damage at the lower dose rates. As the dose rate is further reduced, a sharply increasing trend in the values for median lethal dose is apparent for mice, pigs, dogs, goats, and sheep; the approximate threshold dose rates for this change in response correspond to the accumulation of the LD$_{90}$ in periods ranging from 0.2 days (mouse) to 9 days (goat). This rapid change in LD$_{90}$ with dose rate has been interpreted as the consequence of a shifting balance in the dynamic interaction between dose-rate-dependent cell loss and cell proliferation and maturation kinetics in the haematopoietic system; the latter processes are under homeostatic control, i.e. their rate constants can alter in response to radiation-induced cell loss. The data for the burro (donkey) and the primates do not show any sharp increase in median lethal dose at dose rates down to 8,300 μGy h$^{-1}$ (LD$_{90}$ in 18 days) and 5,400 μGy h$^{-1}$ (LD$_{90}$ in 60 days), respectively. There do not appear to be any data for LD$_{95}$ at dose rates less than 4,000 μGy h$^{-1}$ or for periods of exposure exceeding 60 days, although studies have been made outside these limits for other purposes.

110. For the survivors of acute doses in the LD$_{9999}$ range and for organisms exposed to lower acute doses, it has frequently been suggested that there would nevertheless be consequential life-span reduction from non-specific causes, e.g. accelerated ageing or the earlier onset of the pathological conditions responsible for mortality in the unirradiated population. The available data have been reviewed ([U5], Annex K, "Radiation-induced life shortening") and the conclusion reached that there is little evidence that an observed reduction in life-span arises from anything other than an accelerated onset or increased incidence of neoplastic disease: this conclusion has been confirmed by the Committee's most recent consideration of the available data ([U2], Annex F, "Influence of dose and dose rate on stochastic effects of radiation"). Analysis of the results for mice exposed to x rays or gamma radiation, including those results that show an extension of life-span at doses less than 2 Gy, indicates that the percentage of life-shortening could be most simply expressed by a linear, non-threshold dependence on dose. The slope of the dose-effect relationship yielded a 5% reduction in life-span per gray down to the lowest doses. The much more limited data available for the rat, dog and hamster show that their responses are not very different from that of the mouse at doses below 6 Gy, and in this dose range a factor of 5 would cover the overall intra- and interspecies variability.

111. For chronic lifetime exposure of mice to low-LET radiation at dose rates where haematopoietic damage (bone marrow failure) does not occur, the percentage life-shortening shows an essentially linear response with dose in the range 0-45 Gy (dose rates less than 3,800 μGy h$^{-1}$). Thus, chronic exposure is substantially less effective, by a factor of 7, than acute exposure. Again, there is no evidence that anything other than radiation-induced cancer is responsible for the increased loss of life-span relative to the controls [U5]. At a dose rate of 420 μGy h$^{-1}$ (a lifetime dose to mice of approximately 7 Gy) the average loss of life-span amounts to 5% (equivalent, for example, to 20% of the population dying from the consequences of irradiation at 75% of the normal mean age). Extrapolation of these specific data on the mouse to the radiation exposure experienced by a population in a contaminated "natural" environment is not straightforward:

(a) natural mortality in a wild population of mice subjected to competition (intra- and interspecies) and predation is unlikely to have the same age dependence as observed for control populations in the laboratory; thus a late, incremental incidence of tumours is unlikely to have the same overall effect on life-span;

(b) extension to other species, especially those with longer average life-spans is unjustified; and

(c) if the fertility of the older members of the population represents a significant buffer capacity, then earlier than normal mortality due to radiation exposure might have a disproportionate effect on the population at times of stress [F4].

The very limited data available for other species (guinea-pigs, goats and dogs) are insufficient to allow meaningful comparison; they do, however, identify tumour induction as a consequence of radiation exposure [U5].

112. Acute or chronic whole-body exposure to high-LET radiation (fast neutrons) has been shown to be more
effective than the corresponding low-LET exposure regime in producing a reduction in life-span. The relative biological effectiveness (RBE) is greater, as is to be expected, for chronic irradiation than for acute exposure [U5]. These results underline the importance of the potential internal exposure from contaminant radionuclides that decay by alpha emission. There is a body of evidence to show that the injection of radioisotopes of bone-seeking elements (Sr, Pu, Th, Ra and Am) into rats and dogs results in life shortening due to the induction of bone tumours, with the alpha emitters being more effective per unit of absorbed dose than the beta-emitting \(^{90}\text{Sr}\)\(^{89}\text{Y}\) (although the precise site of deposition is also a modifying factor). In apparent sharp contrast. \(^{239}\text{Pu}\) chronically administered to rats results in very little change in the life-span compared with the controls, although there is an increased incidence of marrow damage, leukaemia and bone cancer [U5]. It is clearly important to identify the appropriate target tissues and organs and to know the exposure from internal or external contaminant radionuclides when attempting to assess the potential impact on the environment.

113. The influence of hibernation on the response of mammals to acute irradiation is complex and depends on the status of the animals before, during and after exposure. For the ground squirrel (Citellus tridecemlineatus), hibernation induced by maintenance at 5°C for 2-5 days prior to and during irradiation consistently provided some protective effect in terms of increased mean survival time and percentage survival at 30 days. The degree of protection could be modified by the post-irradiation maintenance conditions, with immediate arousal to an active state improving survival relative to animals maintained in hibernation for an additional 20-30 days [B32, J4, M21]. The conditions employed to induce effective hibernation also modified the degree of protection. Maintenance for 2-5 days before exposure at 13°C, or undisturbed, but closely confined, at 23°C both improved survival relative to animals maintained at 5°C, which, in turn, survived better than animals irradiated while normally active [B32]. Split dose experiments have shown that repair of radiation damage continues during hibernation at 5°C [J4].

114. Some limited data are available indicating that the acute effects of radiation in small mammals are less severe when experiments are carried out under controlled conditions in the laboratory rather than in the natural environment, where additional stresses are present. Although the LD50 obtained for female cotton rats was similar for a laboratory study and for irradiated animals released into quasi-natural conditions in large field enclosures, the mortality of rats exposed to doses less than the LD50 was greater under field conditions [F7]. Exposure of house mice and field mice at the LD90 established under laboratory conditions produced the same and lower survivals, respectively, when the animals were released to field enclosures [G4]. In laboratory studies, the LD90 for the female house mouse was found to be greater when the treated animals were housed singly than when the females were kept in groups of five [D6]. Although the data were not entirely conclusive, chronic irradiation of pocket mice in an eight-hectare enclosure at approximately 420 µGy h\(^{-1}\) appeared to marginally reduce their survival relative to otherwise similar controls. The survival of three field populations (one irradiated and two control) was less than that of an irradiated laboratory group, which in turn was less than that of the laboratory controls. In addition, under laboratory conditions, the irradiated and control male mice survived longer, on average, than the corresponding females [F3].

115. It has to be accepted that the number of mammal species that has been or, indeed, is likely to be studied is an extremely limited, and probably atypical, selection from those extant. Nevertheless the available data, even taking account of substantial interspecies variability, provide very little evidence that dose rates below 400 µGy h\(^{-1}\) (approximately 10 mGy d\(^{-1}\)) to the most exposed members of the population would seriously affect their mortality (and, thus, the death rate in populations of these species) from either deterministic or stochastic responses.

(b) Reproductive effects

116. The effects of radiation on reproduction have also been much studied. With most of the results suggesting that natality is a more radiosensitive parameter than mortality in species other than man and, therefore, of more relevance in an environmental context. The minimum dose required to depress reproduction rates may be less than 10% of the dose required to produce direct mortality [W5]. Reproductive effects may be apparent at doses that cause no other observable response in the animal. For example, the LD90 in mice is 6-12 Gy, depending on strain and species, but an acute dose of 0.08 Gy produced a 50% reduction in the number of oocytes at their most sensitive stage in newborn mice [O3]. Because more immature oocytes are normally present than will be utilized for reproduction, the 50% reduction does not translate to a 50% decline in fecundity; it could, however, conceivably lead to a minor shortening of the reproductive span [M5]. In male mice, by contrast, an acute dose of 10 Gy may only temporarily impair fertility in adults, although in young mice (3-5 days of age), it can induce permanent sterility [L6, Annex H, "Genetic effects of radiation"]). The differences in response are a consequence of the quite different processes of gametogenesis in the two sexes [D2]. There are also substantial differences in response to the same dose between species, particularly for oogenesis, with most species showing greater radioresistance than the mouse [C6].
117. Chronic irradiation probably affects oocyte viability by different mechanisms than acute irradiation at the particularly sensitive stages of oogenesis, as discussed in the preceding paragraph. The differences arise from both the timing of the oogonial cell division and the limited size of the stem cell pool. In a female mammal exposed throughout its life, from conception to reproductive maturity, the greater part of the total dose is likely to be accumulated by oocytes in the resting, immature stage rather than in any particularly sensitive stages of oogonial cell proliferation. The effects of chronic exposure are more relevant to environmental concerns. The number of immature oocytes in mice can be reduced by 50% by a dose rate of 130 μGy h\(^{-1}\) from tritiated water during the period 19-33 days after conception [D5]. For irradiation from tritiated water from conception to 14 days after birth, the median lethal dose rate for mouse primary oocytes was 180 μGy h\(^{-1}\), and an RBE of about 2 (relative to \(^{60}\)Co gamma rays) was estimated. At lower dose rates (and lesser effects) the RBE increased to 3 [D16, D18]. In 11-week-old female mice chronically exposed to either beta radiation from tritiated water or \(^{60}\)Co gamma rays for 10 days with similar dose-rate profiles, the number of primary oocytes declined exponentially with cumulated dose. A total dose of 0.16 Gy from tritium reduced the number of primary oocytes by 80%, and an RBE of 2 was estimated relative to \(^{60}\)Co gamma rays [D20]. The developing oocytes of the squirrel monkey, exposed to tritium from conception to birth, showed an even higher radiosensitivity, with a median lethal dose rate of 42 μGy h\(^{-1}\); neonates that had been exposed to 420 μGy h\(^{-1}\) were found to be sterile [D18]. Similar results have been observed for tritium exposure in monkeys in the last third of pregnancy [C6] and for \(^{90}\)Sr,\(^{90}\)Y exposure of mice [R2]. The total accumulated doses were 40-200 mGy. A total dose of 900 mGy from \(^{90}\)Sr,\(^{90}\)Y reduced fertility in the mouse [R2], and a dose rate of 3,300 μGy h\(^{-1}\) during the period 20-40 days after conception produced complete sterility [R5].

118. The effects of continuous tritium exposure from either tritiated food or tritiated water on primary oocyte production in first-generation (F\(_1\)) and second-generation (F\(_2\)) offspring have been studied in rats. The numbers of primary oocytes were determined in 21-day-old F\(_1\) and F\(_2\) offspring that had effectively been exposed since conception at a dose rate of 77 μGy h\(^{-1}\). Although oocyte numbers were reduced to similar extents under both exposure regimes and in both F\(_1\) and F\(_2\) offspring, the differences from control values were not statistically significant [P18]. In a second experiment, the reduction in oocyte numbers in 21-day-old F\(_1\) offspring was significant at a dose rate of 610 μGy h\(^{-1}\) derived from tritium in drinking water and at 200 μGy h\(^{-1}\) derived from tritium in food (organically bound tritium) [P14].

119. For mature female rats, dose rates of less than 4,000 μGy h\(^{-1}\) from \(^{60}\)Co gamma radiation did not affect reproductive ability [B15]. Female mice exposed at 800 μGy h\(^{-1}\) from conception became sterile at 25 weeks of age, and those exposed at 4,000 μGy h\(^{-1}\) were sterile at 7 weeks of age [B15]. In eight-week-old female mice exposed to either beta radiation from tritiated water or \(^{60}\)Co gamma rays for 10 days with similar cumulative dose profiles and mated after a further 21 days, preimplantation losses increased linearly with dose. This loss became significantly greater than for the control at a total dose of 0.31 Gy for tritium exposure, and an RBE of 2.5 was estimated relative to \(^{60}\)Co gamma rays [Z7]. In young mice, \(^{109}\)Po injected as PoCl\(_3\) in isotonic saline was found to be preferentially taken up into the ovary and uterus. A dose of 37 mBq g\(^{-1}\) body weight was estimated to deliver an average absorbed dose to the ovary of about 100 μGy over a period of four days, at which time there was a significant reduction in primary oocyte survival (79% of control). Comparisons with other published studies of the effects of gamma radiation [O3] provided an estimate of over 370 for the RBE, although lower values were found for higher absorbed doses of alpha radiation and greater effects [S31].

120. The testes are also sensitive to chronic exposure, although the continuous nature of the spermatogenic process allows sperm production to be maintained under irradiation, often at equilibrium levels lower than in control animals. A dose rate of 570 μGy h\(^{-1}\) over seven months resulted in the stabilization of the spermatogenic cell population in the mouse at 80% of control values. However, a second study showed that at a dose rate of 750 μGy h\(^{-1}\) over 15 weeks, the stem cell population maintained control values, although cell death was occurring [C6, U6]. In male mice a mean absorbed dose rate of 36 μGy h\(^{-1}\) to the testes from \(^{239}\)Pu alpha radiation for 5-8 months reduced testes mass and sperm output by approximately 10% and 8%, respectively: an RBE of 10-15 was estimated relative to the effects of \(^{60}\)Co gamma rays [S50]. In the rat, a dose rate of 580 μGy h\(^{-1}\) reduced the testes weight by 7% relative to the controls after 75 days of exposure, corresponding to a disruption of the process of spermatogenesis. Cessation of exposure allowed recovery to near-normal values [L8]. At a dose rate of 800 μGy h\(^{-1}\) from conception, the fertility of male mice was not affected over the 33-week duration of the experiment [B15]. In beagle dogs, a dose rate of 180 μGy h\(^{-1}\) resulted in progressive cell depletion and sterility within a few months, but exposure at 36 μGy h\(^{-1}\) over the whole life elicited no response [C6]. No more sensitive terrestrial mammal has been identified [M5, U4], although it is accepted that few of the total number of species have been studied.

121. Continuous irradiation at 500-1,000 μGy h\(^{-1}\) for at least 10 generations did not affect the fertility of pairs
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of mice from four different strains, as indicated by the average size of the first litter [S11]. This result is not necessarily inconsistent with the data discussed in paragraph 116, because of the luck, noted there, of a direct relationship between oocyte reduction and fecundity. In the environmental context, it is the effect of radiation on the normal distribution of lifetime reproductive capacities that is the relevant factor. Nevertheless, it seems unlikely that a dose rate of 100 μGy h⁻¹ to the most highly exposed individuals in populations of wild mammals and, by inference, a lower mean dose rate to the whole population will have any damaging consequences for the fecundity of populations as a whole.

(c) Effects on the developing embryo

122. As is to be expected from the degree of cell proliferation and differentiation in progress, the developing embryo has been found to be rather sensitive to the effects of radiation. Damage at this stage of the life cycle can reduce fecundity and postnatal survival and, hence, the potential recruitment to the population. The available data, the majority of which relate to the mouse, were thoroughly reviewed in earlier UNSCEAR Reports [U4, U6] and in a report produced by the Commission on Radiological Protection of the Federal Republic of Germany [C22], so only a brief summary will be included here. It is conventional to divide the temporal development of the mammalian conceptus into three main periods corresponding to significant differences in the processes in progress in the embryo: the pre-implantation period, which encompasses the development of the blastocyst; the period of major organogenesis; and the fetal period. These divisions are also convenient for the discussion of the responses to radiation, which differ in nature and degree between the periods, as can be seen in Figures IV and V, which summarize the situation for the mouse [C22].

123. The most conspicuous effect of acute irradiation during the pre-implantation period is the early death of the embryo: post-implantation and postnatal death are less important sequelae of such exposure. Similarly, growth reduction and malformations are a less frequent consequence of pre-implantation exposure [C22, P13]. Even within the pre-implantation period (up to the late blastocyst stage), however, there are variations in response. Exposure of single-cell mouse embryos to 2 Gy produced mainly pre-implantation deaths with many fewer resorptions (post-implantation deaths) and fetal deaths, while similar exposure at the stage of 32-64 cells only produced resorptions [M18]. The mortality of these very early embryos correlates well with the presence of radiation-induced chromosome aberrations in the blastomeres [C22]. Doses as low as 0.2 Gy to mouse embryos in vitro have been reported to produce mortality at the most radiosensitive time, prior to DNA synthesis in the pronuclear stage. It has been shown that there is a tenfold variation in radiosensitivity through the different stages of the mitotic cycle and between mitotic cycles in the very early development stages. The irradiation also disturbs the normal kinetics of progression through the cell cycle. In vivo studies with rodents have provided qualitative confirmation of these findings. Notwithstanding the general conclusions given above, doses as low as 0.05 Gy to the rat in the pre-implantation period in one experimental series resulted only in fetal mortality, whereas a higher dose (0.1 Gy) produced both embryonic and fetal mortality, with the latter being greater [U4, U6].

124. There appear to have been rather few studies of the effects of chronic irradiation during the pre-implantation period. The impact of chronic exposure from internal radiation (tritium as tritiated water) and external 60Co gamma radiation on pre-implantation mouse embryos maintained in culture has been investigated [Y1]. The radiation exposures commenced at the pronuclear, early two-cell and late two-cell stages, and survival to the expanded blastocyst stage was used as the criterion of damage. Exposure from the pronuclear stage showed the greatest radiosensitivity, with 50% survival at an estimated tritium concentration of 4.4 MBq ml⁻¹ (corresponding to an estimated dose rate of 10.000 μGy h⁻¹). The range of tritium concentrations used does not allow assessing the lowest dose rate to produce an effect. The estimated RBE was not significantly different from unity. Other experiments [U4] have shown that tritiated thymidine produces damage at much lower activity concentrations, underlining the importance for the purposes of dosimetry of information on the relative spatial disposition of the radiation source and the putative target for the biological effect being examined (see also [C22]). The available data are insufficient to assess whether protraction of the exposure reduces the effectiveness of a given dose (the sparing effect), but it should be noted that the restricted time available for the accumulation of the dose (pre-implantation periods of 5-17 days [U4]) also limits the potential total dose to this embryonic stage at low dose rates.

125. It has been concluded that the most characteristic (but by no means the only) response to acute irradiation during the period of major organogenesis is the induction of malformations [C22, U4, U6]. These teratogenic effects develop during embryonic and fetal growth and, if not of lethal consequence, persist into the postnatal period. The time of maximum radiosensitivity for the induction of malformation in a particular organ (although there may be growth disturbances in other organs or the whole body as well) coincides with the surge in cell proliferation in the relevant precursor tissue. This is a general finding for the animal species that have been studied (mouse, rat, hamster, gerbil.
rabbit, monkey, dog, sheep, cattle, pig and marmoset), but the response to a given acute dose strongly depends on the species and its developmental stage at the time of exposure. The dose ranges associated with observable malformations in several species are summarized in Table 8.

126. The dose-response relationships for the induction of malformations are sigmoid and consistent with a deterministic mechanism. Protraction of a given dose reduces the incidence of each class of malformation below that expected as a consequence of the same dose given at the most sensitive stage. Careful experiments with a particular strain of mouse have shown that doses as low as 0.05 Gy at the most sensitive stage of embryonic development (seven days after conception) can triple the incidence of gross skeletal malformations [U4]. Malformations of the central nervous system have been particularly studied, and there is little evidence for any pathological responses at doses below 0.1 Gy (in mice, rats and primates) [U4]. Sterility was induced in 36% of female rats exposed to 0.5 Gy as embryos at nine days after conception [U4]. For the relatively less frequent effect of embryo lethality, rodents show an LD₉₀ of less than 1.5 Gy in the early stages of organogenesis, after which there is an increase with development until the fetal stages, which yield values little different from the postnatal LD₉₀.

127. There appear to be no studies of the effects of chronic irradiation specifically during major organogenesis. A single study of fractionated exposure in rats (four daily doses of 0.01 Gy at 6-9 days after conception) showed a significantly impaired learning capacity at four months of age in behavioural tests in which performance requirements were gradually increased [B19]. Mouse embryos have been exposed to beta radiation arising from a single injection of tritiated water to the mother at 12.5 days after conception, with the male offspring being given behavioural tests from 21 days of age. There was evidence of changes in behaviour, attributed to irradiation, at cumulative doses of 0.1 Gy and greater [W26]. Such a response could lead to reduced viability in the natural environment.

128. During the fetal period of development the main consequences of acute radiation exposure appear to be mortality, with LD₉₀ values similar to those for postnatal exposure, and disturbances of growth. Teratogenic effects become increasingly difficult to detect, although damage to the eye, the central nervous system and the gonads appear to be the main responses [C22, U4, U6]. Acute exposures up to 2 Gy to developing rats between six days after conception and eight days after birth induced no deficit in the immune response up to 12 weeks of age [P8]. Exposure of rats to 1.5 Gy (10-12 days after conception) caused germ cell killing; testis weight was reduced slightly by exposure on day 15 and became progressively more pronounced at later times, with the peak reduction for exposures between 18 days after conception and 3 days after birth [C15]. The weight deficit was due to the loss of spermatogenic cells in the tubules, but the endocrine function of the testis was unaffected. In another study, 2.5 Gy delivered to gravid rats on day 20 after conception caused sterility in 70% of the female offspring [K7].

129. Fractionated x-ray exposures (16 exposures of 0.12 Gy, twice weekly for eight weeks) produced severe damage to the ovaries of female bonnet monkeys when the irradiation was given 77-133 days after conception but produced very little response when given 48-104 days after conception [A3]. A single injection of tritiated water to the females on day 13 after conception was used to deliver total estimated doses of 1.3, 0.6 and 0.2 Gy to fetal mice. At two months of age, all male and 40% of female offspring were infertile at the highest dose, and at three months female fertility was declining, while there were signs of some recovery in the males [T16]. It was concluded that doses in excess of 0.5 Gy were required to affect fertility [U4]. A dose of 3 Gy delivered to female rats at 18,000 μGy h⁻¹ over the period 13-20 days after conception affected ovarian development (smaller ovaries, absence of follicles and corpora lutea) in offspring, whereas an acute dose of the same magnitude on day 18 after conception produced no response [E4].

130. Chronic radiation exposure throughout gestation is the more likely possibility in contaminated natural environments. Exposure of pig embryos to ⁶⁰Co gamma rays at 420 μGy h⁻¹ for 108 days during gestation (112 days duration) reduced the weight of the gonads in the offspring, and at 1,300 μGy h⁻¹ both female and male offspring were rendered sterile. Histological examination of the gonads showed reduced numbers of germ cells at a dose rate of 210 μGy h⁻¹ [E5]. Rat embryos exposed to tritium (as tritiated water) throughout development showed significant reductions in testis weight at an estimated dose rate of 1,300 μGy h⁻¹, and the ovaries were much reduced or absent at 2,500 μGy h⁻¹ [C9]. Exposure of female mouse embryos to tritium (as tritiated water) from conception to 14 days of age showed dose-dependent reductions in the numbers of oocytes, with a significant reduction (13%) in primary oocytes per ovary at an estimated dose rate of 10 μGy h⁻¹ and a reduction to two thirds of the control value at 100 μGy h⁻¹ [D7]. A later series of experiments produced similar results, with the additional finding that the largest part of the response was a consequence of the prenatal exposure and that the tritium beta particles were more effective than ⁶⁰Co gamma rays in producing the damage (an RBE of 1.9; see also paragraphs 117-119) [D8]. After irradiation at 420 μGy h⁻¹ during gestation, germ cell numbers were reduced relative to the controls in the following species
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[U4]: pig (1.1 Gy total dose), 1% (male), 5% (female); guinea-pig (0.62 Gy total dose), 41% (male), 71% (female); rat (0.21 Gy total dose), 50% (male). 90% (female); mouse (0.20 Gy total dose), 71% (male), 87% (female). As noted above, these reductions in germ cell numbers would not necessarily produce a corresponding reduction in fecundity.

131. A significant reduction in the birth weight (stunting) of female and male offspring was observed at 2.500 µGy h⁻¹ from tritium exposure (as tritiated water) during gestation in rats, and the brain weight was significantly reduced at 1.300 µGy h⁻¹ [C9]. A later experimental series [C10] showed significant reduction in brain weight in young born to mothers that had been exposed to 130 µGy h⁻¹ from tritium (3.7 x 10⁴ Bq m⁻³ as tritiated water in drinking water) since their own conception, through 100 days of postnatal life and the 21 days of pregnancy. Simultaneous exposures to graded concentrations of lead in drinking water showed that the interactive effects of these two contaminants were less than additive.

132. The relative effectiveness of tritium beta particles and external ¹³⁷Cs gamma irradiation in reducing cerebral development in rat embryos has been investigated [U4]. The range of estimated dose rates from tritium was 210-1,600 µGy h⁻¹, and cerebral mass at birth was negatively correlated with the cumulative dose during gestation. The ¹³⁷Cs gamma radiation was less effective in producing a response (RBE = 2.1 at 500 µGy h⁻¹ from ⁴⁺He). A dose rate of 1,300 µGy h⁻¹ (⁶⁰Co gamma rays) reduced the pre- and postnatal weight of the brain in pigs [U6]. No studies appear to have been made to determine whether such morphological responses have an associated impairment of function that might be significant in the natural environment: the few data noted in paragraph 126 are, however, suggestive of the potential importance of this response.

133. Damage to the developing mammalian embryo appears to be a potentially significant criterion of impact from contaminant radionuclides in the natural environment. Dose rates of 420 µGy h⁻¹ throughout gestation produce readily detectable reductions in the populations of germ cells in the developing gonads of a number of mammalian species, and the lowest dose rate at which damage has been seen is 10 µGy h⁻¹ from tritium (as tritiated water in drinking water) incorporated in female mouse embryos. In addition, dose rates of the order of 420 µGy h⁻¹ induce reductions in neonatal brain weight, although the significance of this deficit in functional or behavioural terms is unknown. The wider significance of these responses at the population level has not been investigated. Even recognizing that only very limited data are available, it may be concluded that maximum dose rates of 100 µGy h⁻¹ (2.4 mGy d⁻¹) to gravid members of a mammalian population are unlikely to have any consequences for the population as a whole from induction of damage in the developing embryos.

(d) Somatic and hereditary mutational effects

134. The substantial literature on the induction of mutations (genetic damage) in animals by radiation exposure has been thoroughly reviewed in previous reports of the Committee [U2, U3, U4, U5, U6]. The term mutation encompasses a wide range of damage to the genetic material, and its consequences depend on the nature of this damage and also on the site, i.e. in somatic tissue or in germ cells. In many cases, the damage is severe and incompatible with the survival of the cell as an entity with proliferative potential; the damaged cells die either immediately or after rather few division cycles. This form of damage is largely subsumed in the discussion above of mortality, effects on fertility and effects on the developing embryo. There remain the lesser forms of damage that are not inconsistent with the survival and subsequent long-term proliferation of the cells but which, nevertheless, have a potential to harm the host organism. In somatic cells, the consequence of concern is the induction of cancer [U4]; in germ cells, it is necessary to assess the potential impact on the fitness of offspring in the next and subsequent generations of animals and the potential implications for the population [U3].

135. It has already been noted (paragraph 110) that the chronic exposure of animals throughout their life reduces life-span, mainly by the induction of malignant tumours, although it was concluded that at dose rates less than 420 µGy h⁻¹ (10 mGy d⁻¹) the effect would be slight. The data for animals (mainly rats and mice) reviewed in the UNSCEAR 1986 Report [U4] show that there is a wide variation in the sensitivity to tumour induction depending on the tissue and on the species. Nevertheless, there is a consensus that at the dose rates likely to prevail in environments contaminated as a consequence of controlled discharges of radioactive wastes, a linear dose-response relationship would be appropriate for all qualities of radiation. This limited database makes extrapolation to other species, particularly those that are long-lived, uncertain. A review of data on the effects of chronic exposure to ⁶⁰Sr, ⁹⁰Y beta radiation in beagle dogs showed that cumulative chronic exposures up to about 7 Gy, either from a single injection to young adults or from a body burden accumulated via ingestion from the fetal stage (up to the mother) to 540 days of age, did not increase the incidence of cancer in either the bones or the adjacent soft tissues, and there was no significant reduction in life-span compared with controls; this corresponds to a mean dose rate of approximately 60 µGy h⁻¹. There was some evidence from effects at higher total doses that the age at commencement of exposure and the cumulative
dose profile influenced the outcome: for example, the dogs initially exposed in utero showed hematopoietic effects and soft tissue cancers that were not apparent in dogs commencing radiation exposure as young adults. Parallel experiments with internal exposure from $^{226}$Ra indicated that at the lowest doses causing a radiation-induced increase in bone sarcoma, the RBE (alpha radiation compared with beta radiation) was about 25 [N4]. In addition, the $^{90}$Sr body burdens that did not induce cancer also had no effect on the fertility or fecundity of the dogs. As pointed out above, effects on reproduction and on the developing embryo are more sensitive criteria, which leads to the requirement for lower maximal dose rates to individuals in mammalian populations. At lower dose rates the available data indicate that the incremental incidence of radiation-induced tumours is likely to be low and, therefore, of little significance at the population level.

136. Radiation-induced genetic changes in either somatic or germ cells include gross numerical aberrations (e.g., aneuploidy or polyploidy) or structural aberrations (translocations, deletions, duplications etc.) of the chromosomes as well as gene mutations (change in the nucleotide sequence in the DNA constituting the gene). If these occur in germ cells, they may be transmitted to the next generation progeny. In most cases, aneuploidy (at least for certain chromosomes) and polyploidy are incompatible with the production of viable embryos [U4, U5] and would reduce fertility or fecundity. Such effects would be included in the effects described above on reproduction and on the developing embryo. Both aneuploidy and polyploidy occur spontaneously in the oocytes and early embryos of a number of mammalian species, and there is evidence that the incidence increases with maternal age [U3]. Exposure of female mice to acute doses of 0.02-0.16 Gy produces no change in the incidence of either aneuploidy or polyploidy [M9]. The data for male mice indicate a slight positivity that the incidence of aneuploidy in offspring may be increased by the irradiation of sperm and spermatids, but there is no evidence that there is any effect from the irradiation of spermatocytes and spermatogonia [U5]. In the female Chinese hamster an acute exposure of 2 Gy is necessary to produce cytogenetic evidence for a marginal increase in the incidence of aneuploidy. Male northern field voles exhibit increased diplody in spermatids, which is dependent on dose in the range 0.25-2 Gy [U3]. It has also been noted that any effect that depleted the oocyte population (e.g., irradiation during embryonic development) could advance the maternal age effect for aneuploidy [U4]. Clear evidence has been presented of hyperhaploidy and structural anomalies in metaphase I oocytes from young adult mice that had received gamma-ray doses of 1, 2 and 3 Gy at a dose rate of 6,000 $\mu$Gy h$^{-1}$ between 4 and 8 weeks of age [G10]. Although the chromosome aberrations reported are probably not compatible with survival, lesser degrees of cytogenetically undetectable damage may have been present that could result in viable (but, perhaps, less fit) offspring. There appear to have been no studies of the effects of longer-term, lower-dose-rate exposure.

137. Reciprocal translocation (the mutual exchange of DNA between two non-homologous chromosomes) is the structural rearrangement that has received most attention. In the various rodent species that have been investigated, the induction rate in stem cell spermatogonia (assessed in cytological preparations of descendant spermatocytes) is 0.01-0.03 Gy$^{-1}$ at total doses up to 3 Gy of acute low-LET exposure [U3]. Alpha irradiation of male mice for 5-8 months from $^{239}$Pu taken up into the testes (36 $\mu$Gy h$^{-1}$) increased the incidence of reciprocal translocations (derived from irradiated spermatogonia). Acentric fragments (from irradiated spermatocytes) and dominant lethality (determined from post-implantation embryo mortality); an RBE of 22-24 relative to $^{60}$Co gamma radiation was estimated [S50]. In non-human primates the induction rate was 0.01-0.078 Gy$^{-1}$ at doses up to 1 Gy [M19]. The magnitude of the potential sparing effect of low-dose-rate exposure appears to be species-dependent, and the incidence could be lower by a factor of 3-10 [U4]. The gametes resulting from a spermatogonal stem cell containing a reciprocal translocation are produced (assuming random segregation through meiosis) in the proportions 1:1:2 of balanced-normal, balanced-translocated and unbalanced, respectively [S21. U6]. The mortality associated with the output of sperm with an unbalanced chromosomal constitution would be included in the reduction of fertility/fecundity noted above. For offspring heterozygous for the translocation, the total production of gametes will have chromosome constitutions in the proportions given above, so these offspring would be expected to be semi-sterile (and are often found to have even lower fertility) [U6]. The likely low incidence of such individuals means that the consequences for the overall fertility of the population would be less than the consequences arising from the direct effects of radiation on gametogenesis. Experiments with female mice have shown that the great majority of chromosomal aberrations induced in pre-ovulatory oocytes were eliminated through pre-implantation and early embryonic mortality. Again, the effects on fertility/fecundity would be included in the responses already discussed.

138. The final class of genetic changes includes gene mutations that are inherited in a simple Mendelian fashion. Detectable by their phenotypic expression in the offspring of irradiated parents or by conducting appropriate breeding experiments. they include recessive visible, recessive lethal, dominant visible, dominant skeletal and dominant cataract mutations. The available data permit estimates for specific types of
mutation. For instance, at doses up to 6 Gy, recessive mutations at seven specific gene loci in the mouse are induced at a rate of about 5 $10^4$ Gy$^{-1}$ locus$^{-1}$ at a dose rate of 5,000 $\mu$Gy h$^{-1}$, and dominant mutations causing either skeletal abnormalities or cataracts are induced at rates of 4 $10^4$ Gy$^{-1}$ gamete$^{-1}$ and 2.6 $10^4$ Gy$^{-1}$ gamete$^{-1}$, respectively, at low dose rates [S21, S43, U7].

139. Acute, sublethal whole-body irradiation of male mice or localized testicular irradiation over a number of generations has been shown to reduce the reproductive fitness of subsequent unirradiated progeny [G5, G6, S32]. This has been attributed to the accumulation of recessive mutations that, even in the heterozygous condition, combine to produce the observed response. The mean survival time under chronic irradiation (50,000 $\mu$Gy h$^{-1}$) of mice with accumulated ancestral paternal irradiation was also lower than in controls, and simple breeding tests appeared to indicate that the characteristic was recessive in nature [S32].

140. Classical population genetics assumes that some mutations arising from increased radiation exposure would lead to a reduction in fitness (even for recessives present in the heterozygous state) and therefore have an adverse impact on the population. Selection pressure would tend to eliminate the induced mutations from the population over a number of generations inversely related to the specific reduction in fitness. At some stage (with constant radiation exposure of the population over time) a new equilibrium between mutation and selection would emerge, with a slight change in the population age-dependent mortality rate owing to the genetic changes. Laboratory studies of irradiated populations have not shown unambiguous evidence for reduced fitness from an increase in the incidence of this class of radiation-induced mutations [B17, G9, U7]. While the available data suggest a very limited mutational impact at the levels of radiation to which wild populations in contaminated environments are likely to be exposed, it should be noted that the genetic constitution of these laboratory populations is rarely comparable to that of their wild cousins. In these circumstances, the finding should be extrapolated to the natural environment with caution.

141. There have been a number of investigations of possible genetic damage in the somatic cells of mammals subjected to increased irradiation from Chernobyl fallout (primarily caesium radionuclides). The incidence of micronuclei (indicative of the presence ofacentric chromosome fragments) in the erythrocytes of wild house mice was found to be increased, relative to earlier controls, during and after the fallout from the Chernobyl accident at a site north of Rome, Italy, where about 1 kBq m$^{-2}$ of $^{137}$Cs was deposited. The frequency of micronuclei was found to be positively correlated with the $^{137}$Cs body burden (up to 45 Bq kg$^{-1}$). Although no quantitative dosimetric data were given, it was concluded that the dose rate implied by the body burden was insufficient to account for the increased numbers of micronucleate cells [C11]. It could only be suggested that the (unknown) dose rate from external sources might have provided the necessary additional exposure. The external dose rate from $^{134}$Cs (even including $^{134}$Cs), however, would probably have been within the normal variation in the natural background radiation at this location. Indeed, dose estimates from a subsequent study [C12] confirm that the total dose (external plus internal) from $^{134}$Cs and $^{137}$Cs would have been only about 5% of the natural background dose rate.

142. A second study by the same researchers was conducted in areas of much higher Chernobyl fallout in Sweden. The bank vole (Clethrionomys glareolus) was used as the experimental animal, and estimates were made of the dose rates from internal and external sources of both $^{134}$Cs and $^{137}$Cs. The beta component of the radiation from internally deposited caesium radionuclides was the major source of exposure (52%-71%), with external gamma irradiation providing most of the balance. The estimated dose rates (in addition to 0.17 $\mu$Gy h$^{-1}$ assumed for the natural background) at the four sampling sites were 0.01, 0.2, 1 and 1.5 $\mu$Gy h$^{-1}$. The body burdens of $^{134}$Cs and $^{137}$Cs showed substantial variation at each site (coefficients of variation in the range 62%-138% for $n = 22-38$ animals), and the dose rates received by the individual animals would therefore be expected to show a similar substantial variation (the longer-term accumulated doses might show less variation owing to fluctuations of individual body burdens over time). The incidence of micronucleate erythrocytes, although varying greatly in any given exposure group, correlated well with the mean dose rate [C12]. Ludwików [L11], however, was unable to demonstrate such a clear-cut dose-response relationship for the incidence of micronuclei in larger numbers of peripheral blood cells (rather than bone marrow cells) in a laboratory study employing the same species.

143. The incidence of chromosome aberrations was determined in the peripheral blood of semi-domesticated reindeer living in areas of Norway with differing degrees of Chernobyl fallout contamination. If age is disregarded, the frequency of aberration was not correlated with the incremental dose rates estimated for the different areas. In calves from the most contaminated area, where dose rates were about 8-9 $\mu$Gy h$^{-1}$ in 1986-1987, falling to 4-5 $\mu$Gy h$^{-1}$ in 1989-1990, the incidence of two break events (dicentrics, rings) was, however, significantly higher than in calves from other areas, and for this area the reindeer born in 1986 showed a higher incidence than older animals. In a positive control experiment in which 7-8-month-old reindeer calves were fed $^{134}$Cs at four different rates for 23 weeks, there was a significant dose-dependent
increase in chromosome aberrations relative to the controls [R8].

144. A range of data has been obtained concerning the genetic damage induced by increased radiation exposure of the germ cells of male wild house mice captured at different sites within the 30-km zone of the Chernobyl nuclear power station. The external gamma-radiation dose rates at the capture sites were in the range 0.2-2,000 μGy h⁻¹ (if the data given above for the bank vole are applicable, the total dose rate, inclusive of internal exposures, might be greater by a factor of 2-5). Wild male mice were mated to females of a laboratory strain to determine the incidence of dominant lethality (embryonic mortality). For males captured in 1986 there was no consistent relationship between dose rate at capture (0.5-500 μGy h⁻¹) and observed embryo mortality. In the following year, in addition to the three sites used previously, another site with higher dose rates was sampled. There, at dose rates of 1,700-2,100 μGy h⁻¹, two of the captured males produced no offspring and were concluded to be sterile, and the remainder showed a period of temporary infertility and reduced testes mass, which, however, recovered with time after capture. The only group for which embryo mortality (post-implantation) differed significantly from the rather uniform overall picture consisted of the litters sired by males within two weeks of capture from the high-dose-rate site, i.e., litters resulting from sperm which were at the postmeiotic stages at the time of irradiation [S22]. For all the mice collected at the three or four sites in 1986 and 1987, respectively, there was a dose-rate-dependent increase in the incidence of reciprocal translocations scored in spermatocytes at meiotic metaphase I [S22].

145. The results of these four studies [C11, C12, R8, S22] confirm that incremental exposure from: contaminant radionuclides will, as expected, induce genetic changes in both somatic and germ cells in populations of wild mammals. The rather limited nature of the dosimetric data provided makes it difficult to compare these results with the outcome of laboratory studies. In addition, the reports provide no indication of the consequences of the damage for the respective populations. At the two most highly contaminated sites in the Chernobyl 30-km zone, the total dose rates are likely to have been greater than those suggested in paragraphs 126 and 133 as limits for the maximally exposed members of populations in areas subject to controlled contamination from waste disposal practices. It may be concluded that the lower dose rates were completely consistent with the survival of the populations, although it would be desirable to have more data, particularly on population attributes, including such factors as immigration from areas of lower contamination.

2. Birds

146. A review of the effects of ionizing radiation on birds was compiled by Melling and Schulitz [M2]. Wild birds appear to exhibit LD₉₀ values that are in the same general range as small mammals (5-12 Gy). Domestic poultry are reported to exhibit an LD₉₀ₐₙₐₖ of 9 Gy [B2].

147. Studies of radiation effects on the young of three species of wild birds, tree swallow (Tachycineta bicolor), eastern bluebird (Sialia sialis) and house wren (Troglodytes aedon), showed progressively reduced growth following acute doses to hatchlings of 0.9 to 6 Gy [Z2]. The young birds were irradiated and returned to their nests in the field and observed over the 16-day period until fledging. There was no radiation-induced mortality during the nesting period. No observation could be made of possible life-shortening. Doses of 4 and 6 Gy had statistically significant effects on body mass, with reductions of 10% and 13%, respectively, and also on primary feather length and foot length. A dose of 2.6 Gy had less effect, and 0.9 Gy had little effect on initial growth and development [Z2]. In subsequent similar experiments with tree swallows, the growth data were fitted to the von Bertalanffy growth model. The parameter values from this fit showed that doses of 2.7 and 4.7 Gy to the newly hatched nestlings produced significant growth depression, particularly in body mass: the irradiation also influenced the development time [Z4]. In domestic fowl irradiated at 2 days of age, the growth rate over the subsequent 30 days was reduced at all doses but only significantly so at doses greater than 6.7 Gy [B6].

148. From limited data it has been suggested that the juvenile bird is more resistant to radiation than the adult [Z2]. The lethal dose for the eastern bluebird nestling is given as 30 Gy [W4]. In young chickens exposed at age 3-4 days, however, the LD₉₀ₐₙₐₖ was determined to be 7-11 Gy (exposure time less than 1 hour) and 12-20 Gy (exposure time of 24 hours) [S3].

149. The effects of acute radiation on the developing avian embryo have been investigated for the black-headed gull (Larus ridibundus) and the domestic chicken [P6]. The eggs were irradiated at day 10 of development and incubated artificially. The LD₉₅ₐₙₐₖ at hatching for the two species were determined to be 12-13 Gy and 9 Gy, respectively. For the developing tree swallow (Tachycineta bicolor) irradiated at days 7-8 and incubated naturally, total doses up to 3.4 Gy did not affect hatching or fledging success, but the time to hatching increased and growth was depressed at doses greater than 1.6 Gy [Z3].

150. No data appear to have been obtained at acute doses less than 0.5 Gy, but for most of the responses
that have been studied, damage is detectable only at higher doses. Studies of effects of chronic exposures are limited. The nesting success of birds was studied in field experiments with chronic irradiation from large gamma-ray sources. Exposure rates of 8,400-42,000 μGy h⁻¹ caused embryonic mortality [B7, W14, Z2], while no apparent effects were detected at 30-260 μGy h⁻¹ [Z5]. Tree swallows (Tachycineta bicolor) occupied nesting boxes independently of radiation exposure in the range from natural background to 6 μGy h⁻¹. The breeding performance over the season was unaffected by the radiation exposure and the production of fully-fledged young was comparable with controls. These results indicate that the population is unlikely to suffer adversely at annual doses up to 50 mGy [Z6]. Chronic irradiation of developing chicken embryos at dose rates greater than 10,000 μGy h⁻¹ until hatching destroyed the process of spermatogenesis and prevented the production of any resting oocytes, effectively sterilizing both sexes [M12]. Thus, while the chronic dose rates causing effects on embryonic development in birds (8,000-10,000 μGy h⁻¹) have been determined, the minimum dose rates that may cause other clearly evident effects have not been.

3. Reptiles and amphibians

151. Studies of reptiles and amphibians suggest that these groups may have a radiosensitivity similar to that of mammals and birds when the observation period is appropriate for registering the incidence of radiation-induced mortality. Frogs, salamanders, turtles, snakes and lizards yield LD₉₀ values of 2-22 Gy. The cause of death has usually been identified as damage to the haemato poetic system. with mean survival times after irradiation ranging up to 190 days [C13, C14, D9, T12]. For one species of lizard (Uta stansburiana) two separate studies gave LD₉₀ values of 10-12 Gy [D9] and 17-22 Gy [T12]. Differences in radiation quality, dose rate and maintenance conditions were offered as explanations for the different results [T12]. In addition, since it is not evident from the data presented that the short observation period encompassed all the acute radiation mortality, the lethal dose may have been overestimated. An acute exposure of 50 Gy caused temporary sterility in males of this species of lizard, but recovery to normal proportions of spermatogenic stages was well advanced by day 48 after exposure [D9]. Exposure of adult males and females sampled from a natural population to an acute dose of 4.5 Gy to the gonads (head and thorax shielded) resulted in a substantial reduction after release in the production of offspring in the year of irradiation. This in turn reduced the density of adults in the following year (i.e. there was no compensating increase in survival), but by the second year both natality and population density were recovering to control values [T13].

152. An acute dose of 10 Gy was found to be 100% lethal for four species of amphibians. Although only one species showed an LD₉₀ less than 10 Gy. Using data from the literature for two other amphibian species and estimates of the interphase chromosome volume and assuming a linear relationship between interphase chromosome volume and radiosensitivity, LD₉₀ values in the range 8-36 Gy were calculated. Extending the observation period to encompass all the radiation-induced mortality (up to 200 days for one species) at total doses less than 10 Gy yielded lower estimates for LD₉₀ values, in the range 0.8-7 Gy. The interphase chromosome volume appears to be a potentially useful indicator of radiosensitivity [S33]. Adult toads, juveniles and tadpoles showed different radiosensitivities, with estimated LD₉₀ values of 24 Gy, 10 Gy and 17 Gy, respectively. After extending the observation time, the adult LD₉₀ declined slightly to 18 Gy, but the sensitivity of the juveniles and tadpoles was much increased, with both showing an LD₉₀ of 0.1 Gy. In addition, irradiated tadpoles failed to metamorphose [L9]. A toad species exhibiting LD₉₀ values of 22 and 20 Gy, respectively, showed greater survival after 15 Gy if they were allowed to hibernate than if they were kept active. An acute dose of 15 Gy to a natural population as they emerged from hibernation in the spring had little impact on breeding activity, feeding or preparation for hibernation in the following autumn. There was, however, a marked reduction in survival, independent of age and sex, in the population emerging from hibernation one year after irradiation [T18]. A single report [B18] provides evidence for the induction of abnormalities in, and reduced survival of, offspring after paternal exposure of toads to acute doses of 3-20 Gy.

153. There are relatively few data on the effects of chronic irradiation on reptiles and none, apparently, for amphibians. The data for lizards were obtained in field experiments with large gamma-ray sources. A population of Uta stansburiana exposed to average tissue doses of 830 μGy h⁻¹ showed a sex ratio. A maximal life-span and an age distribution that were not significantly different from those of control populations over a period of five years [T8]. An earlier study of the same system had indicated differences between irradiated and control lizards in growth (length and weight) of young of the year, but this response could not be confidently attributed to the direct effects of radiation exposure; an indirect effect mediated by damage to plants was suggested as one possible cause. But non-radiation environmental factors could also have been involved [T14].

154. Observations have also been made of two other longer-lived species of lizard, Crotaphythus wislizenii and Cnemidophorus tigris, that received approximate annual exposures of 4-5 Gy and 2-2.5 Gy, respectively.
in the irradiation facility [T15]. After 3.5 years of exposure, demographic data and the failure of mature female Crotophytus to assume reproductive coloration indicated a lack of reproduction in this species. Direct observations after 5.5 years of exposure showed that the ovaries had regressed completely. At this time, one of three irradiated males was also found to be sterile. Control males and females of the same age were reproductively normal. Similar responses became apparent in Crnemiophorus some two years later than for Crotophytus; the delay simply reflects the lower average dose rate experienced by the latter species. These results underline the significant degree to which demographic (and behavioural) factors determine the relative responses of populations of animals to a given degree of chronic radiation exposure [F5, T15].

4. Invertebrates

155. A very large database exists for radiation effects on invertebrates, especially on insects. O'Brien and Wolfe [O1] prepared a monograph on the subject and concluded that insects are, in general, far less sensitive to radiation than vertebrates. This conclusion should be tempered by the following considerations concerning differences in physiology and in life cycles. For the vertebrates, there are more or less clearly definable ranges of acute absorbed dose for which the post-irradiation survival time is relatively independent of an increase in dose and that correspond to the induction of damage in specific organs or cell systems (in order of increasing dose and earlier expression time, these are the bone marrow, intestinal and neurological syndromes) ([U3], Annex G). For the mammals, there is virtually no acute (short-term) radiation mortality at doses below those that affect the haematopoietic system, and essentially all the mortality from bone marrow damage is expressed within 30 days; hence the LD₁₀₀ is justified and commonly employed as a comparative measure of radiosensitivity. As noted in paragraph 151, longer times (up to 190 days) are necessary to encompass the (low-dose) acute mortality in reptiles. A similar qualification on the use of LD₁₀₀ values has been made with respect to aquatic organisms [W15]. The presence of substantial physiological variations between the different groups of organisms means that the LD₀₉₀ₐ₀, for all its practical convenience, provides an insecure basis for comparing radiosensitivity across a wide taxonomic range. This is not to say that there are not very real differences in radiosensitivity but that these might not be as great as they appear from the comparisons made so far. For example, the apparent low radiosensitivity of many adult insects has been ascribed to the fact that very little cell division and differentiation is in progress, i.e. there is no direct physiological basis for the equivalents of the bone marrow (haematopoietic) and intestinal syndromes. In these circumstances it may be that the appropriate comparison should be with the neurological syndrome in mammals, for which a lesser differential radiosensitivity would be apparent.

156. The life expectancy of 12 species of arthropods (11 insects and 1 isopod) were significantly reduced at doses greater than 80 Gy, and for 6 species a 50% reduction in mean life-span was induced by doses between 20 and 40 Gy [M13]. Acute irradiation of invertebrate populations in soil samples showed that the survival of the majority of the identifiable taxonomic groups was less than 50% of the control values at acute doses less than 100 Gy [E6]. In both studies the qualitative observation was made that the radiosensitivity of the organisms increased with their activity. Adult earwigs (Elaphrus foetida) were found to be less sensitive to acute irradiation (LD₀₉₀ about 650 Gy) than juveniles, for which growth was completely inhibited at 100 Gy, and developing embryos, for which 20 Gy delivered soon after the ova were deposited in the cocoons (i.e. early in embryogenesis) significantly reduced hatching success. A dose of 20 Gy to mature adults also affected the hatchability of eggs produced subsequently, depending on the time between irradiation and egg deposition [S34]. A second species of earwigs (Lumbricus terrestris) also appeared to be unusually radiosensitive, with an LD₀₉₀ of 680 Gy for acute gamma irradiation at a dose rate of 290 Gy h⁻¹ [R3]. The LD₀₉₀ for pill bugs (terrestrial isopod crustaceans) was about 300 Gy, but after 60 days, when essentially all of the acute mortality had been expressed, the median lethal dose had fallen to about 50 Gy. The survivors of the latter exposure grew and mounted normally, and one female laid eggs that developed into fertile adults [N5].

157. The reproductive tissues in adult insects are one system in which significant cell division, i.e. gametogenesis, is in progress, and these tissues can be damaged at much lower acute doses than those leading to mortality. This circumstance forms the basis for the production of radiation-sterilized but otherwise perfectly viable male insects in large quantities for release in pest control programmes. Three examples from a voluminous literature will serve to illustrate the kind of data available. The exposure of mature pupae or adult coding moths to 300-400 Gy completely sterilized the females and reduced male fertility to less than 10% of control values without seriously influencing behaviour except for substantially reducing sperm competitiveness. This reduced male fertility lessened the impact of released irradiated males on population growth unless a high sterile:wild male ratio of 20:1 was maintained. Doses below 250 Gy had a smaller effect on male fertility (15% of control), but the males showed much improved overall mating competitiveness (sperm competitiveness, satisfaction of female mating drive and induction of normal oviposition), with the added advantage that there
was an increased incidence of infertility in otherwise normal $F_1$ males. The release of irradiated males when the natural population was emerging from overwintering and again in mid-summer provided effective control but did not eliminate the pest [P9]. Similar results were obtained in the case of the spruce budworm [E7]. The red palm weevil was found to be much more radiosensitive. At 15 Gy to one-day-old males induced 90% sterility. The effectiveness of these males in population control was again limited by a decline in mating competitiveness, owing partly to a 10%-20% reduction in adult longevity and partly to reduced sperm production [R9]. In all three cases it is clear that even drastic radiation effects on the reproductive capacity of a proportion of the individuals in the population would have only a limited effect on the total population unless they were being induced extensively in space and time.

158. Like the reproductive tissues in adult insects, juvenile insect forms are much more sensitive to the lethal effects of radiation, as would be expected from the high cell turnover rates in these age classes. These findings reduce, but do not eliminate, the extent of the differential radiosensitivity between vertebrates and insects. Many factors have been shown to modify the response of insects to radiation; it is, however, very unlikely that insect species more sensitive than vertebrates to either the lethal or (more important in the environmental context) the reproductive effects of radiation will be discovered.

159. Some relatively high LD$_{50}$ in insects have been reported after short observation periods (e.g. at 1 day or within 3-4 days). Latency periods of these lengths may occur before damage is observable [V1]. Dose-rate effects have also been reported. For example, the LD$_{50}$ in young adult crickets (Acheta domestica) is about 50 Gy for dose rates above 2 Gy h$^{-1}$. At 0.3 Gy h$^{-1}$, however, a 50 Gy dose causes only 10% mortality in 20 days [V2]. Larger, longer-lived insects may be more sensitive than smaller, shorter-lived ones.

160. There may be considerable differences in sensitivity in the different stages of insect growth. In general, radiosensitivity decreases as development proceeds from egg to adult stage. Van Hook [V1] reported the LD$_{50}$ for eggs of the grasshopper Melanoplus sanguinipes to be 4 ± 1 Gy and the first nymphal instar to be one third less sensitive. The LD$_{50}$,8 for the various stages of growth were 13 Gy (first and third instar), 7 Gy (second instar) and 8 Gy (fourth instar and adult) [V1]. For the soil arthropod Collembola, the egg is 10 times more sensitive than the adult. The LD$_{50}$ values were reported to be 150-300 Gy for the adult insect, 130-230 Gy for the juvenile stage and 15 Gy for the egg [S6]. An exposure of 30 Gy had little impact on Collembola population growth over three generations (16 days), but 70 Gy delayed the commencement of the exponential growth phase and at 16 days the population size was approximately half that of the controls [A7]. In invertebrates as well as mammals, populations may be more affected by reduced fecundity and egg mortality than by the death of irradiated individuals.

5. Summary

161. Data on radiation sensitivity of terrestrial animals are dominated by data on mammals. The most sensitive class of organisms. Acute lethal doses (LD$_{50}$) are 6-10 Gy for small mammals and 1.5-2.5 Gy for larger animals and domesticated livestock. When a total dose of similar magnitude to the LD$_{50}$ is delivered over the lifetime, for example 7 Gy to the mouse (420 μGy h$^{-1}$, or 10 mGy d$^{-1}$), the average loss of life-span has been estimated to be about 5% and would result from the induction of neoplastic disease [U5]. There is substantial interspecies variability but, in general, little indication that dose rates below about 400 μGy h$^{-1}$ to the most exposed individual would seriously affect mortality in the population.

162. Reproductive capacity is more sensitive to the effects of radiation than is life expectancy (mortality). The reproductive rates of mammals may be depressed at doses that are 10% of those leading to mortality. Some loss of oocytes may occur at 1% of the lethal dose, but because of excess oocyte production, fecundity should be affected to a lesser extent. Exposed from conception to a dose rate of 800 μGy h$^{-1}$, mice can be made sterile at 25 weeks. In the most sensitive mammal studied, the beagle dog. 180 μGy h$^{-1}$ caused progressive cell depletion and sterility within a few months, but exposure at 36 μGy h$^{-1}$ over the whole life produced no damaging response. It is concluded that a radiation dose rate of less than 40 μGy h$^{-1}$ to the most exposed individual in a population (and most probably, therefore, a lower mean dose rate to individuals in the population as a whole) would be unlikely to have an impact on the overall reproductive capacity of a mammalian population as a consequence of effects on fertility, fecundity or the production of viable offspring.

163. Radiation effects in birds have been shown to be similar to those in small mammals. Reptiles and invertebrates are less radiosensitive, although physiological differences begin to make more direct comparisons with other species less appropriate. The chronic exposure of one short-lived species of lizard in enclosures has shown no evident effects over 5 years at 830 μGy h$^{-1}$. In two longer-lived species of lizard, some individuals were made sterile after 3.5 years at 630 μGy h$^{-1}$ in one species and after 5.5 years at 210 μGy h$^{-1}$ in another species. Adult invertebrates are seemingly quite insensitive to the effects of radiation exposure in terms of induced mortality, but gametogenesis, developing eggs and juvenile stages are more sensitive.
C. AQUATIC ORGANISMS

164. There have been a number of reviews of the studies of the effects of ionizing radiation on aquatic organisms [A2, B4, C1, E1, I2, I3, N1, N3, P4, T6, W9]. A number of these were prepared specifically to provide a basis for assessing the potential effects of discharges of liquid radioactive effluents on aquatic organisms in their natural environment [I2, I3, N1, N3, W9]. In consequence of these many reviews, it does not seem necessary to repeat the exercise here; there have been no more recent reports of results that would alter the general conclusions. It will be sufficient, therefore, to mention the relevant conclusions, accepting that the supporting evidence has been thoroughly examined.

165. It has been concluded that, among the many non-mammalian phyla represented in aquatic environments, fish are the most sensitive to acute radiation exposure; the developing fish embryo is particularly so. The LD_{90} values for 10 marine invertebrates were found to be in the range 2.1-1500 Gy; extension of the assessment period to 60 days reduced this range to 2-680 Gy, and the median lethal doses for the apparently most radioreistant species were still declining [E8, W15]. A similar situation was found for six species of marine fish, in which the range of LD_{90} declined from 11-56 Gy at 30 days to 9-23 Gy at 40-50 days [W15]. The LD_{90} for developing fish embryos can, however, be much lower. Irradiation of silver salmon embryos at the single-cell stage yielded estimated LD_{90} of 0.30 Gy at hatching and 0.16 Gy at a larval age of 90 days; the radiosensitivity decreased with embryonic development [B23]. Other fresh-water fish that have been studied appear to be less sensitive [W9]. A single LD_{90} value of 0.09 Gy was determined for a marine flatfish species (the plaice) irradiated at the blastula stage and assessed at metamorphosis [W22]. When account is taken of their poikilothermic nature and generally lower metabolic rate, fish appear to be somewhat more radioreistant than mammals, but there is substantial overlap in sensitivities. While no data are available for the marine mammals, there is no reason to suppose that they would exhibit radiosensitivities substantially different from those of terrestrial mammals.

166. Exposure of adult female loach (family Cobitidae, related to the carps) to whole-body exposures of 2.5, 5.0 and 10 Gy produced only very slight effects in mature oocytes at the highest dose. For an exposure of 20 Gy, a clear response was obtained in both developing and mature oocytes; a lesser response was obtained by exposure of the head alone (i.e. the ovary was shielded), and this was attributed to a radiation-induced reduction in gonadotropin secretion from the pituitary gland [E9]. Doses as low as 1 Gy caused a temporary reduction in testes weight in mature medaka (rice fish, Oryzias latipes), and slight effects on spermatogonial proliferative...
[B24]. A dose rate of 220,000 μGy h⁻¹ from ⁶⁰Co gamma rays, giving a median lifetime dose of approximately 120 Gy, had little effect on the age-specific survival of *Daphnia pulex* populations receiving a fixed per capita food supply, and there was little effect on life expectancy at birth at the higher dose rate of 760,000 μGy h⁻¹ [M15]. However, in food-limited populations of *Daphnia* (that is, populations under additional stress competing for food), the total death rate, including prenatal mortality, was increased at 35,000-45,000 μGy h⁻¹ [M16]. The mortality of blue crabs (*Callinectes sapidus*) was greater than that of the controls after 50 days exposure to ⁶⁰Co gamma rays at a dose rate of 290,000 μGy h⁻¹ (total dose 330 Gy), whereas a dose rate of 32,000 μGy h⁻¹ had no effect [E11].

169. Exposure of medaka to tritiated water or external ³⁷Cs gamma radiation during embryonic development (average 9.1 days from three hours after fertilization to hatching) at dose rates between 18,000 and 79,000 μGy h⁻¹ had little effect on hatching rate. Larval survival to one month of age was, however, consistently and significantly decreased at dose rates above 35,000 μGy h⁻¹ for tritium beta particles and at the highest dose rate for gamma rays. The incidence of vertebral anomalies was increased for all dose rates from ³⁷Cs (i.e. >18,000 μGy h⁻¹) but only at dose rates above 35,000 μGy h⁻¹ from tritium [H16]. Dose rates in the range 14,000-54,000 μGy h⁻¹ from ⁶⁰Co gamma rays to mosquito fish (*Gambusia affinis*) at either 15 or 25°C for 40 days (total doses 12.5-50 Gy) induced no increased mortality relative to the controls [C17]. Limited data (small samples) have also been obtained for the guppy (*Poecilia reticulata*). Six pairs of fish exposed to ³⁷Cs gamma rays at 13,000 μGy h⁻¹ for 238 days (72 Gy total dose) experienced no mortality. For pairs of fish at the lower dose rates of 4,000 and 1,700 μGy h⁻¹ (771 and 974 days respectively), the onset and extent of male mortality (470 days and 6 of 9; 230 days and 4 of 10, respectively) differed from the controls (520 days and 3 of 12). For the females, there were no deaths among the controls, 1 from 10 (570 days) at 1,700 μGy h⁻¹ and 2 from 9 (onset at 450 days) at 4,000 μGy h⁻¹. Because of the small numbers involved, these results provide no more than an indication of possible radiation-induced mortality [W9].

170. Small groups of the marine polychaete worm *Ophryotrocha diadema*, which is hermaphroditic but not self-fertile, were exposed to chronic ³⁷Cs gamma radiation (1,700, 3,200, 7,700 and 14,000 μGy h⁻¹) over seven generations and the breeding performance recorded. No effects were seen on growth rate or time to first egg laying, but the reproductive performance was affected in all generations. In generation 1, the number of egg sacs, eggs and larvae produced were only reduced at the highest dose rate, but in generations 2 and 3 the reductions were clearly dose-rate-depen-
organisms was similar to that of the much more intensively studied mice and fruit flies. Recent investigations of mutation induction at a single specific locus in the progenial and gonial germ cells of the zebrafish appear to indicate that this species, at least, might be considerably more radiosensitive than the mouse. It was deduced that most of the mutations were due to long deletions and suggested that they occur relatively frequently in progenial cells because the rapidity of cell division reduces the possibility of repair [C20, W23]. A second specific locus test system has been developed based on the fact that strains of the medaka homozygous recessive at either 1 or 3 autosomal loci have a phenotypic expression (colour. or lack thereof) that can be recognized in the first half of embryonic development through the transparent egg membrane. The incidence of dominant lethals (per gram per gamete) from exposure of medaka sperm appears to be similar to that from exposure of the mouse. but the spermatids appear to be less sensitive. Many of the observed radiation-induced colour mutants were not viable (i.e. they were also carrying dominant lethal mutations). As in the mouse. however, some of the colour mutants were viable. showing that the medaka sperm. spermatids and spermatogonia have a radiation sensitivity for mutation induction similar (i.e. within the uncertainties) to that in the corresponding spermatogonic stages in the mouse [S44]. A study of the production of chromosome (mainly chromatid) aberrations in cultured blood cells from the central mudminnow (Umbrina limi) by exposure to either tritiated water in the culture medium or chronic Cs gamma irradiation showed these cells to be somewhat less radiosensitive than human lymphocytes (by a factor of approximately 5), and a value of 1.9 was estimated for the RBE [S35].

174. Summary. Among aquatic organisms. fish are the most sensitive to the effects of radiation. and developing fish embryos are particularly so. The LD_{50} for acute irradiation of marine fish is in the range 10-25 Gy for assessment periods of up to 60 days following exposure. The upper end of the range of LD_{50} for marine invertebrates has been found to be several hundred gray. Embryos. on the other hand. are affected at much lower doses. e.g. LD_{50} of 0.16 Gy for salmon embryos [B23].

175. For chronic exposures. dose rates of 10,000-30,000 μGy h^{-1} have had no effect on mortality for snails. marine scallops. clams and blue crabs. Dose rates somewhat above this range had some effects in food-limited populations of Daphnia pulex. Short-term (40 days) exposure of mosquito fish at dose rates in the range 14,000-54,000 μGy h^{-1} showed no radiation-induced mortality. but for the closely related guppy, there was some indication that long-term exposure (>470 days) at dose rates above 1,700 μGy h^{-1} reduced the normal life-span. particularly for males.