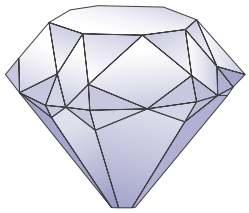
FASSET



Framework for Assessment of Environmental Impact

Deliverable 4

Radiation Effects on Plants and Animals

June 2003

Edited by

Dennis Woodhead, CEFAS, and Irene Zinger, EA

A project within the EC 5th Framework Programme

Contributors

D. P. Daniel, Westlakes; J. Garnier-Laplace, IRSN; M. Gilek, SU;
U. Kautsky, SKB; C.-M. Larsson, SSI; J. Pentreath, UR; A. Real, CIEMAT;
H. Skarphedinsdottir, SU; S. Sundell-Bergman, SSI; Thørring, H., NRPA;
D. S. Woodhead, CEFAS; I. Zinger, EA

FASSET will bring to radiation protection a framework for an assessment of the environmental impact of ionising radiation arising from human activities. The framework will link together current knowledge about sources, exposure, dosimetry and environmental effects/consequences for reference organisms and ecosystems. Relevant components of the framework will be identified on an ecosystem basis through systematic consideration of the available data. The application of the framework in assessment situations will be described in an overall report from the project. The project started in November 2000 and is to end by October 2003.

Proposal No: **FIS5-1999-00329**
Contract No: **FIGE-CT-2000-00102**
Project Coordinator: **Swedish Radiation Protection Authority**

Contractors:

Swedish Radiation Protection Authority	SSI
Swedish Nuclear Fuel and Waste Management Co.	SKB
Environment Agency of England and Wales	EA
German Federal Office for Radiation Protection	BfS
German National Centre for Environment and Health	GSF
Spanish Research Centre in Energy, Environment and Technology	CIEMAT
Radiation and Nuclear Safety Authority, Finland	STUK
Norwegian Radiation Protection Authority	NRPA

Assistant Contractors:

Kemakta Konsult AB, Sweden	Kemakta
Stockholm University, Sweden	SU
Centre for Ecology and Hydrology, UK	CEH
Westlakes Scientific Consulting Ltd, UK	WSC
Centre for Environment, Fisheries and Aquaculture Sciences, UK	CEFAS
University of Reading, UK	UR
Institute for Radioprotection and Nuclear Safety, France	IRSN

Executive summary

The objective of this part of the FASSET project is to develop the tools to allow an effects analysis of the possible impacts of increased radiation exposure in the environment.

Chapter 1 considers the elaboration of this objective in terms of:

- the aim of protecting the environment from any increase in radiation exposure arising from human activities, primarily the waste management activities associated with the nuclear fuel cycle;
- the relevant biological effects;
- the dose - response relationships; and,
- the organisation of the available information.

It also summarises previous work by the FASSET consortium that is relevant, i.e., the definition of reference organisms and their use to integrate the effects data, the conclusion that the object of protection should be the individual organism, that both radiation dose and dose rate should be used to relate exposure to effects, and, that four umbrella categories of effect should be used to aggregate the available information.

The major part of the work has been to assemble and collate the published data concerning the responses of plants and animals to irradiation - this is described in Chapter 2. The major output is a computerised database (FASSET Radiation Effects Database – FRED), which uses Microsoft Access® software. It contains data abstracted from over 1000 publications. Within the constraints of the available resources, this is a subset of the possibly relevant data that has been selected with due recognition of the purpose of the FASSET project and previous reviews carried out with similar objectives. The database is appended to this report and it may be interrogated to produce summmary tables of the data. This has been done for the wildlife groups of interest to the FASSET project and the tables are included here together with supplementary discussion. It is apparent that the availability of data is deficient in many respects, particularly in terms of information relevant to the radiation dose rates likely to occur as a consequence of radioactive waste management activities ($< \sim 10^3$ μGy h^{-1}) and for many of the wildlife groups and umbrella effect categories of concern. This outcome provides a sound basis for the development of future research. As a very broad generalisation, it appears that, although there might be minor effects at lower dose rates in sensitive species and systems, the dose rate threshold for statistically significant effects in most studies is about 10^2 μGy h^{-1}; the responses then increase progressively with increasing dose rate and usually become very clear at dose rates $>10^3$ μGy h^{-1} when these are delivered over a large fraction of the life-span.

In addition to the radiation effects data, there is a number of other factors that need to be considered when applying this information in an effects analysis.

It has long been recognised that different radiations may produce differing degrees of effect for the same absorbed dose - the radiobiological effectiveness (RBE) phenomenon that is dependent in part on the density of energy deposition along a particle track in tissue, e.g., the α-particle is more effective than either the β-particle or the recoil electrons generated by γ-rays. Although this phenomenon is taken into account in human radiation protection practice with the application of radiation weighting factors, there is not, as yet, a comparable system for non-human organisms. This problem is considered in Chapter 3 which concludes that there is not, at present, sufficient relevant information to propose weighting factors for the

organisms and endpoints of concern in environmental radiation protection even though the likely range can be defined. As an interim measure, three values of the weighting factor for α-radiation have been proposed so that the influence of this factor on the aggregated dose rate from both the natural background and contaminant radionuclides may be demonstrated.

In view of the relative paucity of the available information, Chapter 4 considers if it is possible to make extrapolations between data sets. It is concluded that there is not a sound basis to permit extrapolations: from acute, high dose to chronic low dose rate exposure conditions; from one wildlife group of organisms to another, or from one stage in the lifecycle to another; and, from the individual to the population.

Naturally, wild organisms are unlikely to be exposed to increased irradiation from radioactive waste management activities in the absence of other contaminants. Chapter 5 considers what information is available to indicate how this factor might influence the impact of radiation on the environment.

Finally, Chapter 6 provides an overall summary of the conclusions of, and the recommendations arising from, the work within this segment of the FASSET project in the context of the objectives set.

Table of contents

1. Introduction

Any system for assessing the impact of a contaminant on the environment requires an analysis of the possible effects on the organisms and ecosystems concerned. For radioactive contaminants, the effects analysis may be an integral part of the overall assessment framework to provide estimates concerning the effects of radiation on biota and the further ecological consequences of such effects. Alternatively, the effects analysis may be performed separately in order to derive, *e.g.* dose rates that are considered acceptable or environmentally 'safe', mainly to provide a basis for assessing compliance. In either case, the effects analysis must identify:

- relevant biological effects for assessing impact (the relationship between exposure and effect); and,
- the severity of effects at different levels of exposure (the relationship between the extent of exposure and the degree of response).

Furthermore, the effects analysis must be:

- relevant for the *protective aim*, which is usually to maintain population viability so that contaminants do not provoke changes in ecosystem structure and function, *i.e.* exclusive of any changes associated with the natural process of ecosystem maturation, or those caused by natural changes in environmental conditions (examples of the latter for northern European ecosystems are the post-glacial land rise and the natural acidification of soils associated with the spread of coniferous forests), but which may also involve protection of endangered or valued species at the level of the individual.

Finally, for integration into an assessment framework, the effects analysis must be:

- manageable, *i.e.* the effects information must be organised into categories that are relevant for the purpose the impact assessment, and checked for quality.

The normal ecotoxicological approach to effects analysis is to screen the relevant effects literature in order to establish dose-effect and dose-response relationship, and - where appropriate - perform experiments, often on a common, representative, test organism such as *Daphnia*. In order to derive environmentally safe contaminant levels, the approach is normally to estimate the degree of exposure to the contaminant that gives either the lowest observed effect, or no observed effect, and furthermore to apply a safety factor to these to accommodate data uncertainty (*e.g.* experimental error or the applicability of the available data to the wider range of organism types present in the environment) and variability (*e.g.* between responses under controlled laboratory conditions as compared with the natural environment). In order to provide a basis for a judgement of the acceptability of an impact, target values for effects on populations, effects on individuals, dose (rate) or, ultimately, for concentrations in the environment can be derived.

1.1 Work under Work Package 3

For the purposes of the FASSET project, a review and interpretation of the radiation effects field (including previous reviews of the literature) was made to determine the basis from which the FASSET approach to effects analysis could be developed. The main objective for Work Package 3 (WP3), as stated in the FASSET technical annex [FASSET, 2000] was:

"to identify critical effects and biological organisation levels of concern".

The WP has addressed the important question of which biological effects of irradiation are likely to be of significance for protection at the appropriate level of biological organisation and in an assessment context. The work resulted in information of both qualitative and semi-quantitative nature.

The output from this WP3 should help define the dosimetric target organisms for WP1. It will also identify a range of dose rates at which different degrees of effects in the environment would be expected (including the threshold dose rates at which effects would be expected to be minimal) with the highest degree of confidence possible, considering the incompleteness of data. These dose rates will form an important input to the overall framework in WP4.

1.2 Structure of the report

It is recognised that there is a need to propose the level in the biological hierarchy at which protection action should be directed and to select both the biological endpoints of concern and appropriate target organisms for inclusion in a framework. The effects of radiation on the defined endpoints of concern in the selected target organisms should be discussed and dose rate/response relationships summarised. A discussion of the sources and magnitudes of the associated uncertainties should also be included for completeness. The collated information may then lead to proposals for the minimum/threshold dose rates at which effects in the environment would be expected to be minimal with a high degree of confidence.

It was also decided that the available information should be organised into a format that will indicate the approximate dose rate - response relationships. This would in turn provide information on the threshold dose rates at which minor radiation effects can currently be expected to become apparent in the defined biological processes in the selected target organisms. The pooling of the effects data was therefore achieved through the development of a radiation effects database, as discussed further in Chapter 2.

This report reviews and discusses a series of topics, based on the radiation effects data entered into the database.

- The biological effectiveness of different radiation types in the context of environmental exposures. This will take into account the influence of radiation quality and dose rate. It will also look into the relevance of RBE at cell *vs* at individual level and the possible use of radiation weighting factors.

- Extrapolation issues. Probable gaps in the effects data may give rise to a requirement for extrapolations, such as: from acute to chronic radiation exposures; from one organism to another; and, from effects at the individual level to the possible consequential effects at the population and community levels.

- Effects of other environmental stressors. Radiation effects data obtained under controlled (but not necessarily un-stressful) laboratory conditions may not be directly applicable to the natural environment where other stresses may be operating. In addition, there may be interactions between radiation exposure and non-radioactive contaminants to modulate the radiation response.

1.3 Previous FASSET work to build upon

A preliminary list of biota, from both aquatic and terrestrial environments, for which an effects analysis might be required (the reference organisms) was drawn up on the basis of the

exposure pathway analysis in FASSET deliverable 1 [Strand *et al*., 2001]. Based on the results of these discussions, and the importance of these reference organisms from the point of view of ecosystem structure and function, and the likely severity of radiation induced changes in these species, this list was accepted for the purpose of the further development of the FASSET project [Larsson *et al*., 2002]. The list, representative of seven major European ecosystem types, is shown in Table 1-1.

Table 1-1 Reference organisms identified for the purpose of the FASSET framework.

Terrestrial ecosystems	Aquatic ecosystems
Soil:	**Sediment:**
– Soil micro-organisms	– Benthic bacteria
– Soil invertebrates, 'worms'	– Benthic invertebrates, 'worm'
– Plants and fungi	Molluscs
– Burrowing mammals	Crustaceans
Herbaceous layer:	Vascular plants
– Bryophytes	Amphibians
– Grasses, herbs and crops	Fish
– Shrubs	Fish eggs
Above ground invertebrates	Wading birds
Herbivorous mammals	Sea mammals
Carnivorous mammals	**Water column:**
Reptiles	– Phytoplankton
Vertebrate eggs	– Zooplankton
Amphibians	– Macroalgae
Birds	– Fish
Canopy:	– Sea mammals
– Trees	
– Invertebrates	

As the use of reference organisms is central to the effects analysis, it is worth re-iterating its working definition, as described within the FASSET framework.

> "A series of entities that provide a basis for the estimation of radiation dose rate to a range of organisms which are typical, or representative, of a contaminated environment.
>
> These estimates, in turn, would provide a basis for assessing the likelihood and degree of radiation effects."

The adoption of the reference organism approach has two advantages:

- it will indicate if, and for what organism type(s), there might be a problem in terms of an unacceptable degree of radiation exposure and, therefore, impact; and,
- it allows comparisons between different sites or situations to be made on a common basis.

The types of organism that should be represented by the reference organisms have been selected with due consideration of three sensitivity criteria.

- Their radioecological sensitivity, *i.e.*the extent to which they are likely to be exposed to radiation from a range of radionuclides in any given environment. This will lead to a consideration of both their habitat preferences and behaviours, particularly in relation to the accumulation of α-, β-, and γ-emitting radionuclides in their local environment, and their innate capacity to accumulate radionuclides into the whole organism, and differentially, into tissues and organs.

- Their radiosensitivity: this will lead to a consideration of the variations in response between: species, *e.g.* the possible differences between poikilotherms and homeotherms; organs and tissues within an organism, *e.g.* the gonads; and, stages in the life cycle, *e.g.* the gametes, the developing embryo, and the adult.

- Their ecological sensitivity: this will lead to a consideration of the role that the type of organism plays in the functioning of the local community, *e.g.* a plant (primary producer); a detritivore (nutrient recycling), etc.

The FASSET deliverable 1 also discussed and substantiated a number of conclusions, which have guided the development of this report. In particular, a number of relevant conclusions were presented by Larsson *et al*. [2002], including:

- the object of protection for biota should be the individual;

- the framework should be on the basis of the concept of reference organisms;

- the FASSET approach to effects analysis should occur at the 3rd stage of an integrated assessment and management framework;

- the radiation dose and dose rate should be used to relate exposure to effects;

- a limited number of reference organisms should be used to pool the available effects data; and,

- four umbrella effect categories will be used to aggregate the available data concerning specific effects, namely morbidity, mortality, reproductive success and mutation.

The considerations outlined above have provided the basis for organising a limited selection of the available radiation effects data into a structured format that will serve the purposes of developing the FASSET assessment framework.

2. The effects of radiation on plants and animals

For a framework that is intended for practical purposes, that is intended to give as realistic information as possible on environmental impact, and that attempts to integrate the effects analysis within the assessment procedure, a solution to the selection and organisation of the available radiation effects data must be achieved.

The Technical Annex to the FASSET project clearly identifies the need to gather scientific information, in order, specifically, to:

- identify a range of dose rates at which different degrees of effects in the environment would be expected (including the threshold dose rates at which effects would be expected to be minimal) with a high degree of confidence;
- derive dose rate/response relationships for the chosen endpoints;
- determine dose-rate thresholds or minimum dose rates at which effects in the environment are expected to be minimal with a high degree of certainty;
- help define the reference organisms for dosimetric purposes;

and, more generally, to:

- describe the biological effects of irradiation that are likely to be of significance for protection, at the intended biological level, in an environmental context; and,
- identify reference organisms which can be used in a radiation protection framework.

The approach to the selection and summarisation of the information was only briefly described in the Technical Annex as:

> "The available information will be organised into a format that will indicate the approximate dose rate - response relationships and, therefore, the threshold dose rates at which minor radiation effects can currently be expected to become apparent in the defined biological processes in the selected target organisms."

This information would include data on:

- acute and high dose rate exposures;
- chronic, low-level exposures extending over a significant fraction of the life time of the organism; and,
- endpoints such as morbidity, mortality, fertility, fecundity and mutation rate.

2.1 Organisation of effects data – FASSET Radiation Effects Database (FRED)

The problem of organising, evaluating and integrating the available radiation effects information within the framework is not trivial. References to a total of 234,725 publications on radiation effects in the last 50 years were found after searching two databases (Nuclear Science Abstracts (1948 - 1976), and Energy, Science and Technology (1977 - present)) for information (this total will, of course, include non-biological endpoints such as dosimeter response and radiochemistry). When additional selection criteria are applied, *e.g.* radiation effects + mammals + mortality, the number of references is reduced, but the total information

apparently available remains substantial (see Table 2-1 for a summary of the search output). In contrast, however, it is also clear that in some subject areas of vital importance to FASSET there are conspicuous data gaps for certain combinations of effect and wildlife, *e.g.* morbidity for soil fauna, amphibians and reptiles. Indeed, the total available data for the soil fauna appears to be very limited.

Table 2-1 Numbers of publications in each field as derived from searches of Nuclear Science Abstracts (1948 - 1976), and Energy, Science and Technology (1977 - present).

	Radiation effects (all types)	Morbidity (from Jul'81)	Mortality (from Dec'74)	Reproduction* (from Oct'91)	Mutation**
Amphibians	357	0	62	62	7
Bacteria ***	6203	26	304	409	3364
Birds	1089	4	465	424	119
Crustaceans	217	1	390	364	50
Fish	1531	18	1881	1136	931
Insects	3415	4	643	1377	2057
Invertebrates	37	1	47	58	15
Mammals	26144	279	2529	1437	6990
Molluscs	194	1	239	157	34
Plants	16965	127	2533	3082	8053
Reptiles	100	0	22	62	7
Soil fauna	12	0	3	11	3
Totals	234725	1967	13285	11520	33632

* including fertility (from December 1974) and fecundity; ** including genetic effects: *** from Jan'81.

In order to make the data collation exercise manageable within the constraints of the FASSET project, it was necessary to apply a number of selection criteria, *inter alia*:

- Concentrate on the most relevant papers, using prior experience and an informed judgement derived from an understanding of the requirements of the FASSET project. Explicitly recognise the application of this judgement and be aware that it risks the introduction of a bias.
- Collect data published since 1945 due to problems in accessing the earlier literature and possible problems in interpreting the radiation exposures in the context of modern dose quantities and units.
- Ignore data derived from studies of, or for application to, human radiobiology, *e.g.* studies of high dose, high dose rate responses of particular tissues for application in the design of radiotherapy treatment schedules.
- Apply criteria such as dose, dose rate, umbrella effect, etc. The dose rate, in particular, will form an important basis for the application of the overall FASSET framework

because it will be the prime determinant of impact from either authorised radioactive waste management practices, or in the long-term after an accidental release of radionuclides when remediation activities might be required.

- Note any apparently relevant references that cannot be accessed.
- Be aware of the need to be open and transparent in collation exercise; this will be as important as the information itself.

At an early stage [Larsson *et al.*, 2002], it was agreed that the radiation effects data in the published literature should be collated in a structured manner, including:

- 16 wildlife groups;
- 4 umbrella effects (morbidity, mortality, reproductive success and mutation); and,
- 3 radiation exposure regimes, *i.e.* acute, transitory and chronic.

In addition to the bibliographic information and these three main categories, there was a requirement to record, where possible: the type and source of radiation; the dose rate and total dose, the lowest dose or dose rate at which an effect was observed (LOED and LOEDR, respectively); the highest dose or dose rate at which no effect was observed (HNED and HNEDR, respectively); information on the actual biological endpoints recorded in the study; and, an indication of whether the data could be used to determine an RBE value.

Initially, it was envisaged that the data could be assembled into an Excel® spreadsheet format, but it soon became apparent that this would not be practicable. This led to the conclusion that a computerised database (*i.e.* Microsoft Access® 97) would be the most appropriate mechanism for collating, and later interrogating and interpreting, all the relevant literature and data on the effects of radiation.

2.1.1 Collation of references

The review of the available literature on the effects of radiation on plants and animals, other than humans, in context of generating the required tools within FASSET, was undertaken by six organisations within the FASSET project, and based on the approach set out above.

In addition to the general searches of the literature databases indicated above, the primary starting points for assembling the relevant literature were major reviews, such as UNSCEAR [1996] and IAEA [1976, 1992], together with prior knowledge of the original literature. The use of a structured approach to the development of the database highlighted important aspects requiring attention during the design of the database and the subsequent data input.

- It is necessary to have a clear view on what data are needed, and restrict the information gathered to that which is relevant to the purpose of FASSET, *i.e.* to provide a basis for relating the estimated dose rate to an organism in a contaminated environment to its possible consequential effects.
- There was a need for guidance on data entry to ensure consistency in the content of the database. An operating manual, embedded into the database, details the information that needs to be reported.
- It was necessary to apply a measure of quality assurance (QA) to the task of inputting information onto the database. Before data entry occurred, two QA exercises were

undertaken to ensure that all participants were operating to the same basic requirements. The main QA exercise consisted of each participant reading ten randomly selected, but relevant, papers and then entering the data into the database. Again, this exercise identified points that needed to be addressed in the operating manual. Once data entry was completed, an overall QA exercise was performed to highlight any erroneous data.

- If information did not fit obviously into one of the four umbrella categories, *e.g.* genomic instability or bystander effects (both of these might affect mutation rate by mechanisms not yet understood), the data would be retained for discussion.

- Data should be collated at species level, with the expectation that it would be condensed to give a generic summary appropriate to the selected reference organisms.

- The units given in the original publication would be entered onto the database, but these would be automatically converted into 'standardised' units for the total dose (Gy) and the dose rate (μGy h^{-1}) to allow for interrogation of the database and ease of interpretation (refer to Appendix B for list of conversions). And,

- both laboratory experiments (so as not to miss out on potentially important and relevant data) and field studies would be recorded.

2.1.2 Data entry and retrieval

The database options are selected from a series of menus. Briefly, the database operation is divided into two main functions: data entry and query reports based on searches.

Data entry is divided into a bibliographic details section and the experimental data extracted from the publication. The majority of users will only use the query reports. There are three search options:

- to make a hierarchical search on wildlife group, umbrella endpoint and dose or dose rate;

- to make a manual search of the database; and,

- to search for references that may be used to generate RBE information.

All search results can be exported to Excel®. Reports can also be created for listing references, and saved as delimited text files that can be opened either into Word 97® or via the Windows Notepad®.

There are three levels of access to the database: basic searches and reports, data entry, and restricted maintenance. This password protected system is needed to secure the integrity of the database: full access to the underlying tables and queries that form the basic structure of the database is reserved to the designer for maintenance and possible further development; data entry access is restricted to personnel that have participated in the QA exercise to ensure consistency in data entry; and, every user may access the searches and reports.

The operating guide, embedded in the database, provides information on the use of the database, detailing how the information should be entered, and describes the search/report functions and capabilities of the database. The operating guide illustrates the different screens and discusses the options that can be taken.

As a result of these iterative developments, significant improvements were made to produce the final "FASSET Radiation Effects Database", named FRED, using Microsoft ACCESS®. This completed database is an addition to the original outputs envisaged for the FASSET

project. It is freely available on www.fasset.org for downloading, and is appended to this report, on a CD.

The database contains, and provides access to, raw data extracted from the original publications. Table 2-2 provides an overview of the 1,033 references included in the database. The Table also shows how the selection of wildlife groups corresponds to the list of reference organisms. The database has been used to generate the outputs that underlie the summary Tables 2-3 to 2-14 for each wildlife group, presented in the next Sections.

Table 2-2 Number of references within the FASSET Radiation Effects Database.

		Number of references*			
Wildlife Group	**Reference Organism** listed in Table 1-1 and Strand *et al.* [2001]	**Morbidity**	**Mortality**	**Reproductive capacity**	**Mutation**
Amphibians	Amphibians	13	7	1	7
Aquatic invertebrates	Benthic invertebrates, 'worms'	6	7	8	8
Aquatic plants	Vascular plants, macroalgae, phytoplankton	15	11	1	4
Bacteria	Soil micro-organisms, benthic bacteria	7	1	0	0
Birds	Wading birds, birds	15	21	31	3
Crustaceans	Crustaceans	11	12	13	0
Fish	Fish eggs, fish	59	35	83	28
Fungi	Fungi	3	0	0	0
Insects	Canopy invertebrates Soil invertebrates	11	21	12	9
Mammals	Burrowing mammals, herbivorous mammals, carnivorous mammals, sea mammals	58	54	71	29
Molluscs	Molluscs	8	8	5	0
Mosses/lichens	Bryophytes	5	0	0	0
Plants	Trees, plants, grasses, herbs and crops, shrubs	147	26	81	121
Reptiles	Reptiles	7	6	1	3
Soil fauna	soil invertebrates, 'worms'	6	15	3	3
Zooplankton	Zooplankton	5	1	1	0

* Note that some references have information for several endpoints

In addition to providing the information needed for the operation of the FASSET framework, the database may also be used to identify significant gaps in knowledge, and may, therefore, guide further research. It is also hoped to secure the maintenance and update of the database beyond the duration of the current FASSET project, potentially through the FP6 EC programme.

Whilst a rigorous QA has been carried out, some errors may still be present within the database. The original reference should be checked when making specific use of detailed information.

2.2 Overall summary on radiation effects

The available publications concerning the effects of radiation on plants and animals that have been included in the database to date are heavily weighted (2:1) towards acute (*i.e.* high dose rate and, usually, high dose), as compared with chronic, exposure regimes; there are rather few data concerning the effects of exposures that have been classified as transitory; for this reason, this category of studies has been excluded from the summary discussions below. For the acute exposures, and across all organisms, the effects on reproductive capacity have been most commonly studied, with progressively fewer publications giving data on morbidity, mortality and mutation. For chronic exposure regimes, morbidity has been the most commonly studied endpoint, closely followed by reproductive capacity, and then to a lesser degree by mutation and mortality. The capability, or otherwise, to make extrapolations from the more numerous acute exposure/effects data to the low dose rate chronic exposure situations in a contaminated environment is considered in more detail in Chapter 4. Here, attention will be focussed on the data that are available for chronic exposure regimes and the insights that these may provide for assessing the possible effects in environments contaminated by radionuclides arising from radioactive waste management activities.

Table 2-3 provides an overall summary of the availability of data relating to chronic exposure conditions, i.e. those that are most relevant to environments contaminated by authorised releases of radionuclides. It is immediately apparent that, for many wildlife groups and umbrella endpoints, there are no, or very few, data from which relevant conclusions can be drawn. Even when experimental data are available, these most often relate to dose rates above 10^3 μGy h^{-1}, *i.e.* at levels that are only very occasionally approached in environments contaminated by authorised waste management practices, for which dose rates are generally less than ~10^2 μGy h^{-1} [UNSCEAR, 1996]. Although the publications frequently give graphical dose rate/response relationships (or the corresponding data in tabular form), these are for so many different species, and for particular endpoints (these may well be related, but differ in detail with insufficient information from which to generalise), that it is difficult to provide a concise general summary.

Some very broad conclusions may, however, be drawn:

- the relatively large differences between the taxonomic groups that are seen in the responses to acute irradiation, particularly in terms of the LD_{50} values (see, for example, Figure 4-3), become less pronounced for continuous, low dose rate radiation exposure, and particularly for endpoints other than mortality;

- although minor effects may be seen at lower dose rates in sensitive species and systems, *e.g.* haematological cell counts in mammals, immune response in fish, growth in pines, and chromosome aberrations in many organisms, the threshold for statistically significant effects in most studies is about 10^2 μGy h^{-1}; the responses then increase progressively with increasing dose rate and usually become very clear at dose rates >10^3 μGy h^{-1} given over a large fraction of the life-span;

- there are, however, some data that do not fit too comfortably within this broad generalisation, *e.g.* the effects of tritium β-radiation on the developing immune response in fish embryos (although the studies available [84, 85, 86, 189] give somewhat contradictory results), on the developing goose barnacle embryo [404], and also, perhaps, on the developing oocytes in embryonic and neonatal mice [262]; and,

- the significance for the individual, or for the population more generally, of the minor responses, particularly in terms of morbidity and cytogenetic effects, seen at dose rates less than 10^2 μGy h^{-1} has yet to be determined.

Table 2-3 Overall summary for chronic effects data for the wildlife groups, based on the FASSET Radiation Effects Database (FRED).

Wildlife Group	Reference Organisms	Morbidity	Mortality	Reproductive capacity	Mutation
Amphibians	Amphibians	Too few data to draw conclusions.	No data available.	No data available.	Too few data to draw conclusions.
Aquatic invertebrates	Benthic invertebrates 'Worms'	No data below 10^3 μGy h^{-1}. No effects on worm growth at 1.7 10^3 μGy h^{-1}. Limited data to draw conclusions.	Dose rate dependent effect on worm survival above 1.7 10^3 μGy h^{-1}. Too few data to draw conclusions.	Too few data to draw conclusions. Out of five references, only one listed two LOEDR for dose rate > 10^4 μGy h^{-1}, and an HNEDR of 190 μGy h^{-1} for *Neanthes arenaceodentata*.	Too few data to draw conclusions.
Aquatic plants	Vascular plants Macroalgae Phytoplankton	Too few data to draw conclusions.	Too few data to draw conclusions.	No data available.	No data available.
Bacteria	Soil micro-organisms Benthic bacteria	Too few data to draw conclusions.	No data available.	No data available.	No data available.
Birds	Wading birds Birds	No data available.	No data available.	Only six references were recorded, with data on a wide range of dose rates. Conclusive dose-effects relationships could be drawn for chicken for dose rates > 10^4 μGy h^{-1}.	Too few data to draw conclusions.
Crustaceans	Crustaceans	No data for low chronic exposures. Only three references were recorded, with all dose rates > 10^4 μGy h^{-1}.	No data on low chronic exposures. Only three references were recorded, with all dose rates > 10^4 μGy h^{-1}.	No data for low chronic exposures. Only three references were recorded, with all dose rates > 10^4 μGy h^{-1}.	No data available.
Fish	Fish eggs Fish	One experiment, but not another, indicates effects on immune system at <8.3 μGy h^{-1}.	Too few data to draw conclusions.	One study showing effects on gametogenesis at 230 μGy h^{-1}. Otherwise effects at > 10^3 μGy h^{-1}.	Radiation exposure increases the mutation rate.
Fungi	Fungi	Too few data to draw conclusions.	No data available.	No data available.	No data available.

Table 2-3 Overall summary for chronic effects data for the wildlife groups, based on the FASSET Radiation Effects Database (FRED).

Wildlife Group	Reference Organisms	Morbidity	Mortality	Reproductive capacity	Mutation
Insects	Canopy invertebrates Soil invertebrates	Only seven references were reported with no experiments below 500 μGy h^{-1}. Only two described effects under gamma exposures for wide ranging dose rates, all above ~10^3 μGy h^{-1}.	No data on low chronic exposures. Only one reference was reported, with all dose rates > 10^4 μGy h^{-1}.	Too few data to draw conclusions.	Too few data to draw conclusions. Only two papers for dose rates > 10^4 μGy h^{-1}.
Mammals	Sea mammals Burrowing mammals Herbivorous mammals Carnivorous mammals	Rat growth not affected at 16 μGy h^{-1} but affected at >3 10^3 μGy h^{-1}. Some blood parameters affected at 180-850 μGy h^{-1}. No effect on thyroid function at 9 10^3 μGy h^{-1}.	No effect on mouse lifespan at 460 μGy h^{-1}, but significant reductions above ~10^3 μGy h^{-1} in the mouse, goat and dog.	Threshold for effects at ~100 μGy h^{-1}, with clear effects at >10^3 μGy h^{-1}.	Too few data to draw conclusions. One of nine references gives an LOEDR of 420 μGy h^{-1} for mice.
Molluscs	Molluscs	Too few data to draw conclusions. One of the two reported references gives an LOEDR of > 10^4 μGy h^{-1} for *Physa heterostrophaone*.	Too few data to draw conclusions. Two references reported, both with LOEDR of > 10^4 μGy h^{-1} for *Mercenaria mercenaria*, and *Physa heterostrophaone*.	Too few data to draw conclusions. One of the two references gives an HNEDR of 10^4 μGy h^{-1} and an LOEDR > 10^4 μGy h^{-1} for *Physa heterostrophaone*.	No data available.
Moss/Lichens	Bryophytes	Too few data to draw conclusions.	No data available.	No data available.	No data available.
Plants	Plants Grasses Herbs and crops Shrubs Tree	Plant growth begins to be affected at >100 μGy h^{-1}. Continued exposure at 21 μGy h^{-1} for 8 years increases the sensitivity in pines.	50% mortality at 8 years at ~10^3 μGy h^{-1} in pines.	A field study indicated a decrease in seed weight of a herb at 5.5 μGy h^{-1}.	The mutation rate in micro-satellite DNA increased at ~40 μGy h^{-1}.
Reptiles	Reptiles	No data available.	No data available.	No data available.	Too few data to draw conclusions.

Table 2-3 Overall summary for chronic effects data for the wildlife groups, based on the FASSET Radiation Effects Database (FRED).

Wildlife Group	Reference Organisms	Morbidity	Mortality	Reproductive capacity	Mutation
Soil fauna	Soil micro-organisms Soil invertebrates 'Worms'	Too few data to draw conclusions.	Too few data to draw conclusions. One of nine references gives an LOEDR of $> 10^4$ μGy h^{-1} for various species.	No data available.	Too few data to draw conclusions.
Zooplankton	Zooplankton	Too few data to draw conclusions.	No data available.	Too few data to draw conclusions. The only reported reference gives an LOEDR of 440 μGy h^{-1} for *Tetrahymena pyriformis*.	No data available.

2.3 Terrestrial plants, moss/lichen and fungi

The list of references included in the database consists of more than 250 articles, including a selection of Russian studies, recently translated to English. The majority of studies of radiation effects on plants has been limited to field crops and woody species (there are very few references relating to mosses, lichens and fungi - all for chronic exposures and the morbidity endpoint - and, for the purpose of discussion, they have been included with plants), and are, primarily, for external radiation. There appear to be relatively few reports in the literature of radiation damage to plants resulting from the experimental incorporation of radioactive material into soil in field conditions. Presently there are no articles in the database on effects of α-radiation.

The number of experimental studies in which chronic radiation exposure of plant communities has been considered, is relatively small. This is because of the logistic difficulties in having plants growing for an extended time in elevated radiation fields. There exist, however, some studies associated with sites with enhanced natural radiation background. The studies relevant to effects of long-range fallout are mainly those undertaken after the 1957 Mayak - East Urals Radioactive Trail (EURT) - and 1986 Chernobyl accidents in contaminated areas.

A number of studies of the effects of external radiation on forest in field conditions has also been undertaken. The attention in these studies has been directed towards effects at high dose rates while the concern for long-term effects at lower dose rates has mostly been neglected. This may partly be explained by the lack of sensitive assay methods.

The radiosensitivity of plants can be manifested in several ways. The three manifestations of radiation damage most important in vegetation studies are inhibition of growth, reduction of reproductive capacity and death. One important factor influencing the radiation exposure is the gross morphology of the plant, which may result in differential shielding of sensitive parts. Size, shape and the density of the plants stand may alter the exposure and consequently the radiation dose. It is known that the age of a plant or its stage of differentiation or development affects the radiosensitivity. The entire life cycle of the plants also includes the sexual reproduction and data suggest that the dry seed is most resistant while the gametogenic cells at meiosis are most sensitive. However this period is very short and therefore the radiosensitivity of pollen is of importance. The water content of the seed is an important determinant of sensitivity.

Younger plants generally exhibit a higher radiosensitivity than mature plants. In plants, as in other organisms, cells with high proliferation rates are more radiosensitive than non-proliferating, resting cells. Radiosensitivity also varies with season. For example the effect of exposure of pine trees in spring or autumn is different. The vegetative stage is more radioresistant than the flowering stages as may be expected from the known mechanisms of radiation damage in meiotic cells. Deposition of radionuclides onto the plants may be heterogeneous, leading to non-uniformity in the dose rates they receive, as for example in the pine forest around the Chernobyl. Species with exposed meristems or buds may receive much higher doses to critical tissues than plants with underground growth and reproduction, or protection by thick scales.

Polyploidy is common to species that survive in extreme environments. Polyploid plants show greater radioresistance; this can probably be attributed to the fact that a large amount of DNA in the cell nuclei is redundant. In addition the reproduction of these plants is generally achieved by vegetative growth. It has been assumed that radiosensitivity is related to the size

of the genome. The wide range in radiosensitivity of plants species irradiated and grown under similar conditions can be attributed to variation in the size of the chromosomes of these plants, where species with large chromosomes seems to be more radiosensitive. These correlations have been used to predict mortality ratios after low LET (Linear Energy Transfer) radiation for a variety of plants.

Traditionally, the focus of plant improvement by breeding has been to increase mutations by radiation in order to produce more productive plants. Several studies in the database claim statistically significant increases in yield after exposures to relatively low doses. However, whether this is beneficial or not for plants and plant communities, remains to be determined.

Certain environmental factors influence the degree of response caused by radiation. Among the most important factors are temperature, light and competition. This may render comparisons between different field experiments difficult. Plants with a growing season limited by conditions of climate may be vulnerable with regard to yield. For irradiation of crops, a common response endpoint used in the studies is the dose or dose rate required to reduce yield by fifty per cent.

In the database, five of the most important cereal crops (wheat, barley, rye, maize, and rice) have been studied in regard to the four umbrella endpoints. They vary appreciably in sensitivity. Among the legumes, pea, pepper, broad bean, horse bean, soybean and red kidney bean have been studied and all are sensitive or have sensitive stages. The four root crops that have been studied are onion, carrot, potato and sugar beet. Experiments have been conducted on vegetable crops such as cabbage, cucumber and lettuce and on miscellaneous fruit such as strawberries, tomatoes, cherry and apples. A few studies have been performed on pasture and forage crops while many Russian investigations have been performed on cotton. Coniferous forests and deciduous trees have been extensively studied in controlled field experiments. It is well known that many of the more important forest trees such as pine, are very sensitive to radiation. The order of increasing radioresistance as determined in forest studies is as follows: coniferous trees, deciduous trees, shrubs and herbaceous plants. Finally, a selection of other angiosperms such as various meadows species has also been investigated.

Table 2-4 summarises effects data on terrestrial plants, moss/lichen and fungi resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). Data on transitory exposures were only recorded in terrestrial plants. No effects data on acute exposure were found for fungi and moss/lichen.

2.3.1 The effects of acute irradiation

The FASSET database contains a total of 163 references concerning acute exposures. Most of the studies reported are related to two endpoints - reproductive capacity and mutation.

Morbidity

Morbidity endpoints include reduced growth, morphological changes, alteration in productivity (yield), and abnormal shape and appearance. Studies have mostly been performed on seeds, seedlings, buds, meristamic tissues and trees. There are 47 references in the database related to this endpoint, where 12 % of the articles are originally published in English. The remaining 88 % of the articles were originally published in Russian. Only three articles report mixed exposures while the others are concern with externally irradiated plants, either in laboratory (60 %) or in controlled field. The doses, where significant effects of acute irradiation of coniferous trees in the spring period were observed, varied between 0.7 to 1 Gy. Analysis of effects of irradiation of vegetative plants suggest that a dose rate of 12 mGy per

year received in a 7 day period during active development is a minimum to observe a significant stimulation of growth and development of seedlings and accelerated opening of buds in woody plants [824, 832]. The intraspecies polymorphism in radioresistance of, for example, hexaploid wheat has been studied after seed irradiation [857, 1003].

Mortality

The number of articles related to this endpoint in the database is 13. Most of the studies are performed on woody plants such as pine or on agricultural crops. The LD_{50} values for pine range between 6 Gy to 30 Gy after 2 years exposure. It was predicted from modelling long term consequences of acute radiation that complete recovery of a pine-birch forest would be achieved after 50 years following an exposure of 25 Gy. Among agricultural crops, cereals such as wheat, barley and oats are the most radiosensitive with LD_{50} values of 20, 16 and 22 Gy respectively [502]. In some articles the number of dead trees have been examined after controlled field experiments. After high acute irradiation the number of dead pine trees in autumn of the 4^{th} year after irradiation was increased 15 % compared with controls after a dose of 2.5 Gy [911]. Critical doses (LD_{25}) of seed irradiation have been determined for more than thirty species of woody plants [978]. When estimating the lethal effects of radiation on trees it should be noted that the death of trees could be observed over a period of several years after exposure. When trees are irradiated at 0.2-0.8 of the lethal dose the maximum of dead trees compared with control death rate is observed by the 4^{th} and 5^{th} year after exposure [911]. After autumn or spring exposures, the LD_{50} at two years was 50 and 30 Gy, respectively. The LD_{50} for the autumn exposure declined to 30 Gy after an additional period of three years. Death of spring-irradiated trees (coniferous trees) has also been reported at doses of 1 to 2.5 Gy [912].

Reproductive capacity

The number of references found under this umbrella endpoint is 69, but only one article is concerned with internal radiation. Barley was exposed to ^{90}Sr ranging from 7 to 37 000 MBq per m² (10 mGy to 50 Gy) and the productivity was investigated using measures such as the fertility of the main ear and the mass of seeds in the main ear [837].

Doses above 3 Gy have been shown to temporarily reduce both fertility and viability of pollen produced by the pine trees [474]. Seed of the ash tree showed a reduction in germination rate and low survival of germinated seed following acute gamma irradiation at doses greater than 100 Gy. The water content of the seed played a vital role for the radiosensitivity with increasing germination rates at higher water contents.

The exposure of pine trees to doses in the range 0.3-22 Gy in autumn, when the early stages of pollen formation takes place, has been shown to produce damage [913]. Doses greater than 3 Gy resulted in a substantial reduction in fertility and viability of pollen produced in coniferous forest. Doses exceeding 0.7 Gy induced morphological changes in the male cones, particularly in size and pollen production rate. There was a recovery to control values some years after exposure.

Mutation

In the database there is one article concerned with internal radiation [837] while the remaining 78 articles are related to external radiation with X- and γ- rays, and neutrons. Several studies provide data on the relative biological effects of γ-rays, X-rays and neutron radiation on mutations. Methods used for studying mutagen-induced reproductive death in higher plants are pollen germination, seedling height and root growth. The aberration frequency of a mutagen is then correlated to some of these effects. Studies on *Tradescantia paludosa*

showed, for example, that the proportion of seeds germinating and the proportion of seeds without severe chromosomal aberrations were correlated after irradiation with doses between 0 and 10 Gy [Evans, 1968]. In the broad bean, a correlation between the reduction of root growth and the frequency of chromosomal aberrations after irradiation has been found [812, 943].

Studies on barley and maize using the pollen test have shown a linear dose-response relationship after acute gamma-irradiation of homozygous non-waxy maize plants during meiosis at doses up to 1 Gy [Ehrenberg and Eriksson, 1966]. Higher mutation rates per unit dose were achieved at the lowest doses (30–250 mGy) compared with medium doses (>500 mGy). The study also confirmed that the induced mutations could be transferred to the subsequent diploid generation. Additional evidence was also given to the higher relative effectiveness of the low doses in experiments on growing barley plants.

A lack of a linear dose-response relationship has been observed for structural aberrations in the root meristem of barley seeds in the dose range 0-10 Gy [919]. In the region of dose independence (10–500 mGy and 1-10 Gy), the rate of aberrant cells significantly exceeded the spontaneous level. Similar findings were achieved for barley seedling systems in the dose range 50–300 mGy [481].

The lowest dose level at which effects on plants have been registered are on externally irradiated barley seedlings and spiderwort. An increase in the yield of aberrant cells was noticed after a dose of 0.01 Gy and 0.022 Gy respectively [954]. Barley growing on ^{90}Sr contaminated soil showed an increase in the yield of aberrant cells after a dose of 0.2 Gy [837].

Numerous works report the existence of an adaptive response. For example it has been shown that the yield of chromosomal aberrations after acute γ–irradiation declines if the seeds were previously irradiated [920, 941].

2.3.2 The effects of chronic irradiation

The database contains a total of 97 references concerning chronic exposures. The studies reported are mostly related to the umbrella endpoints: morbidity, reproductive capacity and mutation.

Morbidity

The majority of the 46 papers related to this endpoint in the database concern controlled field experiments in forests, especially irradiation of various pine species. About 24 % of the papers are related to the contamination after the Chernobyl accident. In most studies with forest irradiation the exposure period covers both vegetation and dormancy.

Several studies have reported small detrimental effects in pine at dose rates above 2.4 $mGyday^{-1}$ [478, 482]. One of the most sensitive studies involves a doubling of the needle length of Scots pine, as compared with controls, in field experiments [476]. For deciduous trees the values are about 2 to 10 times higher. Exposure of forest to external γ–radiation at a dose rate of about 0.5 mGy per day (20 hours) for a long time period showed that trees became more radiosensitive after longer exposure periods, indicating accumulation of unrepaired damage [492]. After the Chernobyl accident the decrease in shooting increment of pine was registered at 0.43 Gy and cessation of growth at 3.45 Gy [930]. Morphological alterations in pine needles and undergrowth of deciduous trees were registered at dose rates of 1 mGy h^{-1} (dose of 13 Gy) [501].

The very few data available in the database for mosses, lichens and fungi render it impossible to draw any conclusions.

Mortality

There are only six papers in the database related to this endpoint. One of the better-referenced studies concerns long term studies on radiation tolerances in pine [416]. Eight years exposure of pine trees to external Co-60 irradiation at an average dose rate of 31 mGy per day (58 Gy) revealed that 50 % of the trees had been killed. A few trees, however, survived dose rates as high as 100 mGy per day. After an additional period of two years, 20 per cent of the trees had been killed at a dose rate of 25 mGy per day (50 Gy) and at an average exposure rate of 30 mGy per day 50 percent mortality occurred.

Reproductive capacity

More than half of the 34 articles in the database related to this umbrella endpoint, concern studies performed after the Chernobyl accident. Moreover, most of these studies are recently published, the two latest in 2001. One of these articles reports long- term effects on dandelion populations in two EURT areas where the contamination of ^{90}Sr and ^{137}Cs is 13-440, and 2-500, times higher than the background. A survey of the 3rd post-irradiation dandelion generation collected at two different locations near Chernobyl where the radiation background reached 3 x 10 $^{-2}$ to 19 x 10 $^{-2}$ mGy per hour and 0.2 x 10 $^{-2}$ to 0.9 x 10^{-2} mGy per hour, revealed that the mass of one thousand seeds decreased to 75 % and 85 %, respectively, of control values [926]. Effects on the variability in the survival rate of seed, growth and development of seedlings are reported in another article from 2001 [952]. Reproductive damages in pine forest and deciduous trees such as degradation of seed qualities has also recently been reported for areas close to the Chernobyl reactor [876]. In the database there appears to be one article on internal radiation from ^{89}Sr on bean plants. The radionuclide was introduced into the soil at different stages of plant development. Various endpoints related to reproduction were studied such as the number of stems, legumes and beans per plant [811].

Mutation

Two–thirds of the 32 references in the database related to this endpoint are studies performed in areas contaminated by radionuclides after radiation accidents (Chernobyl and EURT). The exposures in these studies are from a mixture of internal and external sources of radiation.

One of the most recent studies, was reported for wheat grown for one generation on contaminated soil (27 MBq per m²) near Chernobyl. It showed an increase in microsatellite mutations as compared with wheat grown on uncontaminated soil [339]. The mutation rate was estimated to increase from 1.03 x 10^{-3} to 6.63 x 10^{-3} per locus over one generation. The total dose to the wheat plants was estimated to be about 300 mGy. Adaptive responses in irradiated plants have been observed [876] and also higher genetic effectiveness (point mutations) per unit absorbed dose at lower contamination levels than at high densities. Long-term studies on mutation induction in populations of *Arabidopsis* exposed at dose rates ranging from 2 x 10^{-2} μGy to 24 mGy per hour for six years (Chernobyl) have been reported [925, 945]. The results indicate that high doses rates are less effective than low dose rates. Studies on population of cornflower exposed to ^{90}Sr/^{90}Y from the EURT areas at annual dose rates of 2.83 Gy from 1966 to 1974 showed increased mutations rates (chromosomal aberrations) compared to controls [1004]. Even 38 years after the accident, an elevation in the frequency of chlorophyll mutations could be observed. Studies on genetic variability in the cornflower have been conducted for longer time periods showing increases above control level [921].

Experimental studies on barley plants, irradiated internally with ^{90}Sr showed that the lowest daily doses (0.01-0.11) 10^{-2} Gy gave higher rates of mutational events (pollen test) per dose unit than the highest daily doses (> 0.25 x 10^{-2} Gy). The lowest dose rate that was significantly higher than the spontaneous rate was 0.03 x 10^{-2} Gy per day corresponding to a total dose between 1 and 10 mGy [Ehrenberg and Eriksson, 1966].

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Triticum aestivum,*	Beta (<10 keV)	36(1)	*Triticum aestivum*	Gamma	1(1)	Pinus *sylvestris*	Beta (> 10 keV)	6(1)	*Pisum sativum*	Beta (> 10 keV)	4(1)
	Tradescantia	Alpha	2(1)	Ecosystems	Gamma	15(1)	*Hordeum vulgare*	Gamma	40(10)	*Vicia faba*	Beta (> 10 keV)	72(1)
	Triticum aestivum,	Gamma	2(1)	Hordeum *vulgare*	Gamma	1(1)	*Triticum aestivum*	Gamma	59(7)	*Hordeum vulgare*	Alpha	6(1)
	Triticum durum,	Gamma	1(1)	*Pinus sylvestris*	Gamma	9(3)	*Gossipium hirsutum*	Gamma	47(2)	*Tradescantia*	Alpha & Gamma	2(1)
	Hordeum vulgare	Gamma	7(4)	*Betula pendula*	Gamma	3(1)	*Solanum tuberosum*	Gamma	15(2)	*Hordeum vulgare*	Gamma	88(13)
	Meadow fescue	Gamma	11(1)	Aboreal plants	Gamma	69(1)	*Oryza sativa*	Gamma	23(1)	*Arabidopsis thaliana, Nicotiana tabacum*	Gamma	36(1)
	Zea mays	Gamma	10(1)	Woody & herbaceous plants	Gamma	2(1)	*Tradescantia*	Gamma	3(1)			
	Solanum tuberosum	Gamma	5(2)	*Cerasus vulgaris*	Mixed	2(2)	*Pinus sylvestris*	Gamma	21(7)	*Pinus sylvestris*	Gamma	72(6)
	Malus domestica	Gamma	1(1)				*Rhaponticum carthamoides*	Gamma	10(1)	*Crepis capillaris*	Gamma	27(3)
	Pinus sylvestris	Gamma	35(11)				*Pisum sativum*	Gamma	6(2)	*Glycine hirsutum*	Gamma	15(1)
	Pinus elliotti	Gamma	22(2)				*Gracilaria*	Gamma	34(1)	*Gossipium hirsutum*	Gamma	41(3)
	Betula pendula	Gamma	21(5)				*Dioscorea deltoidea*	Gamma	2(1)	*Cucumis sativus*	Gamma	3(1)
	Phaseolus vulgaris	Gamma	10(1)				*Glicinia max*	Gamma	3(1)	*Oryza sativa*	Gamma	10(1)
	Gossipium hirsutum	Gamma	4(1)				*Betula pendula*	Gamma	15(3)	*Triticum aestivum*	Gamma	200(7)
	Rhaponticum carthamoides	Gamma	2(1)				*Cucumis sativus*	Gamma	38(3)	*Pisum sativum*	Gamma	47(1)
	Perilla frutescens	Gamma	4(1)				*Helianthus cucumerfolius*	Gamma	12(1)	*Tradescantia*	Gamma	3(1)
	Vicia faba	Gamma	6(1)				*Tilia*	Gamma	8(1)	*Malus domestica*	Gamma	26(2)
	Beta vulgaris	Gamma	1(1)				*Zea mays*	Gamma	6(1)	*Caragena arborescens*	Gamma	3(1)
	Linum usitatissimum	Gamma	1(1)				*Capsicum*	Gamma	32(1)	*Tradescantia*	X-rays	21(4)
	Field crops	Gamma	7(1)				*Allium cepa*	Gamma	8(1)	*Vicia faba*	X-rays	12(1)
	Higher plants	Gamma	6(1)				Forest trees	Gamma	2(1)	*Triticum aestivum*	X-rays	6(2)
	Solanum tuberosum	X-rays	4(1)				*Malus domestica*	Gamma	13(1)	*Pisum sativum*	X-rays	3(1)
	Cabbage	Mixed	1(1)							*Hordeum vulgare*	Mixed	119(1)
	Carrot	Mixed	1(1)							*Triticum aestivum*	Mixed	20(1)
	Corn	Mixed	1(1)									
	Onion	Mixed	1(1)									
	Hordeum vulgare	Mixed	24(1)									
	Pisum sativum	Mixed	18(2)									
	Cerasus vulgaris	Mixed	28(1)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute **Plants** Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background (continued)							*Vicia cracca*	Gamma	29(1)		Neutrons	
							Betula *verrucosa*	Gamma	9(1)	*Tradescantia*	& X-rays	2(2)
							Betula pubescens	Gamma	6(2)	*Glycine*	Neutrons & Gamma	21(1)
							Perilla frutescens	Gamma	2(1)	*Triticum aestivum*	Neutrons, Gamma & X-rays	38(1)
							Vica faba	Gamma	1(1)	*Triticum aestivum*	Neutrons	27(1)
							Glycine	Gamma	4(1)	*Gossipium hirsutum*	Neutrons	1(1)
							Meadows	Gamma	5(1)	*Tradescantia*	Neutrons	3(2)
							Grass	Gamma	19(1)			
							Maize tripsucum	Gamma	2(1)			
							Solanum tuberosum	X-rays	9(1)			
							Pisum sativum	X-rays	5(2)			
							Triticum aestivum	X-rays	20(2)			
							Hordeum vulgare	X-rays	10(1)			
							Zea mays	X-rays	12(1)			
							Vicia cracca	Mixed	3(1)			
							Festuca pratensis	Mixed	6(1)			
							Plantago lanceolata	Mixed	8(1)			
							Hordeum vulgare	Mixed	5(1)			

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
< 0.199	*Gossipium hirsutum*	Gamma	10(1)				*Hordeum vulgare* *Hordeum vulgare*	Beta (> 10 keV) Gamma	10(1) 6(1)	*Hordeum vulgare* *Arabidopsis thaliana, Nicotiana tabacum* *Hordeum vulgare* *Triticum aestivum* *Crepis capillaris* *Malus domestica* *Tradescantia* *Tradescantia* *Triticum aestivum* *Tradescantia* *Hordeum vulgare* *Tradescantia*	Beta (> 10 keV) Gamma Gamma Gamma Gamma Gamma Gamma & X-rays Neutrons & X-rays Neutrons, Gamma & X-rays X-rays Mixed Neutrons	18(1) 4(1) 57(3) 12(1) 12(1) 23(1) 16(1) 138(4) 3(1) 20(1) 1(1) 9(1)
0.2-0.499	*Triticum aestivum*	X-rays	6(1)				*Pinus sylvestris* *Hordeum vulgare* *Allium cepa* *Triticum aestivum* *Betula pubescens* *Betula verrucosa* *Cucumis sativus*	Beta (> 10 keV) Beta (> 10 keV) Gamma Gamma Gamma Gamma Gamma	6(1) 10(1) 8(1) 19(3) 2(1) 2(1) 26(1)	Hordeum vulgare *Hordeum vulgare* *Triticum aestivum* *Pinus sylvestris* *Malus domestica* *Tradescantia* *Tradescantia* *Tradescantia*	Beta (> 10 keV) Gamma Gamma Gamma Gamma Neutrons & X-rays X-rays Neutrons	12(1) 27(2) 10(3) 50(1) 15(1) 22(7) 21(3) 4(1)

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
0.5-0.99	*Pinus sylvestris*	Gamma	8(3)	*Cerasus vulgaris*	Mixed	1(1)	*Pinus sylvestris*	Gamma	12(3)	*Arabidopsis thaliana,*		
	Solanum tuberosum	Gamma	4(1)				*Allium cepa*	Gamma	8(1)	*Nicotiana tabacum*	Gamma	4(1)
	Cerasus vulgaris	Mixed	23(1)				*Solanum tuberosum*	X-rays	1(1)	*Pinus sylvestris*	Gamma	67(4)
										Triticum aestivum	Gamma	24(1)
										Hordeum vulgare	Gamma	26(1)
										Malus domestica	Gamma	5(1)
										Glycine	Gamma	11(1)
										Tradescantia	Gamma & X-rays	49(2)
										Tradescantia	Neutrons & X-rays	10(4)
										Tradescantia	X-rays	11(2)
										Tradescantia	Neutrons	2(1)
1.0-1.99	*Hordeum vulgare*	Beta (>10 keV)	6(1)	*Pisum sativum*	Beta (>10 keV)	1(1)	*Pinus sylvestris*	Beta (> 10 keV)	6(1)	*Pinus sylvestris*	Gamma	21(2)
	Pisum sativum	Beta (> 10 keV)	2(1)	*Hordeum vulgare*	Gamma	1(1)	*Gossipium hirsutum*	Gamma	15(1)	*Vicia faba*	Gamma	4(1)
	Vicia faba	Gamma	4(1)	Woody & herbaceous plants	Gamma	1(1)	*Solanum tuberosum*	Gamma	3(1)	*Hordeum vulgare*	Gamma	20(5)
	Hordeum vulgare	Gamma	2(1)	*Pinus sylvestris*	Gamma	6(1)	*Hordeum vulgare*	Gamma	4(2)	*Triticum aestivum*	Gamma	24(1)
	Cerasus vulgaris	Gamma	22(1)	*Cerasus vulgaris*	Mixed	1(1)	*Dioscorea deltoidea*	Gamma	2(1)	*Malus domestica*	Gamma	7(1)
	Betula pendula	Gamma	5(2)				*Allium cepa*	Gamma	8(1)	*Tradescantia*	Gamma & X-rays	5(1)
	Pinus sylvestris	Gamma	5(2)				*Papaver ssp*	Gamma	4(1)	*Tradescantia*	Neutrons & X-rays	19(4)
	Malus domestica	Gamma	1(1)				*Betula pendula*	Gamma	3(1)	*Tradescantia*	Neutrons & Gamma	181)
	Triticum aestivum	X-rays	18(1)				*Pinus sylvestris*	Gamma	14(4)	Glycine	Neutrons & Gamma	22(1)
	Solanum tuberosum	X-rays	4(1)				*Solanum tuberosum*	X-rays	1(1)	*Tradescantia*	X-rays	22(2)
	Cabbage	Mixed	1(1)							*Vicia faba*	X-rays	12(1)
	Carrot	Mixed	1(1)									
	Corn	Mixed	1(1)									
	Onion	Mixed	1(1)									
	Hordeum vulgare	Mixed	2(1)									
	Cerasus vulgaris	Mixed	23(1)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
2.0-4.99	*Hordeum vulgare*	Beta (>10 keV)	6(1)	*Pisum sativum*	Beta (> 10 keV)	1(1)	*Pinus sylvestris*	Beta (> 10 keV)	6(1)	*Hordeum vulgare*	Beta (> 10 keV)	9(1)
	Pisum sativum	Beta (> 10 keV)	2(1)	*Hordeum vulgare*	Gamma	1(1)	*Hordeum vulgare*	Beta (> 10 keV)	5(1)	*Hordeum vulgare*	Alpha	24(1)
	Vicia faba	Gamma	4(1)	*Pinus sylvestris*	Gamma	1(1)	*Solanum tuberosum*	Gamma	3(1)	*Hordeum vulgare*	Gamma	13(4)
	Malus domestica	Gamma	3(1)	Woody & herbaceous plants	Gamma	3(1)	*Pinus sylvestris*	Gamma	38(7)	*Arabidopsis thaliana, Nicotiana tabacum*	Gamma	4(1)
	Pinus sylvestris	Gamma	8(5)	*Cerasus vulgaris*	Mixed	1(1)	*Hordeum vulgare*	Gamma	4(2)	*Pinus sylvestris*	Gamma	72(5)
	Hordeum vulgare	Gamma	2(1)				*Gossipium hirsutum*	Gamma	17(1)	*Crepis capillaris*	Gamma	81(3)
	Cerasus vulgaris	Gamma	22(1)				*Glicinia max*	Gamma	3(1)	*Triticum aestivum*	Gamma	2(1)
	Solanum tuberosum	Gamma	8(1)				*Allium cepa*	Gamma	8(1)	*Malus domestica*	Gamma	21(1)
	Betula pendula	Gamma	3(1)				*Papaver ssp*	Gamma	8(1)	*Tradescantia*	Neutrons & X-rays	18(4)
	Fragaria ananassa	X-rays	8(1)				*Betula pendula*	Gamma	3(1)	Glycine	Neutrons & Gamma	11(1)
	Cabbage	Mixed	1(1)				*Solanum tuberosum*	X-rays	1(1)	*Tradescantia*	X-rays	20(2)
	Carrot	Mixed	1(1)				*Pisum sativum*	X-rays	1(1)	*Pisum sativum*	X-rays	1(1)
	Corn	Mixed	1(1)							*Hordeum vulgare*	Mixed	18(1)
	Onion	Mixed	1(1)							*Zea mais*	Mixed	10(1)
	Hordeum vulgare	Mixed	2(1)							*Triticum aestivum*	Mixed	10(1)
	Cerasus vulgaris	Mixed	23(1)							*Triticum aestivum*	Neutrons	28(1)

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Hordeum vulgare*	Beta (> 10 keV)	12(1)	*Pisum sativum*	Beta (> 10 keV)	17(1)	*Hordeum vulgare*	Beta (> 10 keV)	10(1)	*Hordeum vulgare*	Beta (> 10 keV)	11(1)
	Pisum sativum	Beta (> 10 keV)	19(1)	*Triticum aestivum*	Gamma	3(1)	Forest trees	Gamma	17(1)	*Pisum sativum*	Beta (> 10 keV)	20(1)
	Triticum aestivum	Gamma	49(3)	*Pisum sativum*	Gamma	6(1)	*Pinus sylvestris*	Gamma	117(6)	*Hordeum vulgare*	Gamma	70(11)
	Solanum tuberosum	Gamma	59(3)	*Hordeum vulgare*	Gamma	3(1)	*Solanum tuberosum*	Gamma	78(3)	*Arabidopsis thaliana, Nicotiana tabacum*	Gamma	8(1)
	Zea mays	Gamma	21(1)	*Betula pendula*	Gamma	14(2)	*Triticum aestivum*	Gamma	236(9)	*Pinus sylvestris*	Gamma	170(4)
	Triticum durum,			*Pinus sylvestris*	Gamma	37(3)	*Pisum sativum*	Gamma	15(2)	Glycine	Gamma	45(1)
	Meadow fescue	Gamma	3(1)	Woody & herbaceous plants	Gamma	30(1)	*Zea mays*	Gamma	6(1)	*Crepis capillaris*	Gamma	114(1)
	Perennial ryegrass	Gamma	4(1)	*Euglena gracilis*	X-rays	12(1)	*Gossipium hirsutum*	Gamma	139(2)	*Gossipium hirsutum*	Gamma	84(3)
	White clover	Gamma	4(1)	*Cerasus vulgaris*	Mixed	4(1)	*Malus domestica*	Gamma	9(1)	*Cucumis sativus*	Gamma	12(1)
	Beta vulgaris	Gamma	4(1)				*Betula verrucosa*	Gamma	32(2)	*Oryza sativa*	Gamma	30(1)
	Pisum sativum	Gamma	26(2)				Glycine	Gamma	15(1)	*Solanum tuberosum*	Gamma	12(1)
	Vicia faba	Gamma	12(1)				*Maize tripsucum*	Gamma	27(1)	*Pisum sativum*	Gamma	129(2)
	Malus domestica	Gamma	36(2)				*Hordeum vulgare*	Gamma	114(9)	*Malus domestica*	Gamma	89(2)
	Pinus sylvestris	Gamma	1(1)				*Cucumis sativus*	Gamma	68(2)	*Caragena arborescens*	Gamma	6(1)
	Rhaponticum carthamoides	Gamma	78(9)				*Oryza sativa*	Gamma	69(1)	*Tradescantia*	Gamma & X-rays	4(1)
	Pinus elliotti	Gamma	12(1)				*Allium cepa*	Gamma	16(1)	Glycine	Neutrons & Gamma	77(1)
	Pinus taeda	Gamma	56(2)				*Rhaponticum carthamoides*	Gamma	66(1)	*Triticum aestivum*	Neutrons & X-rays	71(1)
	Hordeum vulgare	Gamma	24(1)				*Perilla frutescens*	Gamma	4(1)	*Triticum aestivum*	X-rays	21(3)
	Secale cereale	Gamma	18(4)				*Vicia faba*	Gamma	16(1)	*Tradescantia*	X-rays	8(1)
	Betula pendula	Gamma	12(1)				*Papaver ssp*	Gamma	12(1)	*Lycopersicum esculentum*	X-rays	3(1)
	Perilla frutescens	Gamma	73(5)				*Dioscorea deltoidea*	Gamma	4(1)	*Pisum sativum*	X-rays	11(1)
	Cabbage	Gamma	16(1)				Meadows	Gamma	54(1)			
	Corn	Gamma	2(1)									
	Carrot	Gamma	3(1)									
	Onion	Gamma	4(1)									
	Linum usitatissimum	Gamma	5(1)									
	Solanum tuberosum	X-rays	8(1)									
	Fragaria ananassa	X-rays	12(1)									
	Cerasus vulgaris	Mixed	8(1)									
	Pisum sativum	Neutrons	92(1)									
			47(2)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0 (continued)							Grass	Gamma	6(1)	*Zea mais*	Mixed	15(1)
							Betula pendula	Gamma	24(2) 92(1)	*Triticum aestivum*	Mixed	66(1)
							Graciliaria			*Hordeum distichum*	Mixed	68(1)
							Betula pubescens	Gamma	4(1) 36(1)	*Triticum aestivum*	Neutrons	56(1)
							Vicia cracca	Gamma	32(1)			
							Capsicum					
							Triticum monococcum	Gamma	42(1)			
							Triticum sinskajae	Gamma	42(1)			
							Pisum sativum	X-rays	46(2) 9(1)			
							Zea mays					
							Solanum tuberosum	X-rays	15(2)			
							Festuca pratensis	Mixed	24(1)			
							Hordeum distichum	Mixed	20(1) 18(1)			
							Vicia cracca					
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) X-rays Alpha Neutrons			500	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) X-rays Alpha Neutrons		351 396 397,401, 466,470, 471,472

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Acute Plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Dbase paper IDs	350,420,425,467,475,476,491,499, 500,506,522,824,832,854,857,858, 863,864,868,869,870,872,873,874, 877,879,894,897,903,904,906,909, 910,911,913,915,924,935,954,956, 968,969,971,972,996,1003			208,502,858,864,871,894,911,912, 924,956,972,978,983			474,808,809,810,813,815,817,818, 820,823,825,829,830,833,834,836, 837,839,842,844,846,849,851,852, 854,856,858,859,861,862,871,872, 873,874,875,878,879,884,885,888, 890,894,896,898,901,902,903,905, 909,917,918,922,931,935,942,944, 954,956,960,961,974,981,982,987, 989,990,991,996,998,1003			337,339,351,352,353,354,396,397, 399,401,419,466,469,470,471,472, 481,807,808,812,814,816,820,821, 822,823,826,827,828,831,,833,835, 837,840,843,844,845,846,847,848, 850,851,852,853,855,857,858,862, 863,872,881,882,888,889,894,898, 917,919,920,923,924,933,941,943, 954,956,957,958,970,971,973,974, 975,976,978,991,1007, 1012		
Observations "rejected" (paper ID)[c]	11(746),13(500)			None			None			15(962)		
Last paper published in:	2000			1989			1989			2001		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
Plants	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Triticum aestivum*	Mixed	34(1)	*Hordeum vulgare*	Mixed	6(1)	Bean plants	Beta (> 10 keV)	35(1)	*Centaurea scobiosa*	Beta (> 10 keV)	50(4)
	Betula sp.	Mixed	6(1)	*Fraxinus nigra*	Gamma	2(1)	*Pinus sylvestris*	Beta (> 10 keV)	5(1)	*Numerous1*	Beta (> 10 keV)	18(1)
	Picea A.	Mixed	36(1)	*Pinus rigida*	Gamma	26(1)	*Hordeum vulgare*	Mixed	6(1)	*Pinus sylvestris*	Beta (> 10 keV)	5(1)
	Pinus L.	Mixed	36(1)				*Hordeum vulgare, Triticum, aestivinum, Zea mays*	Mixed	21(1)	*Festuca pratensis*	Mixed	9(2)
	Tremula, Picea A., Betula sp.,Pinus sp., Alnus glutinosa	Mixed	140(1)				*Vicia cracca*	Mixed	1(1)	*Hordeum vulgare*	Mixed	4(1)
	Robinia pseudocacia, Sorbus aucuparia, Matricaria perforata						*Pinus sylvestris*	Mixed	103(3)	*Triticum aestivum*	Mixed	24(1)
	Taraxacum officinale	Gamma	6(1)				*Plantago lanceolata*	Mixed	1(1)	*Vicia cracca, Pinus sylvestris*	Mixed	41(3)
	Pinus banksiana	Mixed	1(1)				*Oenothera l.*	Mixed	6(1)	*Arena sativa, Hordeum vulgare, Secale cereale, Triticum aestivum*	Mixed	144(1)
	Forest trees (7 sp.)	Gamma	79(4)				*Fagopyrum esculentum*	Gamma	57(1)	*Crepis tectorum*	Mixed	4(1)
	Gaylussacia bacata,	Gamma	65(1)				*Pinus rigida, Quercus alba, Q. coccinea, Q., illicifolia*	Gamma	2(1)	*Arabidopsis thaliana*	Mixed	10(1)
	Vaccinium vacillans	Gamma	10(1)				*Hordeum vulgare*	Gamma	1(1)	*Pinus sylvestris*	Mixed	4(1)
	Shrub sp.	Gamma	7(1)				*Triticum monococcum*	Gamma	1(1)	*Vicia cracca*	Gamma	16(1)
	Forbes, Semi shrubs, Grasses, Sedges, Annuals	Gamma	3(1)							*Hordeum vulgare*	Gamma	1(1)
	Meadow sp.	Gamma	36(1)									
	Plants	Gamma	1(1)									
	Triticum durum	Gamma	24(1)									
	Conifers	Gamma	36(1)									
	Solanum tuberosum	Gamma	32(1)									
	Pinus rigida	Gamma	32(2)									
	Tradescantia paludosa	Gamma	7(1)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
< 99.9	*Pinus sylvestris*	Mixed	69(3)	*Pinus L*	Mixed	1(1)	*Pinus sylvestris*	Beta (> 10 keV)	15(1)	Numerous[1]	Beta (> 10 keV)	16(1)
	Arabidopsis thaliana	Mixed	5(1)	*Viola matulina*	Mixed	2(1)	*Taraxacum officinale*	Mixed	6(1)	*Pinus sylvestris*	Beta (> 10 keV)	15(1)
	Plantago lanceolata	Mixed	18(1)	*Taraxacum officinale*	Mixed	2(1)	*Dactyllis glomerata*	Mixed	10(1)	*Centaurea scobiosa*	Beta (> 10 keV)	53(2)
	Duschecia fructicosa	Mixed	24(1)				*Picea excelsa*	Mixed	4(1)	*Arabidopsis thaliana*	Mixed	325(2)
	Taraxacum officinale	Mixed	25(1)				*Pinus sylvestris*	Mixed	96(4)	*Taraxacum officinale*	Mixed	2(1)
	Forest trees[2]	Gamma	2(1)				*Plantago lanceolata*	Mixed	131(4)	*Dactyllis glomerata*	Mixed	5(1)
	Forest trees[3]	Gamma	1(1)				*Viola matulina*	Mixed	13(2)	*Pinus sylvestris*	Mixed	71(3)
	Boreal forest & herbaceous plants	Gamma	2(3)				*Taraxacum officinale*	Mixed	70(1)	*Crepis tectorium*	Mixed	20(1)
	Shrub species	Gamma	8(1)				*Vicia cracca*	Mixed	26(1)	*Plantago lanceolata*	Mixed	13(2)
	Abies balsamea	Gamma	18(1)				*Duschesia fructicosa*	Mixed	16(1)	*Crepis tectorium*	Mixed	20(1)
	Cerasus sp.	Gamma	2(1)				*Cerasus sp.*	Gamma	2(1)	*Taraxacum officinale*	Mixed	25(1)
							Festuca pratensis	Gamma	2(1)	*Vicia cracca*	Mixed	36(1)
							Solanum tuberosum	Gamma	12(1)	*Pinus sylvestris*	Mixed	12(1)
										Festuca pratensis	Gamma	2(1)

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
100-199.9	*Pinus sylvestris*	Mixed	23(3)	*Pinus L.*	Mixed	2(1)	*Pinus sylvestris*	Mixed	28(4)	Numerous[1]	Beta (> 10 keV)	16(1)
		Gamma	3(1)	*Taraxacum officinale*	Mixed	1(1)	*Taraxacum officinale*	Mixed	3(1)			
	Forest trees[2]	Gamma	1(1)				*Dactyllis glomerata*	Mixed	2(1)	*Centaurea scobiosa*	Beta (> 10 keV)	41(1)
	Forest trees[3]						*Plantago lanceolata*	Mixed	8(2)			
	Boreal forest & herbaceous plants	Gamma	2(2)				*Viola matulina*	Mixed	1(1)	*Vicia cracca*	Mixed	4(1)
		Gamma	2(1)				*Festuca pratensis*	Gamma	4(1)			
	Abies balsamea	Gamma	10(1)							*Taraxacum officinale*	Mixed	1(1)
	Pinus sylvestris									*Dactyllis glomerata*	Mixed	1(1)
										Pinus sylvestris	Mixed	6(1)
										Arabidopsis thaliana	Mixed	32(1)
										Plantago lanceolata	Mixed	8(2)
										Hordeum vulgare	Mixed	3(1)
										Vicia cracca	Gamma	4(1)
										Festuca pratensis	Gamma	4(1)
200-499.9	*Arabidopsis thaliana*	Mixed	1(1)	*Viola matulina*	Mixed	2(1)	*Dactyllis glomerata*	Mixed	4(1)	Numerous[1]	Beta (> 10 keV)	9(1)
	Pinus sylvestris	Mixed	11(2)				*Picea excelsa*	Mixed	3(1)			
	Abies balsamea	Gamma	8(1)				*Pinus sylvestris*	Mixed	9(1)	*Centaurea scobiosa*	Beta (> 10 keV)	41(1)
	Cerasus sp.	Gamma	2(1)				*Plantago lanceolata*	Mixed	20(3)			
							Viola matulina	Mixed	12(2)	*Pinus sylvestris*	Mixed	5(2)
							Cerasus sp.	Gamma	2(1)	*Arabidopsis thaliana*	Mixed	46(2)
										Dactyllis glomerata	Mixed	2(1)
										Plantago lanceolata	Mixed	3(2)

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
500-999.9	*Arabidopsis thaliana*	Mixed	2(1)				*Picea excelsa*	Mixed	1(1)	Numerous[1]	Beta (> 10 keV)	2(1)
	Forest trees[2]	Gamma	2(1)							*Pinus sylvestris*	Mixed	4(1)
	Pinus rigida	Gamma	4(1)							*Arabidopsis thaliana*	Mixed	33(2)
	Abies balsamea	Gamma	8(1)							*Plantago lanceolata*	Mixed	2(2)
	Boreal forest & herbaceous plants	Gamma	1(1)									
	Pinus rigida	Gamma	2(1)									
1,000-1,999.9	*Arabidopsis thaliana*	Mixed	1(1)	Pinus rigida	Gamma	3(1)	*Dactyllis glomerata*	Mixed	2(1)	Numerous[1]	Beta (> 10 keV)	1(1)
	Plantago lanceolata	Mixed	6(1)				*Plantago lanceolata*	Mixed	6(1)	*Pinus sylvestris*	Mixed	2(1)
	Abies balsamea	Gamma	2(1)				*Cerasus sp.*	Gamma	2(1)	*Arabidopsis thaliana*	Mixed	25(1)
	Boreal forest & herbaceous plants	Gamma	21(3)				*Solanum tuberosum*	Gamma	4(1)	*Dactyllis glomerata*	Mixed	1(1)
	Cerasus sp.	Gamma	2(1)							*Vicia cracca*	Gamma	1(1)
2,000-4,999	*Arabidopsis thaliana*	Mixed	1(1)				*Plantago lanceolata*	Mixed	13(2)	*Arabidopsis thaliana*	Mixed	12(1)
	Plantago lanceolata	Mixed	6(1)				*Festuca pratensis*	Gamma	2(1)	*Plantago lanceolata*	Mixed	2(2)
	Boreal forest & herbaceous plants	Gamma	9(1)				*Solanum tuberosum*	Gamma	4(1)	*Pinus sylvestris*	Mixed	4(1)
	Forbes, Semi shrubs, Grasses, Sedges, Annuals	Gamma	1(1)							*Vicia cracca*	Gamma	4(1)
	Forest trees[2]	Gamma	2(1)							*Festuca pratensis*	Gamma	2(1)
	Aphid sp.	Gamma	15(1)									
	Abies balsamea	Gamma	14(1)									
	Pinus rigida	Gamma	24(1)									
	Quercus alba	Gamma	2(1)									
	Forest trees[4]	Gamma	10(1)									
	Pinus rigida	Gamma	7(1)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
5,000-9,999	Forest trees[2]	Gamma	2(1)				*Solanum tuberosum*	Gamma	4(1)	Numerous[1]	Beta (> 10 keV)	1(1)
	Forest trees[3]	Gamma	1(1)				*Festuca pratensis*	Gamma	2(1)			
	Abies balsamea	Gamma	1(1)				*Triticum sp.*	Gamma	31(2)	*Festuca pratensis*	Gamma	2(1)
	Boreal forest & herbaceous plants	Gamma	1(1)							*Vicia cracca*	Gamma	1(1)
	Forbes, Semi shrubs, Grasses, Sedges, Annuals	Gamma	1(1)									
	Pinus rigida	Gamma	8(1)									
	Pinus rigida, Quercus alba	Gamma	18(1)									
	Pinus rigida	Gamma	3(1)									
	Forest trees[4]	Gamma	5(1)									
	Carex pensylvanica	Gamma	4(1)									
> 10,000	Forest trees[3]	Gamma	4(1)				*Pinus sylvestris*	Mixed	9(1)	*Centaurea scobiosa*	Beta (> 10 keV)	2(1)
	Boreal forest & herbaceous plants	Gamma	24(3)				*Hordeum vulgare*	Gamma	3(1)	*Pinus sylvestris*	Mixed	5(2)
	Quercus sp.	Gamma	8(1)				*Triticum sp.*	Gamma	54(1)	*Hordeum vulgare*	Gamma	3(1)
	Quercus sp., Carex sp.	Gamma	8(1)				*Triticum sp.*	Gamma	8(1)	*Vicia cracca*	Gamma	2(1)
	Fraxinus nigra	Gamma	11(1)				*Solanum tuberosum*	Gamma	8(1)			
	Forbes, Semi shrubs, Grasses, Sedges, Annuals	Gamma	12(1)									
	Short grass	Gamma	5(1)									
	Pinus rigida	Gamma	43(1)									
	Meadow sp.	Gamma	14(1)									
	Pinus rigida, Quercus alba	Gamma	24(1)									
	Tradescantia paludosa	Gamma	8(1)									
	Forest trees[4]	Gamma	7(1)									
	Carex pensylvanica	Gamma	20(1)									
			11(1)									

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for:	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta(energy<10keV) Beta(energy>10keV) Alpha Neutrons		
Dbase paper IDs	327,329,331,336,338,340,343, 347,410,416,417,418,422,468, 477,478,479,480,480,482,483, 484,485,486,487,488,492,497, 498,501,504,505,523,635,740, 742,747,866,867,877,925,927, 930,950,985,995,1016,1018, 1019,1020			331,416,916 ,926 ,929,1000			743,811,838,841,860,865,876,880,893,908, 916,926,928,932,936,937,940,949,950,951, 952,964,967,985,989,993,995,998,999,1000, 1001,1015,1017,1019			838,860,876,893,895,899,900,908, 921,925,926,928,930,932,934,937, 945,949,950,952,953,959,963,980, 984,985,992,997,1004,1010,1011, 1013		
Observations "rejected" (paper ID)[c]	12(494),16(641)			None			6 (838)			212 (921)		
Last paper published in:	2001			1994			2000			2000		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

1 Numerous species: *Androsace septentrionalis, Centaurea scobiosa, Crepis tectorum, Draba hemorosa, Lilium martagon, Plantago major, Tradescantia*. 2 Forest trees: A*bies balsamea, Picea mariana, Populus tremuloides, Salix bebbiana.* 3 Forest trees: *Picea mariana, Pinus banksiana, Populus balsamifera, Betula papyrifera*. 4 Forest trees: *Secale cereale, Capsun burse, Conyza canadensis, lepidium virginicum*

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Transitory Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Betula , Tremula, Pinus , Picea A. Dietr, Alnus glutinosa* *Pinus , Picea A. Dietr* *Arabidopsis thaliana* *Hordeum vulgare*	Mixed Mixed Mixed Beta	28(1) 1281) 2(1) 2(1)	Pinus sylvestris	Beta	3(1)	*Pinus sylvestris* *Secale cereale* *Dactylis glomerata* *Oenothera*	Mixed Mixed Mixed Mixed	29(2) 24(1) 1(1) 6(1)	*Tradescantia* *Hordeum vulgare* *Secale cereale* *Triticum* *Pinus sylvestris*	Mixed Beta Mixed Mixed Mixed	1(1) 174(3) 217(2) 3(1) 20(1)
< 99.9	*Arabidopsis thaliana* *Plantago lanceolata*	Mixed Mixed	2(1) 8(1)				*Dactylis glomerata* *Plantago lanceolata* *Pinus sylvestris L*	Mixed Mixed Mixed	12(1) 76(2) 14(1)	*Dactylis glomerata* *Arbidopsis thaliana* *Plantago lanceolata* *Triticum*	Mixed Mixed Mixed Mixed	6(1) 6(1) 8(2) 5(1)
100-199.9	*Arabidopsis thaliana* *Plantago lanceolata*	Mixed Mixed	1(1) 1(1)				*Plantago lanceolata*	Mixed	8(1)	*Arbidopsis thaliana* *Secale cereale, Triticum*	Mixed Mixed	4(1) 2(1)
200-499.9	*Hordeum vulgare*	Beta	4(1)				*Dactylis glomerata*	Mixed	6(1)	*Hordeum vulgare* *Dactylis glomerata* *Secaele cereale*	Beta Mixed Mixed	9(1) 3(1) 1(1)
500-999.9	*Plantago lanceolata* *Hordeum vulgare*	Mixed Beta	1(1) 2(1)				*Dactylis glomerata* *Plantago lanceolata*	Mixed Mixed	2(1) 7(1)	*Hordeum vulgare* *Dactylis glomerata* *Arbidopsis thaliana* *Secale cereale, Triticum*	Beta Mixed Mixed Mixed	2(1) 1(1) 2(1) 2(1)
1,000-1,999.9	*Hordeum vulgare*	Beta	4(1)				*Plantago lanceolata* *Pinus sylvestris*	Mixed Mixed	4(1) 4(1)	*Hordeum vulgare*	Beta	9(1)

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Transitory Plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
2,000-4,999	*Hordeum vulgare*	Beta	6(1)				*Plantago lanceolata*	Mixed	3(1)	*Hordeum vulgare* *Arbidopsis thaliana*	Beta Mixed	11(1) 4(1)
5,000-9,999							*Plantago lanceolata*	Mixed	1(1)			
> 10,000	*Hordeum vulgare*	Beta	6(1)							*Hordeum vulgare*	Beta	35(1)
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	866,867,887,925,949			986			876,892,928,931,948,964, 967,986			398,883,887,892,928,945,949,963, 967,1004,1006,1014		
Observations "rejected" (paper ID)[c]	None			10(986)			None			None		
Last paper published in:	1996			None			2001			2002		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Moss/Lichen Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Lichen diversity	Gamma	1(1)									
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999	Lichen diversity	Gamma	5(1)									
> 10,000												
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper Ids	349,415,426,427,493			None			None			None		
Observations "rejected" (paper ID)[c]	2(415) [1],6 (426)[1],6(427) [2], 28(493)[1]			None			None			None		
Last paper published in:	1992			None			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates, or doses; 2 Dose reported but no dose rates & no radiation types described

Table 2-4 Summary effects data on terrestrial plants, moss/lichen and fungi, based on the FASSET Radiation Effects Database (FRED).

Chronic Fungi Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background												
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999	*Armillaria* *Lycogala* *Lycoperdon*	Gamma Gamma Gamma	1(1) 1(1) 1(1)									
5,000-9,999												
> 10,000	*Armillaria* *Lycogala* *Lycoperdon*	Gamma Gamma Gamma	2(1) 2(1) 2(1)									
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	495,744			None			None			None		
Observations "rejected" (paper ID)[c]	744(1)[1]			None			None			None		
Last paper published in:	1972			None			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates, or doses.

2.4 Aquatic plants

The wildlife group aquatic plants consist of various photoautrophic protists, mostly green algae. Cyanobacteria (blue-green algae), though not part of the plant kingdom, are also included due to their ability to perform photosynthesis. The database contains 26 aquatic plant references, but [503] was incomplete and therefore excluded (no available data-points). 20 of the references concern the effects of acute irradiation, and only 5 deal with chronic exposure. The most recent paper included in the database, [799], was published in 1996, though year of issue is not specified for all references. The largest amount of effects data is categorized under the headings mortality or morbidity; however, finding the most "suitable" umbrella end-point is not straight forward when dealing with single cells/cell cultures. For instance, reduced cell growth after irradiation may be due to both inactivation of cell division and increased death of cells. If effects on reproduction in aquatic plants are limited to sexual reproduction only, it may be justified to view cell division (i.e. asexual reproduction) as vegetative growth (cf. focus on cell culture as a whole, not on individual cells). Accordingly, effects on cell growth (rate) have been treated as morbidity or mortality depending on focus in the actual references.

Based upon the references included in the database, the information on radiation effects for aquatic plants (*i.e.* algae and cyanobacteria) seems to be rather limited for doses or dose rates relevant for natural ecosystems. Most of the references included describe morphological changes and/or survival of green algae at high acute doses - typically in the 100-1000 Gy range. Information on low doses and chronic irradiation experiments is generally lacking. However, chromosome aberrations have been observed for green algae at doses in the range of 1-5 Gy and certain phases of growth of cyanobacteria may be inhibited at very low dose rates.

Table 2-5 summarises effects data on aquatic plants, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). Data on transitory exposures were only recorded for this wildlife group.

2.4.1 The effects of acute irradiation

The range of acute doses covered by the database is from 1 to several thousand Gy; most data, however, refer to high doses (>5 Gy). Two references do not contain applicable dose-information and are not, therefore, considered in the following text, these are [979] and [802].

Morbidity

Ten papers deal with various responses of aquatic plants to acute irradiation. Inactivation of nitrate reduction in cyanobacteria *Agmenellum quadruplicatum* was observed at X-ray doses of 1000 Gy, photosynthesis was also affected. Slight, negative effects on photosynthesis were also evident for the green algae *Chlorella pyrenadosain* in an anoxic environment [803]. Binucleate cells of *Cosmarium praemorsum* were observed after X-ray irradiation of 50 Gy; the frequency of such cells increased with dose up to 200 Gy. At higher doses the number of binucleate cells decreased [805]. Various morphological changes were observed in *Chlamydomonas reinhardtii* receiving a dose of 90 Gy. Some of the reported effects were: extra-nucleolar material or "patchy" nucleus, abnormal basal body configurations, increased vacuole number and vesiculation, and multiple pyrenoids [679]. X-rays were also found to interfere with the main morphogenic processes of the siphonous green algae *Acetabularia mediterranea*. Reported effects included decreased number of cells with caps at doses higher

than 1000 Gy, decreased caps with cysts above 750 Gy and a progressive increase in chloroplast starch content in the dose range 250-1500 Gy [689, 698].

Giant cells of *Sirogonium* with enlarged nuclei were observed after gamma-irradiation of 150 Gy. These cells did not undergo nuclear division [563]. For *Stigeoclonium pascheri*, the percentage of sporulation of irradiated vegetative cells decreased at gamma-doses of 100 Gy (LOED) or higher. Moreover, the germination of akinetes and germinating akinetes decreased [542]. For marine phytoplankton *Platymonas viridis*, gamma doses of 200 Gy or more caused a sharp decrease in cell growth (compared with a control). Destruction of organelles was manifested at higher doses [799]. Changes in growth rate was also observed for the green algae *Scenedesmus quadricauda* - in the first week after irradiation a reduced growth rate was observed in the dose range 60-120 Gy; in the longer term, however, growth rates for irradiated algae surpassed that of the control [798].

Mortality

Ten references associated with the mortality end-point are included in the database. The relevant studies deal with lethal doses (*e.g.* LD_{50}), survival or mortality and to some extent, growth of populations.

After X-ray irradiation, an LD_{50} of 90 Gy was reported for the cyanobacteria *Chrococcus*, whereas corresponding lethal doses for two green algae *Ankistrodesmus* and *Chlorella* were 110 and 220 Gy, respectively [286]. An X-ray dose of 200 Gy or more proved lethal to desmid *Cosmarium botrytis* [692]. For the giant, unicellular algae, *Acetabularia mediterranea*, the number of dead cells increased at dose-levels of 1000 Gy (LOED) or above [689].

The LD_{50} of *Chlamydomonas reinhardi* irradiated with protons was 50 Gy, and an RBE (proton/X-ray) of about 2 was reported in the study [801]. The lethal beta-dose for the desmid *Cosmarium subtumid* was found to be 1000 Gy [562]. Single-cell survival curves for *Closterium moniliferum* irradiated with beta-particles had flat thresholds up to 100 and 250 Gy in the presence and absence of oxygen, respectively (LOED). None of the desmid cells treated under oxic conditions survived doses higher than 300 Gy. Previously irradiated *Closterium* cells seem to be more resistant to killing by radiation than cells which have not been previously exposed (cf. induced resistance) [699, 797].

The percentage survival of colonies originated from gamma-irradiated vegetative cells of *Stigeoclonium pascheri* decreased in the dose range 100-300 Gy. Survival at 300 Gy was about 40% [542]. For the marine phytoplankton *Platymonas viridis*, the percentage of dead cells was approximately 50%, 30 days after an absorbed dose of 500 Gy [799].

Reproduction

Two references are included in the database. A study of nuclear division in the spermatogenous filaments of treated antheridia of *Nitella flagelliformis* revealed chromsome fragments at both metaphase and anaphase, formation of rings, anaphase bridges and, rarely, of micronuclei. A linear increase in the number of cells showing chromosomal aberrations with increasing dose ranging from 1 to 5 Gy was observed [800].

Mutation

Two references concerning chromosome aberrations in green algae are included in the database. For the desmid *Cosmarium subtumidum* chromosome fragments were observed at beta-doses above 50 Gy [562]. Repair of single-stranded DNA breaks in *Chlamydomonas reinhardtii* after gamma irradiation (50 Gy or more) is presented in [891].

2.4.2 The effects of chronic irradiation

Chronic effects data included in the database are very limited. As mentioned earlier, only 5 references were found. Moreover, two of those references contain non-applicable dose- data, and are therefore not considered further (*i.e.* [132] and [556]).

Morbidity

Two of the remaining references deal with low dose-rate gamma-irradiation of the cyanobacteria *Syenechococcus lividus*. Such exposure may have an inhibitory or stimulatory effect according to the kind of cells used for the irradiation. For instance, cells in the logarithmic phase of growth are inhibited when irradiated with chronic γ-radiation in the range of 1.3-8.5 μGy h^{-1}. Furthermore, the stimulating effect of chronic gamma irradiation is transitory and occurs in a very narrow dose rate range [804, 696].

Mortality

The last reference deals with the survival of the single cell green algae *Chlorella* subjected to chronic gamma doses at a rate of 3600000 μGy h^{-1}. Survival, after approximately 2 days was 20% (i.e. after receiving a dose of 200 Gy). Furthermore, the survival curve (0-15 days of exposure) reflects the gradual appearance of radioresistance [796].

Table 2-5 Summary effects data on aquatic plants, based on the FASSET Radiation Effects Database (FRED).

Acute Aquatic plants Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Cyanobacteria Green algae Green algae	X-rays Gamma X-rays	3(1) 30(3) 11(4)	Green algae Green algae Green algae	Beta Gamma X-rays	3(1) 1(1) 7(3)	Green algae	Gamma	2(1)			
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99							Green algae	Gamma	2(1)			
2.0-4.99							Green algae	Gamma	6(1)			
> 5.0	Cyanobacteria Green algae Green algae	X-rays Gamma X-rays	6(1) 132(4) 71(5)	Cyanobacteria Green algae Green algae Green algae Green algae	X-rays Beta Gamma X-rays proton	1(1) 14(3) 26(2) 46(3) 1(1)	Brown algae Green algae	Gamma Gamma	2(1) 2(1)	Green algae Green algae	Beta Gamma	1(1) 36(1)
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	542,563,679,689,698,798,799, 803,805,979			286,542,562,689,692,699,797,799, 801,802			800,819			562,891		
Observations "rejected" (paper ID)[c]	6 (979)			12 (802)			None			None		
Last paper published in:	1995			1995			1984			1986		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-5 Summary effects data on aquatic plants, based on the FASSET Radiation Effects Database (FRED).

Chronic Aquatic plants Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Cyanobacteria	Gamma	4(1)	*Chlorella*	Gamma	1(1)						
< 99.9	Cyanobacteria	Gamma	68(2)									
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999												
> 10,000				*Chlorella*	Gamma	13(1)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	132,696,804			796			None			556		
Observations "rejected" (paper ID)[c]	30(132)			None			None			1(556)		
Last paper published in:	1986			1985			None			1996		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate

2.5 Mammals

The biological effects of ionising radiation in mammals have been extensively studied since the first suspicion that ionising radiation could have a detrimental effect on health, and these efforts have yielded an enormous number of publications on mammals. Due to the large number of studies for this wildlife group, and considering the limited time available, it has been necessary to apply, in addition to the previously stated criteria, further restrictions, including:

- only papers written in English have been considered;
- a number of book chapters were excluded as they were not easily accessible;
- human data, in vitro studies, and experiments in which only cancer induction was assayed, were excluded;
- acute exposures higher than 10 Gy were excluded; and,
- experiments, in which radionuclides were administered to the animals by injection were excluded. (This administration route is unlikely to occur in the environment and the effects induced might be quite different to those obtained after inhalation or ingestion of the radionuclide.)

After applying these additional criteria, 183 references for mammals have been included in FRED, and these provide more than 3,000 data pointson the effects of ionising radiation exposure. All the references correspond to terrestrial mammals since no studies have been found on aquatic mammals. Most of the references describe studies done in the laboratory with few references on field (or controlled field) studies. Most studies are on the effects of acute exposure to relatively high doses of low LET ionising radiation administered at high dose rates. Some references describe effects of high LET radiation (mainly neutrons of different energies). There are also some references on effects of beta radiation (mainly tritium, but also betas with energy >10 keV). Rodents have been the animals more extensively used.

Table 2-6 summarises effects data on mammals, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED).

2.5.1 The effects of acute irradiation

Morbidity

Parameters analysed to determine the effects of acute irradiation on morbidity are very heterogeneous and include analyses in peripheral blood (cell counts, haemoglobin, piruvic acid content); body and organ weights (kidney, gonads, liver); damage in the central nervous system (brain and cerebellum weight, cingulum volume, learning, memory and behaviour tests); gastrointestinal damage (stomach emptying, faecal excretion of proteins); tibia growth; impaired ventilation function; opacities in the lens and defective eyes; thyroid function; eye opening and tooth eruption time. Also, the irradiation of the animals has been done at different ages (embryos, young and adult), and different radiation types and species have been used.

Within FRED, there are 20 references on effects of acute irradiation on morbidity (1 is a review article) giving 618 data (165 control data and 453 data on effects of radiation). Within the 453 data on effects of radiation, 95 correspond to mice (74 data are for gamma


radiation and 21 for neutrons), 283 to rats (277 for gamma and 6 for neutrons), 37 to dogs, 36 to donkeys and 2 to pigs (in non-rodent species, all the data are for gamma radiation, except a review article that describes the effects of beta radiation in dogs). Some information is also available on the effects of gamma radiation on cow morbidity.

Cows irradiated on day 0 of age with 2.5 Gy gamma rays, had normal levels of haemoglobin from 0 to 20 days post-irradiation. In these days a rapid decrease of the lymphocytes, accompanied by a transient but marked neutrophilic leukocytosis was seen. The thrombocytes usually remained at normal levels for about one week after irradiation, followed by a rapid decrease until day 20 post-irradiation. Thereafter, the content of peripheral blood cells started to recover [791].

Donkeys exposed to gamma radiation at doses of 5, 5.8, 7.22 or 8.07 Gy showed no effects on red blood cells up to 3 weeks post irradiation. For pyruvic acid concentration and thyroid uptake of I-131**,** no dose-effect relationship was seen and only some of the doses assayed induced changes in both parameters [654].

No effect on body weight of rats was seen after gamma irradiation with doses from 0.01 to 0.1 Gy administered at 3, 6, 10, 13 or 17 days of age [723, 806].

Dogs at 2 days of age, exposed to 3.3 Gy gamma radiation, showed reduced body weight compared with the control group 14, 22 and 200 days after exposure, but no effect on body weight was seen 4, 8 and 70 days after irradiation. No significant differences between rate of renal growth in irradiated and control dogs were seen from day 14 to 200 post-exposure [558].

Irradiation of rats with 0.25, 0.5 or 1 Gy gamma rays, did not produce significant effects on whole brain weight or cerebellum weight, regardless of the dose administered and the age of the rats when irradiated (0, 3, 6, 10, 13 or 17 days after birth) [723]. Significant increases in pyknotic cells (6 hours after irradiation) were seen in rats exposed at 3, 6, 10, 13 or 17 days of age to 0.06 Gy gamma rays, while no effect was seen in rats irradiated at 0 days of age [795].

Mice exposed to 10 Gy gamma radiation showed a decreased ratio of actual tibia growth against potential growth. The value of the rate was 0.75-0.79 at 1-3 weeks after irradiation and 0.26 on week 4 after irradiation. Lower doses of 14 MeV neutrons were needed to reduce tibia growth in mice (3-fold reduction after 5-7.5 Gy) [669].

Adult mice exposed to 0.8-1.6 Gy gamma radiation showed a nearly 2-fold increase in the number of opacities in the posterior region of the lens. The LOED (Lowest Observable Effect Dose) for this endpoint varied depending on the time after irradiation when the analysis was done (1.6, 0.8 and 1.2 Gy at 3, 8 and 20 months after irradiation, respectively). In mice irradiated with 14 MeV neutrons, the LOED for increased opacities in the posterior region of the lens were 0.165 Gy at 3 months post irradiation and 0.076 Gy on months 8 and 20 after exposure [598].

A study of mice irradiated with doses from 0.0002 to 1.04 Gy of neutrons with different energies (0.43, 1.8 or 14 MeV) showed that the 0.43 MeV neutrons were the most effective in inducing minute optical defects [1048].

Different parameters have been measured to estimate damage in the gastrointestinal system after acute irradiation. Rats irradiated with 0.7 or 1 Gy of neutrons showed slower stomach emptying than the control group, 4 and 12 hours after irradiation, suggesting radiation sickness in the irradiated rats. Doses of 5.5 Gy did not modify the leakage of protein through the intestine (an indicator of gastrointestinal damage) [702].


In gamma irradiated pigs the LOED was 11.5 Gy for impairment of the ventilation function [773].

Many references describe the morbidity effects after an acute irradiation during the gestation phase of mammals. In mice, gamma irradiated on day 20 of prenatal life, the LOED for body weight reduction was 1.5 Gy. Doses up to 1.5 Gy did not cause any alteration in crawling behaviour. No effects on offspring mean left eye opening and lower jaw tooth eruption times were seen. The LOED was 1.5 Gy for upper jaw tooth eruption time and mean cliff avoidance (behaviour). No significant differences between males and females were observed in any of the parameters assayed [719].

Irradiation of mice on day 17 of gestation with doses from 0.3 to 1.5 Gy had no effect on brain weight/body weight ratio at 6 months after irradiation. An LOED of 1.0 Gy for learning and memory tests was described. The LOED for a locomotor test was 0.3 Gy. It has been suggested that retardation of higher brain functions due to exposure during the late foetal period may have a threshold of 0.3 Gy [636].

Rats exposed on day 9 or 17of gestation to gamma radiation (doses of 0.4, 0.6 or 0.8 Gy) showed no differences compared with controls on postnatal growth rates, although exposure on day 17 caused prenatal growth retardation. Rats irradiated on day 9 of gestation had a significant reduction of gonadal weight. No other significant changes in organs weight (brain, liver, kidney) were seen in the irradiated groups. The results show that, although low dose irradiation on day 17 of gestation causes prenatal growth retardation, it does not affect post-natal offspring growth rate [709].

Gamma irradiation of pregnant rats on days 10, 13 or 15 of gestation, with doses of 0.2 Gy or higher, increased the number of pyknotic cells (10-21% increase). The ventricular zone of the central nervous system of day 13 foetuses was the most radiosensitive. The highest radiosensitivity in terms of acute cell death was seen in the same developmental stage of the brain, *i.e.* the beginning phase of cerebral cortical histogenesis, in both mice and rats [785].

Irradiation of rats on day 11 of gestation with doses from 0.5 to 2.0 Gy of gamma rays, increased the percentage of animals with one or two eyes defective at 30 days of age, although there was not a clear dose-effect relationship. The incidence of defective eyes was dose rate dependent (animals with defective eyes after 1.5 Gy administered at dose rates of 600,000 and 1,980,000 μGy h^{-1} were 18 and 100%, respectively) [600].

Irradiation of rats on day 15 of gestation with gamma doses of 0.455 Gy reduced brain weight (18.6% reduction). Doses of 0.1 and 0.15 Gy significantly reduced the cingulum volume (9.8 and 15.6% reduction, respectively) [659]. A reduction of 10% in the body weight, as compared with controls, was seen at 1, 21 days and 3 months of age, after exposure to 0.75 Gy. No differences between irradiated and control rats were seen on continuous corridor activity at 1 month of age, while at 3 months there was an increase in the number of turns in irradiated rats (39 turns) compared with controls (29 turns). Control rats increased their time spent standing by about 50% in males and 20% in females from 1 to 3 months of age. Irradiated males increased standing only 10% and irradiated females decreased their standing time by 30% from 1 to 3 months of age. These results support other evidence that some behavioural alterations from perinatal exposure to radiation become more marked with maturation. No significant differences with controls were seen in the gait of irradiated male rats at either 1 or 3 months of age, while female rats had a significantly shorter and wider gait following irradiation [713].

Irradiation of male pigs with a single gamma dose of 3.0 Gy, had no effect on birth weight of the descendants [779].

RBE values for neutrons of different energies, in different species and for different endpoints, have been described. The RBE for neutrons became much more than 10 at low doses, and at the energy of 0.43 MeV it appears to exceed 100 for a dose of 0.00022 Gy. Such RBE values are far larger than those hitherto reported for mammals [1048].

Mice irradiated with 14 MeV neutrons showed RBE values for tibia growth from 2.0 to 3.6, depending on the dose. No differences in RBE were found with age [669]. RBE values for induction of opacities in the posterior region of the lens in mice varied from 4 to 63, depending on the dose range considered and on the time when analyses were done [598].

In pigs irradiated with 42 MeV neutrons, an RBE value < 1.2. for acute reaction of the lung (3-9 months) was determined. The RBE for late lung damage (15-24 months) was 1.4 [773].

Mortality

The parameters assayed have been doses needed to kill 50% of the animals (at different days after irradiation $LD_{50/6}$, $LD_{50/30}$, $LD_{50/60}$) or the capacity of radiation to produce life shortening.

There are 23 references in the database on effects of acute irradiation on mortality (2 references correspond to review articles) that provide 400 data (101 control data and 299 on effects of radiation). Within the 299 data on effects of radiation, 9 correspond to cattle, 11 to pig, 19 to donkey (in the three species gamma radiation was used), 28 to dog (6 for alpha and 22 for gamma radiation) and 232 to mouse (162 for gamma and 70 for neutrons).

The LD_{50} for the gastrointestinal syndrome varied with the species studied, with values of 11-12 Gy for rodents and 8 Gy for dogs [633]. In mice there are data on the influence of dose rate on $LD_{50/6}$, showing that LD values increased as the dose rate decreased ($LD_{50/5}$ of 11.24 and 23.32 Gy for dose rates of 844,200,000 and 2,436,000 $\mu Gy\ h^{-1}$, respectively) [610].

For high LET radiation (neutrons) $LD_{50/6}$ values were lower than for low LET radiation ($LD_{50/6} = 3.77$ Gy) [1054].

LD_{50} values for the haemopoietic syndrome vary from 1.6 to 10 Gy, depending on the species studied [633]. In donkeys exposed to gamma rays $LD_{50/30}$ values between 5.8 and 7.84 Gy were obtained [627, 654]. Adult pigs irradiated with gamma rays showed an $LD_{50/30}$ of 6.18 Gy, while irradiation of 14 day-old pigs gave values of $LD_{50/30}$ of 2.86 and 3.38 Gy in conventional and germ free piglets, respectively [720]. In cows exposed to gamma radiation, 100% mortality within 24 hours was seen after 2.5 Gy doses, while irradiation with 1.5 Gy had no effect on survival during 360 days [791]. Mice irradiated with gamma rays showed $LD_{50/30}$ values between 6.21 and 8.5 Gy.

Lethal doses are influenced by several factors. For example,fractionation of the dose increased the dose needed to kill 50% of the animals (in mice $LD_{50/30}$ values of 6.21 and 11.2 Gy were described for single dose and 10 fractions in 12 days, respectively) [1054]. Differences in LD values have also been observed between germ free mice and those housed in a vivarium ($LD_{37.5/30}$ of 9 and 8 Gy, respectively) [1034]. No differences in $LD_{50/30}$ values were observed between males and females in pigs [627] donkeys [654] and mice [1034, 1054].

As for the gastrointestinal syndrome, LD_{50} values for the haemopoietic syndrome after high LET irradiation (neutrons) were lower than for low LET radiations (3.38-3.62 Gy in adult mice) [716, 1054].


No effect on survival of adult mice has been seen at doses up to 0.64 Gy of gamma radiation [1043]. However, the irradiation of mice during the developmental stage with doses of 0.009 or 0.050 Gy increased the postnatal mortality. The magnitude of the effect was dependent on the gestation day on which irradiation took place (preimplantation, early organogenesis or late organogenesis). The postnatal mortality rate increased compared with control values in all the irradiated groups except in the group receiving 0.009 Gy during the preimplantation phase. Offspring exposed on day 6.5 of gestation showed an LOED of 0.05 Gy in postnatal mortality [1038].

Regarding the effects of acute irradiation on life shortening, data are available for mice and dogs. In adult mice exposed to gamma radiation, the LOED for life shortening was 0.9 Gy (33.8% reduction) [1042].

Several factors affect the life-shortening produced by acute irradiation in mice: the strain of mouse used (4 Gy gamma radiation reduced life time to 61 and 88% the control values in RFM and BALB/c mice, respectively) [1029]; the fractionation of the dose administered (life shortening per cGy of 0.4 ± 0.035 and 0.2 ± 0.01 for single dose and 24 weekly irradiation, respectively). No significant differences were seen between sexes [591].

The life shortening induced by 5.7 Gy of gamma radiation in adult mice was very similar regardless of the age at irradiation (17 days post coitus, at birth or 35 days of age) [666]. The same results have been obtained in dogs. Exposure to doses of 0.159-0.883 Gy of gamma radiation had no significant effect on the lifetime of the dogs, regardless of whether the irradiation was done on day 2, 8 or 28 post coitus or 2 days after birth [1047].

Irradiation of male mice with 3.0 Gy gamma rays (mated with control females) had no effects on life span of the F1 offspring [590].

Several studies have been done on the effect of high LET radiation on life shortening, mainly in mice exposed to neutrons. LOED values of 0.05 and 0.1Gy neutron radiation were seen in female and male adult mice, respectively [587, 1042]. Unlike the case with low LET radiation, no differences were detected in the effect of neutron irradiation in life shortening in different strains of mice (80 and 78% life shortening after 0.47 Gy in BALB/c and RFM mice, respectively) [1030]. Life shortening (days) per cGy for adult mice exposed to a single dose of 0.85 MeV neutrons were 2.4 ± 0.59 for females and 1.75 ± 0.25 for males. Fractionation did not significantly increase the values for life-shortening per cGy [591]. Neutrons of 1 and 5 MeV had the same effectiveness inducing life shortening [614].

Two studies are included in the database on the effects of Pu-238 (inhaled) on mortality of dogs. Male and female dogs were exposed to single inhalation of Pu-238 (two sizes of particles were used, 1.6 and 2.9 micron AMAD, although no differences between them were seen either in distribution or in the effects produced). Doses of 1.64 Gy or higher (cumulative dose in lung to death; ILB = 1.05 KBq/kg body weight) reduced the lifetime of the dogs to 80% the control value [626]. Dogs exposed by inhalation (10-30 min nose-only) to $^{238}PuO_2$ showed no reduced survival with doses up to 3.1 KBq (ILD: initial lung deposition). Reductions in survival to 56 and 38% of the control values were seen after exposure to 52 and 210 KBq (ILD), respectively [631].

RBE values have been described for the effects of neutrons on mortality and life shortening of mice. Fast neutrons showed a RBE of 2 for $LD_{50/30}$ (compared with gamma radiation) [716]. RBE values for 5.6 MeV neutrons were 1.84 ± 0.12 for $LD_{50/30}$ and 2.25 ± 0.12 for $LD_{50/6}$. RBEs did not significantly change with fractionation [1054]. A RBE of 12.3 for mean survival of mice was seen for 1.5 MeV neutrons [1043].

For life shortening in mice, RBE values for fission neutrons were 2.4-3.8 for doses ranging from 0.5 to 4 Gy [1029]. Values within that range were obtained for 1 or 5 MeV neutrons (RBE = 2.9) [614]. No differences were seen in RBE values for fission neutrons in RFM and BALB/c strains of mice [1030].

For both single and fractionated exposures, the RBE of 0.85 MeV neutrons varied inversely with the square root of the neutron dose (for doses between 0.2 and 2.4 Gy). For doses of 0.2 Gy, RBEs for life shortening per cGy were 6.7 (males) and 8.8 (females) for single exposure and 18.2 and 23.2 for fractionated exposures [591]. Other studies have also shown that RBE values for fractionated neutron exposures, at any given dose, are about twice that for single dose [587].

For doses between 0.01 and 0.4 Gy, an upper limit of the RBE exists for life shortening from all causes of death after single neutron exposures; this value is 15 ± 5.1. The RBE values vary between 2 to 24 depending on the cause of death considered [1042].

Reproductive capacity

The processes studied regarding reproductive capacity are either related with fertility (fertility span, female and male reproductive cells, testes and ovary weight, implantation sites, changes in mounting) or with fecundity (litter size, litter number, sex ratio, embryos with malformations, preimplantation or postimplantation death).

There are 41 references in the database on effects of acute irradiation on reproductive capacity (1 is a review article), that provide 970 data (207 control values and 763 data on effects of irradiation). Within the 763 data on reproduction effects, 13 correspond to bulls, 8 to hamsters, 250 to rats (12 are for beta radiation < 10keV, 182 for gamma radiation and 56 for neutrons) and 492 to mice (3 for beta radiation < 10keV, 381 for gamma radiation, 3 for mixed radiation (neutron + gamma) and 105 for neutrons).

The studies on the effects of acute irradiation on reproductive capacity are extremely heterogeneous, making the comparison of results from different studies very difficult.

Exposure of mice to 0.015 Gy of gamma radiation just after mating (fertilised mouse eggs prior to cleavage) increased the percentage of abnormal early embryos measured at 6 and 24 hours after irradiation. Even at this low level of exposure the first cleavage was delayed and there was an 8-fold increase in the number of ‘abnormal’ in the irradiated group. The anomalies included cytoplasmic damage appearing as a wave of necrosis over the egg, hyperchromaticity of both cytoplasm and nucleus, exudation of cytoplasm through ruptured cell membranes, pyknosis of nuclei and congealing chromosomes. These anomalies are rarely, if ever, found in the controls. On the basis of this and other recent studies it is believed that the newly fertilised egg is probably the most radiosensitive cell in the mouse, except possibly the germ cell [776].

In mice gamma irradiated 7 hours after presumed fertilisation, the LOED on day 19 of gestation for an increase in early resorptions and reduced embryos alive was 0.5 Gy (3-fold increase and 1.6-fold decrease, respectively). The LOED for foetus with external malformations was 0.1 Gy (8-fold increase). No effects on foetal resorptions were seen at any of the doses assayed [596].

Gamma irradiation of mice with 1.5 or 2.0 Gy, 2 hours after mating, increased the number of foetuses alive that were abnormal (3 and 5-fold increase, respectively), and decreased the percentage of implants per female (2-3 fold decrease) [662].

After gamma irradiation of mice on day 7.5 of gestation, the LOED for total prenatal mortality 18 days post coitus was 1.2 Gy (dose rate 7,920,000μGy h^{-1}). With doses equal or higher than 1.2 Gy, mortality increased in a dose-dependent manner [599].

Exposure of mice with doses between 0.05 and 2 Gy of gamma radiation produces a dose-dependent increase in late post-implantation death, pre-implantation death and percentage of malformed foetuses, and a dose-dependent decrease in surviving foetuses [714].

Adult male mice were exposed to gamma radiation either with a single dose of 2.75 Gy or with a daily dose of 0.05 Gy during 55 days. Males were kept celibate for 70 days after irradiation and then mated with control females. Exposure to single doses of 2.75 Gy increased the number of lost litters by F1 females (73 compared with 56 in controls) and the percentage of dead implants (10.75 compared with 7.70 in controls). A decrease in the percentage of pregnant females following mating with irradiated males was also observed (54.49 compared with 59.35 in controls). No effect was seen in percentage survival in weaned litters (80.10 compared with 81.44 in controls). The F1 females from the irradiated groups showed no significant effects on productivity or fertility when compared to the control group. The fractionation of the dose led to no significant effects on any of the parameters assayed. [1032].

Adult female mice gamma irradiated with a single dose of 5 Gy showed a reduced number of implantation sites (8.7 compared with 10.4-11.0 in controls). No reduction was seen in the number of pregnant mice. The LOED for relative survival of embryos to day 16 was 2.5 Gy (rate of 0.87) [1037].

Mice were gamma irradiated on gestation days 3.5 (preimplantation); 6.5 (early organogenesis) or 11.5 (late organogenesis) with doses of 0.009 or 0.05 Gy. No effects were seen on litter size and sex ratio, regardless of the dose or the day of irradiation. The LOEDR was 0.05 Gy for postnatal mortality in the mice irradiated on day 6.5 of gestation (16.1% as compared with 10% in controls), while no effect was seen when the same dose was administered on day 3.5 of gestation [1038].

In utero gamma irradiation of mice during the pronuclear zygote stage not only increased the prenatal mortality in a dose dependent manner (doses from 0.1 to 1.0 Gy), but embryos also died earlier in development. With all the doses assayed, radiation-induced deaths occurred before day 11 of gestation, since as a result of irradiation the early pronuclear zygote cannot progress to a less radiosensitive phase [1049].

In mice gamma irradiated on day 2 of gestation, the LOED was 1.0 Gy for preimplantation death on day 19 of gestation (11% compared with 5% in controls) and for surviving foetuses at the same day (78% compared with 87% in controls). The number of surviving foetuses is strongly dependent on the day of gestation when the irradiation was done, with day 1 showing the highest and day 6 the lowest effect on survival. On day 1, the major contribution to prenatal mortality originates from preimplantation death, whereas the number of early resorptions gains more significance when the radiation exposure is done at later stages of the preimplantation period. Significant increases in the number of malformations were seen when 1 Gy was administered 1 or 3 hours after conception, but no effect was seen after irradiation at 6 or 12 hours after conception. Irradiation on day 8 of gestation with 1 Gy did not reduce survival whereas 7.4 % of the foetuses showed a macroscopically visible malformation, mainly gastroschisis and exencephaly. A high number of whole resorptions (90%) was only seen after 3 Gy administered on day 8 of gestation [1036].

Gamma irradiation of male mice with 3 Gy (mated with non-irradiated females), did not reduce the life span of F1 (females and males), but decreased mean litter size (49 compared with 71 in controls). Sex ratio was not affected by 3 Gy irradiation [590].

In mice exposed to gamma radiation, although depression in mounting (coital) behaviour was seen at some doses, no positive correlation with dose could be established [661].

Exposure of 10 day-old female mice to doses from 0.05 to 0.3 Gy gamma radiation, reduced the number of early oocytes 72 hours post irradiation [544]. After exposure of 14 day-old mice an LD_{50} for oocyte survival of 0.054 Gy was observed [1028]. When radiation was administered at older ages (18 days old female mice) doses higher than 0.1 Gy were needed to reduce the number of primary oocytes [1031]. These studies show that early oocyte stages in young mice are extremely sensitive to acute irradiation.

In mice gamma irradiated on the first day of life the LOED was 1.5 Gy for testis weight and percentage of tubules with deprived spermiogenesis. Doses of 3.0 Gy or higher were needed to increase the percentage of degenerated giant cells in the lumen of seminiferous tubules and the percentage of Leydig cells in the stroma of the testis. The percentage of Sertoli cells in the lumen of the tubules increased only after 4.5 Gy. Late pathomorphological changes in testis were not correlated with changes in the hypophysis [548].

Male mice exposed to 6 or 8 Gy gamma radiation showed mean times of return to fertility of 81.0 ± 4.1 days and 104.8 ± 7.8 days, respectively. No differences were seen in time of return to fertility between groups exposed to single or fractionated irradiation (2 fractions). When mating with control females, all irradiated groups gave higher rates of intrauterine death and lower implantation rates than controls [707].

Gamma irradiation of mice with 1 or 3 Gy produced an increase in necrotic and degenerating type A spermatogonia just after exposure, but returned to control values 72 hours later. Type B cells, as would be expected on the basis of normal spermatogenesis, lag behind type A cells in repopulating the seminiferous tubules. Cell death was the primary factor in radiation-induced depletion of spermatogonia after acute exposure, since radiation-induced mitotic inhibition in spermatogonia was similar to that observed in other mitotically dividing cells and was not a major factor in depletion of the seminiferous epithelium [780]. Although the number of spermatogonia in mice decreased soon after the exposure to gamma radiation, after several hours (depending on the dose administered) it tends to start recovering [706, 778].

In mice exposed to gamma radiation, D_o (i.e. linear regression analysis against dose) values for different spermatogonia types were determined 10 days after irradiation. Thus D_o for undifferentiated spermatogonia was 2.2 Gy; for paired spermatogonia, 1.0 Gy; and, for aligned spermatogonia, 0.7 Gy [656].

Adult mice gamma irradiated showed an LD_{50} for late type A, intermediate and early type B spermatogonia of 0.20-0.24 Gy, all of them showed similar radiosensitivity. LD_{50} for spermatozoa and spermatids (28 days after irradiation) was 0.64 Gy. Testes weight 28 days after irradiation was reduced to 50% the control value after exposure to 3.62 Gy [710, 721, 1033].

In neutron irradiated female mice (on day 8 post coitus), the LOED for percentage of total prenatal mortality on day 18 post coitus was 0.354 Gy [599].

Exposure of mice to neutron radiation doses from 0.12 to 0.75 Gy had no effect on mean number of surviving foetuses per female. Doses of 0.5 Gy or higher increased the early post implantation death, while increase in late postimplantation death was induced with doses of


0.75 Gy (or higher). Doses as low as 0.12 Gy increased preimplantation death (18.6% compared with 4.4 % in controls). Surviving foetuses decreased as the dose increased (92.1% in control; 74.5% after 0.12 Gy and 26.6% after 0.75 Gy). Doses of 0.25 Gy or higher increased the percentage of both malformed foetuses (6.88 % compared with 0.93% in controls) and of skeletally malformed foetuses (7.6% compared with 3.9 % in controls) [714].

Pregnant mice irradiated with fast neutrons (0.53-1.94 Gy) showed no alteration in the number of implantation sites per pregnant mouse after doses up to 1.21 Gy. The number of pregnant mice decreased after exposure to 0.82 Gy, but not in those groups irradiated with 1.04 or 1.21 Gy. Decrease in relative survival of embryos to day 16 was seen with doses of 0.82 Gy or higher (survival ratio of 0.75 after 0.82 Gy) [1037].

In utero, irradiation of mice with 1.2 MeV neutrons during the pronuclear zygote stage decreased the number of live embryos on day 16 of gestation when doses of 0.1 Gy or higher were administered. With increasing doses, not only did prenatal mortality increase, but embryos also died earlier in development [1049].

Mice (14 days old) irradiated with different energy neutrons showed LD_{50} values for oocyte survival of 0.039 Gy for 0.43 MeV neutrons, 0.065 Gy for 15 MeV neutrons and 0.07 Gy for ^{252}Cf fission neutrons. For gamma radiation the LD_{50} value was 0.054 Gy. The results showed that neutrons (of several energies) and gamma rays were equally effective at killing oocytes, which are known to be extremely radiosensitive [545, 1028].

Neutron irradiation of mice gave LD_{50} values for type B spermatogonia of 0.05, 0.06 and 0.1 Gy for neutrons with energies of 1, 3 and 5.6 MeV, respectively [710]. Exposure of mice to 5.5 MeV fast neutrons gave LD_{50} values of 0.14 Gy for spermatozoa and spermatids 28 days after irradiation and reduced testes weight (50% the control value after exposure to 0.85 Gy) [721].

Mice exposed to beta radiation (< 10keV) at 14 days of age (doses from 0.00792 to 0.792 Gy) showed no modification in the number of maturing oocytes. Reduction in primary oocyte numbers were seen after exposure to 0.0792 Gy (50% the control value) but the maturing follicles were normal in number, indicating that the effect is predominantly on primary oocytes [262, 545].

In rats exposed to 1.5 Gy gamma radiation at day 9.5 of gestation, a dose rate-dependent increase was observed in resorption rate (48.34 % at 300,000 $\mu Gy\ h^{-1}$; 60.71% at 60,000,000 $\mu Gy\ h^{-1}$, compared with 2.84% in controls). A dose rate-dependent decrease in percentage of live foetuses at term was observed (51.6 % at 300,000 $\mu Gy\ h^{-1}$; 39 % at 60,000,000 $\mu Gy\ h^{-1}$, compared with 94.3% in controls). A dose-rate dependent increase in mean resorptions per litter was also seen (5.1% at 300,000 $\mu Gy\ h^{-1}$; 7.8 % at 60,000,000 $\mu Gy\ h^{-1}$, compared with 0.3% in controls). No effects on mean term weight or placental weight at term were seen at any of the dose rates assayed. An increase in malformed embryos was described in the irradiated groups [595].

In gamma irradiated rats, on day 9.5 after conception, the LOED was 2.05 Gy for the four parameters analysed 21.5 days after exposure: body weight of offspring, intrauterine death, live offspring and percentage of malformed offspring. The LOED decreased to 0.25 Gy when neutrons were administered [597, 1022].

Exposure of 8 day-old rats to 0.06 Gy gamma radiation lead to a reduction in litter size and in the body weight of pups on the weaning day (85% the control value). The reduced litter size was a consequence of increased death rate of embryos (5-fold increase) [546].

Exposure of rats on day 14 (oogonia) or 18 (zygotene) of gestation to 5 Gy gamma radiation was lethal for germ cells. Irradiation on day 16 of gestation (leptotene) could have a sublethal effect. Differential sensitivity could depend on the meiotic stage at time of irradiation [717].

Rats gamma irradiated on day 15 of gestation with 0.95 Gy, showed increased percentage of cross section of sterile seminiferous tubules and decreased total number of germ cells and testes weight [604].

Rats (aged 2 or 12 days) exposed to 2.85 Gy gamma radiation showed permanent reduction in the stem spermatogonial population (analysis done from days 5 to 120 post irradiation). The loss of testicular weight observed 24 days after exposure was a consequence of the loss of spermatocytes through mature depletion. By 40 days post irradiation much of the spermatocyte population was restored, but the pre-irradiation stock of spermatids had matured and flowed from the testis, resulting in losses of testicular weights. The results showed that irradiation produced a permanent decrement in the stem spermatogonial population which was age dependent [784].

Long term damage to the reproductive system of the male rats has been described after whole body exposure to a single dose of 0.1 Gy gamma radiation [806].

Female Chinese hamsters exposed to 1 Gy gamma radiation at 4 days of age, showed significantly reduction of the fertility span (17% the control value). No significant effects were seen when the same dose was administered at 0, 2 or 14 days of age [788].

Bulls gamma irradiated with single doses between 0.38 and 2.20 Gy, showed a significant reduction in the number of germ cells in the seminiferous tubules at 30 and 60 days of age (10% the control value). No clear dose or dose-rate relationship was observed [603].

Several references give information on RBE values, mainly for neutrons in mice.

In female mice neutron irradiated, an RBE value of 2.4 - 3.4 was seen for prenatal lethality and induction of major malformations. However, these values were calculated for relative high doses of neutrons [599].

Mice irradiated with 0.25 Gy of neutrons showed RBE values of 0.85 for early post-implantation death, 1.6 for pre-implantation death, 0.86 for surviving foetuses and 3.05 for malformed foetuses [714].

Fast neutrons administered to pregnant mice at doses from 0.82 to 1.21 Gy showed an RBE value of 4 for relative survival of embryos to day 11 - 14 or 16 [1037].

Rats exposed to neutrons on day 9.5 of conception showed an RBE of 5.8 for embryotoxic effects on day 21.5 post conception [597].

In mice irradiated with neutrons, the RBEs for oocyte killing were 3 (for doses of 0.05 Gy), 1.8 (for doses of 0.1 Gy) and 1.7 (for doses of 0.2 Gy) (545). For mice primary oocytes the RBE for beta radiation (< 10 keV) was 1.1 - 3.5 for dose ranges of 0.039 - 0.246 Gy [545].

In mice exposed to 5.5 MeV fast neutrons an RBE of 4.25 for a number of spermatozoa and spermatids 28 days after irradiation was described [721]. Mice exposed to neutron doses of 0.2-0.25Gy, showed RBEs for 50% survival of spermatogonia B of 5.7, 4.6 and 3.0 for 1, 3 and 5.6 MeV neutron [710].

2.5.2 The effects of chronic irradiation

As already mentioned, there are relatively few studies on mammals chronically exposed to ionising radiation, compared with the number of studies done after acute irradiation. Most of the chronic exposure studies have been done with rodents irradiated with gamma rays.

Morbidity

The parameters analysed to determine effects of chronic irradiation on morbidity have been: body weight, brain atrophy, peripheral blood cell counts, biochemical parameters (hormone concentrations) and thyroid dysfunction.

There are 9 references on effects of chronic irradiation in mammals morbidity (1 is a review article), providing 130 data (31 control values and 99 for effects of radiation). Most of the data correspond to rodents (mouse and rat; 70 data: 34 correspond to gamma radiation and 36 to beta radiation with energy < 10 keV), with one study carried out in dogs exposed to gamma radiation (22 data) and one in sheep exposed to I-131 (7 data).

The data on morbidity are very heterogeneous in relation to the endpoints studied, the species and radiation type used, and the age at which animals were irradiated.

Gamma radiation produced no significant effects on body weight of adult mice when administered at 16 μGy h^{-1} for up to 960 days (total dose 0.361 Gy) [1046]. Rats irradiated with up to 2,919 μGy h^{-1} during up to 90 days (total dose 6.3 Gy) showed a slightly slower growth rate than the control group, but the reduction in body weight was not statistically significant [671, 724].

Dogs exposed to 854.5 μGy h^{-1} gamma radiation for 53 to 1,862 days (total doses from 1 to 35 Gy) showed no significant reduction in erythrocyte numbers in peripheral blood. Lymphocytes, thrombocytes and neutrophilic granulocytes decreased within the first 200-500 days after irradiation (cumulative doses 3.8-9.0 Gy) and remained stable at subnormal levels until 1,700 days after exposure [790].

Adult dogs exposed, via inhalation, to Sr-90 (beta irradiation >10keV), showed depressed platelet and neutrophil counts 1,000 days after irradiation (lower initial skeletal dose rate 179.2 μGy h^{-1} corresponding to a long-term retained burden (LTRB) of 0.04 MBq Sr-90/kg). With the exception of those dogs receiving LTRB lower than 0.37 MBq/kg (initial skeletal dose rate of 1,833 μGy h^{-1}), all exposed dogs had depressed lymphocyte values through 1,000 days. Depression of erythrocyte mass occurred only in dogs with LTRB greater than 0.37 MBq/kg (initial skeletal dose rate of 1,833 μGy h^{-1}). By 150-200 days after inhalation, most hematologic parameters had gradually returned to normal levels (in those dogs surviving to 4,000 days) [632].

Sheep fed with 1,800 μCi d^{-1} of I-131 (1,785,833 800 μGy h^{-1}) during 420 days showed decreased levels of peripheral leukocytes (50% the control values). Dose rates < 5μCid^{-1} (< 8,917 μGy h^{-1} in thyroid) had no apparent effect in the thyroid function. Moderate to slight damage in the thyroid was observed in sheep treated with dose rates of 15 and 30 μCid^{-1} (11,917 or 23,792 μGy h^{-1} in thyroid, respectively). Higher dose rates (135 μCid^{-1}; 148,750 μGy h^{-1} in thyroid) produced severe thyroid damage, with ablation at dose rates higher than 240μCid^{-1} (208,333μGy h^{-1} in thyroid). A reduction in mean weight gain in first-year and in thyroid weights of six-year-old ewes was observed after exposure to dose rates >5 μCid^{-1} (8,917 μGy h^{-1} in thyroid) [623].

Rats irradiated with beta radiation (H-3 in the drinking water) at a dose rate of 1,250 μGy h^{-1} during 42 days (total dose 1.26 Gy), showed no significant modifications in the concentration


of different hormones analysed (dopamine, follicle stimulating hormone and norepinephrine), regardless that the irradiation started the first day of pregnancy, the day of birth, or at 42 or 74 days of age [1024].

Gamma irradiated rats, at dose rates between 417 and 5,542 μGy h^{-1} during the gestation period (days 12 to 16 or 14 to 20 post-coitus), showed significantly reduced brain weight. A significant reduction in cingulum volume was also observed in rats exposed to a cumulative dose of 0.8 Gy during days 14 to 20 post coitus. The cingulum is a particularly radiosensitive structure in the prenatal central nervous system [659].

Pregnant mice were exposed to tritium (beta radiation <10keV) on day 12.5 of gestation, at a concentration that gave cumulative doses during 7 days (until the end of gestation) to offspring of 0, 0.05, 0.10 or 0.30 Gy (dose rates of 297, 595 and 1,786 μGy h^{-1}, respectively). The LOEDR was 595 μGy h^{-1} (0.1 Gy) for the three endpoints studied: food labyrinth tests (mean time in finding food), learning and memory tests (hole board dipping test-number of holes dipped) and locomotor tests (open field test, latency to leave centre). However, the uncertainty was very high in the three parameters assayed. Analysis of the mistakes in the food labyrinth, water maze, avoidance acquisition and avoidance maintenance tests, indicated that the irradiated animals, especially those of the 595 and 1,786 μGy h^{-1} groups, had difficulties in both learning and memory retention for skill performance, though they showed hyperactivity in their young age period [787].

No RBE data are available for morbidity effects after chronic irradiation of mammals.

Mortality

The parameters analysed in mortality studies are mainly lethal doses for animals ($LD_{50/30}$, $LD_{50/60}$) or life shortening induced by radiation.

A total of 20 references in the database describe effects of chronic irradiation on mammals mortality (1 reference is a review article). The data available are 366: 64 data for control (non exposed groups) and 302 data on effects of radiation (242 in mice; 42 in dogs, 8 in goats, 5 in sheep and 5 in guinea pigs). Within the 242 data in mice, 3 correspond to beta radiation (< 10 keV), 204 to gamma radiation and 35 to neutrons. Except for 7 data with beta radiation (< 10 keV), all the data in species different to mice correspond to gamma radiation.

LD_{50} values have been obtained after chronic gamma irradiation in different species. It seems that there are no data on LD for dose rates lower than 4,000 μGy h^{-1} and for periods of exposure exceeding 60 days [633].

In adult mice, LD_{50} values of 27.6 and 7.72 Gy were obtained for dose rates of 48,000 and 25,300,000 μGy h^{-1}, respectively. It was observed that the LD_{50} was relatively independent of the dose rate, between 2,400,000 and 25,300,000 μGy h^{-1} [628]. For lower dose rates, the accumulated dose needed to induce mortality increased as the dose rate decreased. No effects on survival have been observed at dose rates of 3,750 μGy h^{-1} or lower (even after 700 days of exposure) [1021].

Combining the data on mortality induced by gamma radiation in four strains of mice and for both sexes, the excess mortality ratios (/Krad) have been calculated for different ranges of dose rates: 0.194 ± 0.012 for dose rates of 1,320-2,000 μGy h^{-1}; 0.3 ± 0.05 for dose rates of 24,000 μGy h^{-1}; and 0.41 ± 0.06 for dose rates of 31,800 μGy h^{-1} [615].

In sheep, $LD_{50/60}$ values of 6.37 and 2.37 Gy were seen at dose rates of 20,000 and 6,600,000 μGy h^{-1}, respectively [609].

Dogs exposed to gamma radiation showed LD_{50} values of 3.44 and 40 Gy for dose rates of 9,000,000 and 4,167 μGy h^{-1}, respectively. At dose rates < 2,000 μGy h^{-1} LD_{50} values could not be determined [683].

In adult goats, the $LD_{50/30}$ was 5.5 Gy for gamma radiation [620].

Even when mammals do not die after radiation exposure, their life can be shortened, an effect relevant for the potential consequences at the population level.

No effects have been observed in life span of adult mice exposed to dose rates of 460 μGy h^{-1} gamma radiation, or lower (during up to 526 days) [614]. Moreover, mice exposed to 8.1 and 16.2 μGy h^{-1} during up to 32 months, showed a significantly higher life span than the control group. These results support the possibility of no harmful effects (hormesis) of low LET radiation [1046].

Dose rates of 959 μGy h^{-1} gamma rays administered to mice during 735 days (16.8 Gy) reduced survival time to 66% the control value [618]. Higher dose rates were more effective in reducing life span [786, 1027]. Thus as the dose rate increased, the exposure time needed to reduce the life time decreased (116 or more days for dose rates of 2,200 μGy h^{-1}; 35-46 days for dose rates between 5,000 and 9,999 μGy h^{-1}, and 14-28 days for dose rates > 10,000 μGy h^{-1}) [614, 618]. One study has shown somewhat contradictory results since after exposure to gamma dose rates up to 23,644 μGy h^{-1} (during 28,5 days, dose 16 Gy) no reduction in mean life time of mice was seen [613]. However, this difference could be in part a consequence of the different strains of mice used in the different studies [615].

Combining the data for four different strains of mice and for both sexes, the values of life shortening (days) per cGy obtained were: 0.031 ± 0.008 for dose rates of 1,320-12,000 μGy h^{-1}; 0.047 ± 0.04 for dose rates of 24,000 μGy h^{-1} and 0.064 ± 0.005 for dose rates of 31,800 μGy h^{-1}. It has been suggested that the dose rate effect crosses the chronic-acute boundary at approximately 30,000 μGy h^{-1} and that all exposures above 10,000 μGy h^{-1} should probably be considered acute exposures [619].

In adult guinea pigs irradiated with gamma rays the LOEDR for life shortening was 2,750 μGy h^{-1} (125 days; 2.75 Gy). Life shortening was dose rate dependent [786].

In adult goats irradiated with 1,083 μGy h^{-1} gamma rays, 25% mortality was observed after 4 years exposure (accumulated dose 37.96 Gy), indicating that even this low dose rate had a marked life-shortening effect in goats. However, the response in all groups of goats was considerably heterogeneous. Comparing the survival times of goats exposed to gamma radiation with those described for rodents (rats and mice), it has been observed that the pattern of response of goats to continuous radiation differs considerably from that of rodents. In terms of percentage life shortening the effect is much greater in goats than in rodents [620].

Dogs exposed from 1 year of age until death to gamma radiation, showed a dose-rate related life shortening due to acute death (haemopoietic failure) (1,704 μGy h^{-1} produced a life shortening of 2,875 days; 24,545 μGy h^{-1} produce a life shortening of 3,445 days). Also a dose-rate related life shortening due to late death was observed (life shortening of 358 days at 340.9 μGy h^{-1}; life shortening of 3,103 days at 5,794 μGy h^{-1}) [1044].

Only four references for effects on mortality of radiations other than gamma rays have been found (2 for neutrons, 2 for beta radiation). Adult mice exposed to beta radiation at dose rates up to 150 μGy h^{-1} (during 728 days or more) showed no reduced survival time [782]. The results suggested that there was a threshold dose-rate in the biological effects of radiation


studied, and that the threshold dose-rate for H-3 beta rays (83.3 μGyh^{-1}) was much lower than for gamma rays (833.3 μGy h^{-1}) [782].

Exposure of dogs to the beta emitter Sr-90 (added in the food) from mid-gestation until 540 days of age at a dose rate of 18,000 μGy h^{-1}, reduced the survival to 76% the control value. As the dose rate increased the survival decreased with no dogs surviving exposures to dose rates of 9,000,000 μGy h^{-1}or higher [630].

Life shortening was induced in adult mice after exposure to neutrons of different energies. Irradiation with 0.7 MeV neutrons at a dose rate of 117 μGy h^{-1}during 623 days, reduced survival time to 55% the control value [618]. Irradiation with 1 or 5 MeV neutrons (no differences were seen between them) at dose rates of 130 μGy h^{-1} during 96 days, produced life shortening in mice. The reduction was dependent on the accumulated dose and independent of the dose rate in the range 1.7-1,918 μGy h^{-1} [614].

Only one reference gives RBE values. Neutrons of 1 or 5 MeV showed an RBE of 7.8-13.9 for life shortening in mice (compared with similar dose rates of gamma radiation) [614].

Reproductive capacity

The processes related with reproductive capacity studied are either indicators of impaired fertility (sterility induction, fertility span, female and male reproductive cells, ovary and testes weight, number of ovulations) or fecundity related parameters (pre-implantation and post-implantation death, embryo length and weight, brain weight, birth rate, litter size, number of litters).

In FRED there are 25 references on reproductive capacity effects of chronic irradiation (1 reference is a review article), giving 572 data (110 control data and 462 data on effects of radiation). Within these 462 data on effects, 25 correspond to goatsand 30 to pigs (in both species, gamma radiation was administered), 86 to mice (3 for beta radiation (< 10 keV) and 83 for gamma radiation) and 321 to rats (83 for beta radiation (< 10 keV) and 238 for gamma radiation).

The studies on the effects of irradiation on reproductive capacity are extremely heterogeneous not only because of the radiation type and the species used, but also because of the developmental stage at which animals are irradiated. Therefore, its almost impossible to compare the results obtained in different studies.

Exposure of female mice to gamma radiation at dose rates of 4,200 or 8,400μGy h^{-1} (during 24 or 16 weeks, respectively), had no effect on mean litter size of females surviving sterility and on mortality between birth and weaning of the offspring. The LOEDR for mean number of litters per female was 4,200 μGy h^{-1} (24 weeks of exposure), which reduced the number of litters to 35% the control value [1039].

Adult female mice gamma irradiated during 40 days with 3,500 μGy h^{-1} (3.38 Gy) showed reduced fertility [589].

Female mice gamma irradiated at 2 weeks of age with 6,000 μGy h^{-1} (during 7 days) were sterile. Exposure at dose rates of 3,000 μGy h^{-1} or higher, during 7 days, reduced the litter size to 53% the control value [624].

Gamma irradiation of mice, from day 19 post coitus to day 2 post birth, at 9,479.2 μGy h^{-1} had no effect on litter size. After exposures of 2,083 μGy h^{-1} or higher, a decrease in the number of litters per fertile female during 245 days after exposure was observed (48% the

control value). The LOEDR for germ cells per ovary (quantified at 165 days of age) was 9,479 μGy h^{-1} [616].

In mice exposed to gamma radiation during 4-6 months, the LOEDR was 100 μGy h^{-1} for mean offspring sired (total dose 0.15 Gy), mean offspring weaned (total dose 0.15 Gy) and percentage of sterile pairs (total dose 0.6325 Gy) [586].

In a study, using more than 30,000 mice, the effects on fertility of irradiation during 3 consecutive generations were determined (each generation was exposed during 80 days with a cumulative dose 0.344 Gy/generation). The 4th generation (not irradiated) was mated to generate the F1 and this one mated again to generate the F2. Exposure during three consecutive generations to 195 μGy h^{-1} had no effect on mean litter size of F1 and F2, but increased the percentage of early deaths both in F1 and F2 (two-fold increase in both). No deleterious effects of radiation in the F1 and F2 individuals, including foetuses, were observed concerning the growth and fertility [611]. Exposures at dose rates of 1,032 and 1,376 μGy h^{-1}, had no effects in the two first generations (mean litter size and sterility), but decrease litter size and increased sterility in the 3rd and 4th generation [602].

Female mice gamma irradiated during 55 days (starting at conception) with dose rates of 2,375 μGy h^{-1} showed irreversible damages in the ovaries. Irradiation at the same dose rate during 95 days rendered the mice infertile. Males exposed during 140 days to 2,375 μGy h^{-1} (7.98 Gy) showed reduced number of spermatogonia, spermatocytes and spermatids (36.9, 50.9 and 57.8% the control values, respectively) [594].

Irradiation of mice from conception to 14 days of age at dose rates of 333 μGy h^{-1} gamma rays (the lowest dose-rate assayed) reduced the number of primary oocytes per ovary to 52% the control value. When mice were exposed during the same period to beta radiation (< 10 keV) dose rates of 700 μGy h^{-1} (LOEDR) reduced the number of primary oocytes per ovary to 6.6% the control value [1031].

Mice exposed to 5,430 μGy h^{-1} gamma radiation at different ages, had decreased survival of stage 1 oocytes. The results showed that early oocytes stages in 10 days old mice are more sensitive to chronic irradiation than are similar stages in the adult [544].

Rats gamma irradiated during the gestation period (from day 0 to day 12, 13, 14, 15, 16, 17, 18, or 19 of gestation) with dose rates of 2,500 μGy h^{-1}, had embryos of reduced length and weight, and an increased percentage of mortality was observed (total resorptions + dead embryos or foetuses + viable embryos but reduced in size/total implantation). In 20 days irradiated embryos a statistically significant reduction in liver/body weight, spleen/body weight and kidney/body weight was observed [601].

Exposure of rats to 18,000 μGy h^{-1} gamma radiation, during 7 or 21 days, had no effect on litter size, weight at weaning and weight at young. At weaning, male and female offspring of each group (control and irradiated) were mated and at 19 weeks of age the offspring were killed and the weight of testes and ovary determined. Reduced ovary and testes weight was seen after exposure to 18,000 μGy h^{-1} (7 days; 3 Gy) [605].

Rats exposed to 2,919 μGy h^{-1} gamma radiation showed no alterations on average litter size. Reduction of testes weight was observed after exposure to 2,085 μGy h^{-1} during 70.6 days and to 2,919 μGy h^{-1} during 69.6 days (50% and 38% the control value, respectively) (LOEDR) [1067].

Rats exposed to gamma irradiation during 180 days at a dose rate of 2,085 μGy h^{-1} (9 Gy), showed no effect on litter size and diminished fertility on week 1 and 9 post irradiation, but

the fertility recovered to 75% of the control value 25 weeks after exposure. Irradiation during 180 days to 2,085 μGy h^{-1}, reduced testes weight (38% the control value) and increased the number of tubules devoid of germ cells (27% increase). Exposure during 12.6 days at the same dose rate decreased type A spermatogonia (55% the control). The content of preleptotene spermatocytes decrease after 25.6 days of exposure (35% the control value). Testis weight, type A spermatogonia per testes and number of pre-leptotene spermatocytes per testes remain under the control values even 33 weeks after irradiation [668].

Irradiation of rats with dose rates of 2,919 μGy h^{-1} gamma rays, during up to 92 days, had no effect on number of sertoli cells. These dose rates reduced the number of spermatogonia/testis, pre-leptotene and pachytene spermatocytes and round spermatids per testes, after 20-30 days of exposure or longer. After 92 days of exposure all the cell types were reduced to 10 % the control value. No effects were seen on seminal vesicle or ventral prostate weight in any group. Growth rate was only slightly slower in irradiated rat when compared to controls. No significant changes were observed in testosterone concentrations or in the weight of testosterone-dependent accessory organs. LH plasma concentrations did not significantly increase in the irradiated groups [671].

In rats exposed to gamma radiation during the first 21 days of the gestation period (total gestation 22 days) the LOEDR was 1,360 μGy h^{-1} for germ cells in female and male rats. The results showed that in rats the doses needed to reduce the percentage of germ cells in both males and females, were nearly 3 times higher than those needed to produce the same reduction in the pig germ cells [629].

Dose rates of gamma radiation of 420 μGy h^{-1} administered during 1 to 6 months to rats reduced the A1 spermatogonia numbers to 50% the control value, while it had no effect on A4 spermatogonia. Irradiation with dose rates of 1,260 μGy h^{-1} or higher reduced A4 spermatogonia, as spermatogonia and testis weight [593].

Rats were exposed to H-3 in the drinking water during F0 and F1 at dose rates of 1.251, 12.51, 125.1 and 1,251 μGy h^{-1}, giving cumulative doses from conception to delivery of F2 between 0.0046 and 4.6 Gy. Regardless of the dose rate, all offspring in the F1 and F2 were morphologically normal. No effects were observed, at any dose rate administered during 22 days, on preimplantation death and on lungs, heart, thymus, liver, spleen and kidney weight. Exposure to dose rates of 1,251 μGy h^{-1} during 22 days increased the number of resorptions (2.6-fold increase) [607].

In rats, infusion with H-3 (290-1,440 μCi/day/pregnant rat) induced developmental impairment, gross malformations, excess of neonatal death and reduction in number of oocytes [1025].

Exposure of rats to beta radiation during 42 days (from conception) with 1,250 μGy h^{-1} (1.26 Gy) produced a significant increase in the percentage of resorptions of the F2, 3 litters (23.2% compared with 6.4 % in controls). No significant effects were seen under the same irradiation conditions on ovary weight. Rats exposed from the first day of pregnancy or birth to the same dose rate showed significant reductions in testis weight and sperm content. Rats exposed from first day of pregnancy were considered to be more sensitive to the effects of chronic beta irradiation than adult rats [1024].

In pigs, irradiated during the first 108 days of gestation (total gestation 112 days) with gamma rays, the LOEDR were: 3,200 μGy h^{-1} for body weight (total dose 7.56 Gy); 1,360 μGy h^{-1} for brain weight (total dose 3.24 Gy); 450 μGy h^{-1} for ovary and testis weight (total dose 1.08 Gy) and 230 μGy h^{-1} for germ cells in females and males (total dose 0.54 Gy). No effects


were seen on thyroid, thymus, liver, kidney, lung and pituitary weights at any dose-rate assayed [629].

Pigs continuously irradiated between days 0-108 of gestation, with dose rates of 104 and 417 μGy h^{-1} of gamma rays (doses of 0.27 and 1.08 Gy respectively), showed no increase of dead piglets or dead foetuses in first and second pregnancy, respectively. The LOEDR was 104 μGy h^{-1} for reduction in number of primitive stem germ cells per cross section of seminiferous tubules (41% the control value). After exposure to 417 μGy h^{-1} 40% of the pigs were infertile. Irradiation apparently did not alter either age at or regularity of estrus. For their first pregnancy, the groups did not differ significantly in either incidence of infertility or number of offspring farrowed. Irradiation had no apparent effect on piglet birth weight, survival to weaning and weight at weaning. Nurturing ability of the sows was also unaffected. For second pregnancy control and 0.0025 Gy irradiated sows did not differ either in number of foetuses or ratio of foetuses to *corpora lutea*, but a strong suggestion of dominant-lethal effect existed in the 0.01 Gy exposure group. Diminished reproductive capacity rather than mutation appears to be the major consequence of continuous prenatal irradiation in the pig [1040].

Adult female pigs were daily fed with Sr-90 (beta radiation >10 keV) and bred at apparent Sr-90 skeletal equilibrium to unexposed males. The female offspring were gradually raised to the same Sr-90 level as the dam by 6 months of age. This F1 was bred to provide an F2 (exposed as F1). Animals treated with 3,100 μCi d^{-1} did not survive the gestation period. In original dams treated with up to 625 μCi d^{-1} (16,666 μGy h^{-1} in bone) no effects were observed in litter size, percentage of stillborn and weaned, birth and weaning weight. In the F1, no effects were observed with doses lower than 125 μCi d^{-1} (3,333 μGy h^{-1} in bone) for the same endpoints. Animals treated with >125 μCi d^{-1} did not survive to produce offspring. None of the F2 pigs treated with 625 μCi d^{-1} survived to produce an F3. [625].

Adult goats exposed to 3,500 μGy h^{-1} gamma radiation (during 608 days, 42.55 Gy) showed reduction in the number of born per female in 5 consecutive gestations, but no effects were detected in the fourth generation. Radiation dose rates of 1,300 μGy h^{-1} appeared to have no deleterious effects on conception, gestation and lactation for a period of up to 3 years. Nearly 92% of the goats irradiated with 15,000 μGy h^{-1}died, but those that survived gave birth to apparently normal but small viable twins after 152 days of exposure (accumulated dose 45.6 Gy). The goats irradiated with 3,500 μGy h^{-1} that survived, did not have 5th gestation. A level of 3,500 μGy h^{-1} may have caused a slight decrease in reproductive capacity, but the survivors continued to reproduce after most of the group had succumbed to the lethal effects of irradiation. The ability to survive in the radiation environment was the primary limiting factor affecting reproductive performance for female goats. The effects of radiation on reproductive capacity of goats appear to be much less than that observed in rodents [622].

After gamma irradiation of goats with 1,300 μGy h^{-1} (210 days; total dose 5.46 Gy) the growth rate of offspring was normal, and although sperm production and semen quality were reduced, males were considered fertile. In offspring exposed from conception to 60 days of age to 1,300 μGy h^{-1} no gross abnormalities were observed and viability was not affected. In the group exposed to 3,500 μGy h^{-1} (210 days; total dose 14.70 Gy) the offspring of the 1st generation weighed 12% less than the control offspring at 1 year of age; all males were sterile (aspermic at 220 and 465 days of age) [621].

There is only one field study, made in Rock Valley (Nevada), which analysed the effects of chronic gamma irradiation on desert rats populations. Rats received a gamma irradiation of 2.11-3.60 Gy y^{-1} (241-411 μGyh^{-1}) from April-May 1963 to May-June 1968. The irradiated population showed reduced survival rate 1 month after the irradiation started (0.60 compared


with 0.83 in control populations). Although a higher birth rate was seen in the irradiated population (0.58 compared with 0.51 in controls at birth), they also showed increased rate of death (0.33 compared with 0.12 in controls at birth), leading to a lower increase ratio in irradiated rats (0.25 compared with 0.38 in controls at birth). Effects on fertility could not be measured in the study, but from the data of birth and death rate, a 40% reduction in the multiplication rate per generation could be estimated. The results showed that the response of the field rat populations to chronic gamma radiation was similar to the response observed in laboratory rats. The authors conclude that chronic exposure to dose rates of 241- 411 μGyh^{-1} gamma radiation is clearly detrimental for a population of desert rodents [678].

Only one study gives information on RBE values related with the effects of chronic irradiation on the reproductive capacity. Mice exposed to beta radiation (< 10 keV) showed an RBE of 2.8 for oocyte survival. RBE was found to decrease at higher doses and dose rates, possible due to the limited ability of the oocytes to recover [1031].

The main gaps in information for mammal species is the lack of data on the effects that exposure to alpha emitters, via inhalation or ingestion, have on mortality, morbidity or reproductive capacity. It has to be pointed out that most, if not all, of the results showing a deleterious effect of radiation exposure have not been validated in replicate experiments either in the same or in other laboratory. Thus, mainly for chronic exposures during prolonged period of time, data should be confirmed. Due to practical problems, most of the studies are done using mice and rats.

2.5.3 Mutation

Literature on radiation induced mutations in mammals is overwhelmingly dominated by experiments on mice designed to derive risk estimates for genetic disease in man. In contrast to other endpoints and other species, these experiments have involved hundreds of thousands of individual animals, mainly male mice in which it is assumed that the spermatogonial stem cell is the most important stage of germ cell development for evaluating hereditary effects. Most of this work was accomplished in the 1970s and 1980s. More recent research has tended to focus on novel genetic effects such as minisatellite mutations and genetic instability.

In view of the considerable effort expended by UNSCEAR [1993a] to review the effects of chronic exposure to low LET radiations on the mutation rate in the mouse, it would be perverse to attempt to repeat the exercise here and only the main conclusion will be presented.

There are good theoretical reasons to assume that there is no threshold radiation dose for the induction of mutations. Methods of risk assessment, therefore, have estimated the increase in the rate of mutation rather than the no effect dose. The indirect or doubling dose method estimates the amount of radiation needed to induce the same number of mutations as those that occur spontaneously in a generation. The doubling dose of chronic low LET radiation for hereditary disease in mice has been estimated to be approximately 1 Gy [UNSCEAR, 1993a]. This estimate is based mainly on specific locus data for recessive genes.

Table 2-6 Summary effects data on mammals, based on the FASSET Radiation Effects Database (FRED).

Acute Mammals Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Donkey Cattle Cattle Dog Guinea pig Mouse Mouse Pig Rat	Gamma Beta Gamma Gamma Gamma Gamma Neutrons Gamma Gamma	5(1) 8(1) 12(1) 35(1) 3(1) 18(4) 4(1) 2(1) 78(8)	Dog Dog Mouse Mouse	Alpha Gamma Gamma Neutrons	2(2) 1(1) 60(9) 38(6)	Bull Cattle Mouse Mouse Mouse Mouse Rat Rat Rat Sheep	Gamma Beta Beta < 10 keV Gamma Mixed (N+ γ) Neutrons Beta < 10 keV Gamma Neutrons Gamma	1(1) 14(1) 16(2) 93(17) 1(1) 20(4) 4(1) 50(7) 7(2) 1(1)	Mouse Marmoset Hamster Guinea pig Swine	X-rays, Gamma X-rays X-rays X-rays X-rays	2(2) 1(1) 5(1) 3(1) 1(1)
< 0.199	Mouse Mouse Rat	Gamma Neutrons Gamma	14(1) 15(1) 14(3)	Dog Mouse Mouse	Gamma Gamma Neutrons	11(1) 13(3) 19(4)	Bull Mouse Mouse Mouse Mouse Rat Rat	Gamma Beta < 10 keV Gamma Mixed (N+ γ) Neutrons Gamma Neutrons	1(1) 3(1) 59(12) 2(1) 55(6) 29(2) 35(2)			
0.2-0.499	Mouse Mouse Rat Rat	Gamma Neutrons Gamma Neutrons	10(2) 4(1) 72(3) 6(1)	Mouse Mouse	Gamma Neutrons	9(4) 11(4)	Bull Mouse Mouse Mouse Rat Rat	Gamma Gamma Mixed (N+ γ) Neutrons Beta < 10 keV Neutrons	3(1) 51(12) 1(1) 15(4) 5(1) 21(2)	Marmoset	X-rays	1(1)
0.5-0.99	Mouse Rat	Gamma Gamma	13(2) 140(5)	Dog Dog Mouse Mouse	Alpha Gamma Gamma Neutrons	1(1) 11(1) 20(6) 7(2)	Bull Mouse Mouse Rat Rat	Gamma Gamma Neutrons Beta < 10 keV Gamma	4(1) 51(9) 25(3) 4(1) 23(3)	Mouse Marmoset	X-rays X-rays	1(1) 1(1)
1.0-1.99	Dog Mouse Rat	Gamma Gamma Gamma	2(1) 27(3) 43(3)	Dog Cattle Mouse Mouse	Alpha Gamma Gamma Neutrons	1(1) 1(1) 20(6) 10(4)	Bull Hamster Mouse Mouse Rat Rat	Gamma Gamma Gamma Neutrons Beta < 10 keV Gamma	1(1) 8(1) 131(14) 10(1) 2(1) 96(3)	Mouse Marmoset Hamster Guinea pig	X-rays X-rays X-rays X-rays	6(2) 1(1) 4(1) 3(1)

Table 2-6 Summary effects data on mammals, based on the FASSET Radiation Effects Database (FRED).

Acute Mammals Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
2.0-4.99	Dog Pig Rat	Gamma Gamma Gamma	35(1) 2(1) 4(1)	Dog Cattle Mouse Mouse Pig	Alpha Gamma Gamma Neutrons Gamma	1(1) 8(1) 38(8) 21(4) 7(2)	Bull Mouse Rat Rat	Gamma Gamma Beta < 10 keV Gamma	4(1) 63(12) 1(1) 32(5)	Mouse Marmoset Hamster Guinea pig Swine	X-rays X-rays X-rays X-rays X-rays	2(1) 1(1) 5(1) 3(1) 1(1)
> 5.0	Donkey Mouse Mouse Rat	Gamma Gamma Neutrons Gamma	36(1) 10(1) 2(1) 4(1)	Dog Donkey Mouse Mouse Pig	Alpha Gamma Gamma Neutrons Gamma	3(1) 19(2) 62(7) 2(1) 4(1)	Mouse Rat	Gamma Gamma	26(5) 2(1)	Mouse	X-rays	4(1)
Data relevant[c] to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			598,669, 773,1048	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		587, 591, 614, 716, 1029, 1030, 1042, 1043,1054	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		545 545, 597, 599, 714, 721, 1037, 1049	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper ID	558,598,600,636,654,655, 659,669,702,709,713,719, 723,773,779,785,791,795, 806,1048			587, 590, 591, 610, 614, 626, 627, 631, 633, 651, 654, 666, 716, 720,791,1029, 1030,1034,1038,1042,1043, 1047, 1054			262,507,544,545,546,548,560,590,595, 596,597,599,603,604,612,656,661,662, 704,706,707,710,714,717,721,776,778, 780,784,788,806,1022,1028,1031,1032, 1033,1036,1037,1038,1049,1056			567, 566, 579, 706		
Papers "rejected" (ID)[c]	507,666,1030 (tumour induction),1,557,1045, 1051, 1052, 1055 (i.v. injection), 655,659,715,779,773,783, 792,793, 1053 (Partial body irradiation),543 (Dosimetry), 1023 (No data)			608,1045,1052 (i.v. or i.p. injection), 1043 (Some files: Tumour induction), 701,792,1053 (Partial body irradiation)			664, 682, 684, 1051 (i.v. injection), 706 (i.v. injection), 661 (partial body irradiat.), 775 (No dose information available)			421 (in vitro cloning efficiency), 582 (in vitro),571 (dominant lethal mutation = "Reproduction"), 406 (follicular development = "Reproduction"),583 (somatic mutation),581(somatic mutation),565 (in vitro),662 (epigenetic)		
Last paper published in:	1999			1998			2001			1978		

a Number of data values in the dose rate interval. b Number of papers providing the data. c Data values omitted as not possible to estimate the dose or dose-rate.
Latin names: *Cavia porcellus* = guinea pig; *Mus musculus* = Mouse; *Clethrionomys glareolus* = Bank vole; *Perognathus spp., Dipodomys spp*. = Kangaroo rats; *Equus asinus* = Donkey; *Rangifer tarandus* = Reindeer; *Macac mulatta* = rhesus monkey; *Rattus norvegicus* = Rat; *Mesocricetus auratus* = golden hamster; *Sprague pawley* = Rats

Table 2-6 Summary effects data on mammals, based on the FASSET Radiation Effects Database (FRED).

Chronic Mammals Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Dog Mouse Mouse Rat Rat Sheep	Gamma Beta < 10 keV Gamma Beta < 10 keV Gamma Beta > 10 keV	2(1) 3(1) 5(1) 8(1) 12(3) 1(1)	Dog Dog Dog Goat Guinea pig Mouse Rat	Beta < 10 keV Beta > 10 keV Gamma Gamma Gamma Gamma Gamma	1(1) 1(1) 2(2) 2(1) 1(1) 45(11) 12(1)	Goat Mouse Mouse Pig Rat Rat	Gamma Beta < 10 keV Gamma Gamma Beta < 10 keV Gamma	5(1) 1(1) 26(8) 6(2) 26(3) 46(6)	Mouse Mouse Bank vole Reindeer	Gamma Neutrons Mixed Gamma	8(5) 7(4) 1(1) 1(1)
< 99.9	Mouse Rat	Gamma Gamma	10(1) 10(1)	Mouse Mouse Mouse	Beta < 10 keV Gamma Neutrons	2(1) 14(1) 7(1)	Mouse Rat	Gamma Beta < 10 keV	1(1) 10(1)	Reindeer	Gamma	1(1)0
100-199.9	Rat	Gamma	1(1)	Dog Mouse Mouse	Gamma Beta < 10 keV Neutrons	1(1) 1(1) 7(2)	Mouse Pig Rat	Gamma Gamma Beta < 10 keV	19(3) 5(1) 5(1)			
200-499.9	Mouse Rat	Beta < 10 keV Gamma	3(1) 1(1)	Dog Mouse Mouse	Gamma Gamma Neutrons	1(1) 7(2) 4(1)	Mouse Pig Rat	Gamma Gamma Gamma	4(2) 13(2) 6(2)	Mouse Bank vole	Gamma Mixed	1(1) 1(1)
500-999.9	Dog Mouse	Gamma Beta < 10 keV	22(1) 3(1)	Dog Mouse Mouse	Gamma Gamma Neutrons	1(1) 8(3) 6(2)	Mouse Mouse	Beta < 10 keV Gamma	2(1) 8(3)			
1,000-1,999.9	Mouse Rat	Beta < 10 keV Beta < 10 keV	3(1) 27(1)	Dog Guinea pig Mouse Mouse	Gamma Gamma Gamma Neutrons	5(2) 1(1) 12(2) 10(2)	Goat Mouse Mouse Pig Rat Rat	Gamma Beta < 10 keV Gamma Gamma Beta < 10 keV Gamma	11(2) 1(1) 9(2) 6(1) 29(2) 6(1)	Mouse	Gamma	1(1)
2,000-4,999	Rat	Gamma	3(1)	Dog Goat Mouse Mouse	Gamma Gamma Gamma Neutrons	11(3) 2(1) 30(5) 1(1)	Goat Mouse Pig Rat	Gamma Gamma Gamma Gamma	9(2) 25(4) 6(1) 232(5)	Mouse Bank vole	Gamma Mixed	2(2) 1(1)
5,000-9,999	Rat Sheep	Gamma Beta > 10 keV	9(1) 1(1)	Dog Goat Mouse	Gamma Gamma Gamma	9(2) 2(1) 44(7)	Goat Mouse	Gamma Gamma	2(1) 13(3)			

Table 2-6 Summary effects data on mammals, based on the FASSET Radiation Effects Database (FRED).

Chronic Mammals Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 10,000	Sheep	Beta > 10 keV	6(1)	Dog Dog Goat Guinea pig Mouse Sheep	Beta > 10 keV Gamma Gamma Gamma Gamma Gamma	7(1) 7(3) 4(1) 4(1) 89(8) 5(1)	Goat Mouse Rat	Gamma Gamma Gamma	3(1) 4(1) 39(2)	Mouse Mouse	Gamma Mixed	4(2) 3(1)
Data relevant[c] to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		614	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		1031	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		569,573, 576,577
Dbase paper IDs	623,632,659,671,724,787790, 1024,1046			609,613,614,615,618,619,620,628,630, 633,774, ,683,782,786,1021,1027,1035, 1044,1046			544,586,589,593,594,601,602,605,607, 611,616,621,622,624,625,629,668,671, 678,1024,1025,1031,1039,1040,1067			569,572,573,574,575,576,577,578, 584		
Papers "rejected" (ID)[c]	547 (No data available), 683 (No control values), 789 (Type of exposure), 1026 (Tumour induction)			789 (Type of exposure),782,786, 1021 (Tumour induction)			588 (i.v. injection), 1039 (Pu-239 i.v. injected)			568 (dominant lethal mutation = "Reproduction"), 570 (data included in 572)		
Last paper published in:	1998			1998			1990			2002		

a Number of data values in the dose rate interval. b Number of papers providing the data. c Data values omitted as not possible to estimate the dose or dose-rate.
Latin names: *Cavia porcellus* = guinea pig; *Mus musculus* = Mouse; *Clethrionomys glareolus* = Bank vole; *Perognathus spp., Dipodomys spp*. = Kangaroo rats; *Equus asinus* = Donkey; *Rangifer tarandus* = Reindeer; *Macac mulatta* = rhesus monkey; *Rattus norvegicus* = Rat; *Mesocricetus auratus* = golden hamster; *Sprague pawley* = Rats

Table 2-6 Summary effects data on mammals, based on the FASSET Radiation Effects Database (FRED).

Transitory Mammals Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Rat	X-rays	12(1)	Mouse Mouse Mouse	Beta Gamma Neutrons	2(1) 7(3) 13(4)						
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999				Mouse	Neutron	4(1)						
> 10,000	Rat	X-rays	12(1)	Mouse Mouse	Gamma Gamma	33(3) 28(3)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		591,592, 1041	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		1050	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	667			591,592,617,580,1041			1050			582		
Observations "rejected" (paper ID)[c]	None			2(580)[1],23(1041)[1]			18(1050)[1]			4(582)[1]		
Last paper published in:	1965			1988			1991			2001		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 effects described but no dose rates reported
Latin names: *Mus musculus* = Mouse; *Rattus norvegicus* = Rat

2.6 Birds

There were no collated bird FRED data in the "transitory" type of exposure, and no data from the acquired literature relevant to the derivation of RBE or weighting factor values.

The majority of the references predates UNSCEAR [1996], and post-1996 literature looks at morbidity and mutation effects under chronic exposures. Overall there were not enough data available to draw conclusions on dose-effects relationships.

Table 2-7 summarises effects data on birds, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED).

2.6.1 The effects of acute irradiation

A wide range of bird species has been studied, dominated by research on chickens. Most results comprise gamma and X-ray exposures, using Cs-137 (gamma only) and Co-60. Mortality and reproduction endpoints are the most studied, with no references reported under mutation. No data were recorded for doses below 0.2 Gy (excluding the controls). The latest reference quoted was 1988.

Morbidity

Observed effects in morbidity included changes in: weight, spatial avoidance, asymtotic body mass, pathological changes and feather length. LOEDR are reported above 2.5 Gy in tree swallows [737], bluebirds [735,739], and at 0.9 Gy in wrens [734] and 2 Gy in chickens [554].

Mortality

A wide ranges of bird species was studied, with the majority of results looking at percentage mortality (either LD_{50}, or $LD_{50/30}$).

LOED were reported between 3 and 4 Gy for mallards [736] under gamma exposures. Other LOED were reported for doses above 5 Gy.

Reproductive capacity

Observed effects in reproductive capacity included changes in hatchability, fertility, incubation period, egg production, ovulation rate, embryo survival, number of oocytes, number of germ cells produced and time to achieve sexual maturity. Some of these observations could also have featured under morbidity.

LOED are reported at and above 4 Gy [448, 732, 694, 680, 441, 431, 738, 739] for numerous bird species.

Mutation

No references were reported under this endpoint for acute exposures.

2.6.2 The effects of chronic radiation

Most results centred on gamma radiation, using Cs-137. Reproductive capacity has been the most studied endpoint, with no data reported on mortality.

Morbidity

Only two references were recorded under this endpoint, looking at the after effects of Chernobyl, through for example the levels of immuno-globulins, ratios of heterophil:lymphocyte (as an indication of stress). Whilst morbidity effects are recorded, no dose rates were provided.

Mortality

No references were reported under this endpoint for chronic exposures.

Reproductive capacity

A total of six references were identified for various species of birds, looking at breeding success and growth performance, hatching success, nesting growth/success, number of sperms and oocytes.

Whilst data are recorded on all dose rate ranges, few conclusions can be drawn related to dose-effects relationships. An extensive study on chickens was published in 1972 [384], but all dose rates were greater than 10,000 μGy hr^{-1}. The last publication relating to this endpoint dates from 1993, and appears in the UNSCEAR [1996] review. The review mentions that breeding performance of tree swallows were unaffected by irradiation [439], and that results suggest that populations are unlikely to suffer adversely at annual doses up to 50 mGy. This would equate to a dose rate of around 5.7 μGy hr^{-1}.

Mutation

Only one reference was found under this endpoint looking at leg malformations. However doubt was reported in attributing the effect to the Cs-137 dose rate of 564 μGy hr^{-1}.

Table 2-7 Summary effects data on birds based on the FASSET Radiation Effects Database (FRED).

Acute Birds Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Sialia sialis*	Gamma	14(1)	Chicken	Gamma	6(2)	*Sialia sialis*	X-rays	5(1)			
	Chicken	Gamma	6(1)	Chicken	X-rays	4(2)	Chicken	Gamma	27(5)			
	Chicken	X-rays	1(2)	*Quelea quelea*	X-rays	1(1)	Chicken	X-rays	35(5)			
	Anas platyrhynchos	Gamma	1(1)	*Anas platyrhynchos*	Gamma	5(1)	Duck	Gamma	1(1)			
	Tachycineta bicolor	Gamma	10(2)	*Columba liva*	X-rays	2(1)	*Quelea quelea*	X-rays	5(1)			
	Troglodytes aedon	Gamma	4(1)	*Sturnus vulgaris vugaris*	Gamma	3(1)	Goose	Gamma	1(1)			
				Tachycineta bicolor	Gamma	3(1)	*Phasianus colchicus*	X-rays	2(1)			
				Anas discolor & Anas crecca & Anas clypeata	Gamma	1(1)	*Coturnix coturnix japonica*	Gamma	7(1)			
				Melospiza melodia & Junco hyemalis	X-rays	2(1)	*Colinus virginanus*	Gamma	14(1)			
							C. coturnix	Gamma	6(1)			
							Tachycineta bicolor	Gamma	4(1)			
							Numerous species[2]	Gamma	5(1)			
< 0.199												
0.2-0.499	*Tachycineta bicolor*	Gamma	4(1)	*Tachycineta bicolor*	Gamma	1(1)	Chicken	X-rays	6(2)			
							Tachycineta bicolor	Gamma	2(1)			
0.5-0.99	*Tachycineta bicolor*	Gamma	7(2)	Chicken	X-rays	2(1)	Chicken	X-rays	18(5)			
	Troglodytes aedon	Gamma	4(1)	*Quelea quelea*	X-rays	1(1)	*Quelea quelea*	X-rays	2(1)			
				Tachycineta bicolor	Gamma	3(2)	*Tachycineta bicolor*	Gamma	3(1)			
1.0-1.99	Chicken	Gamma	1(1)	Chicken	X-rays	4(1)	Chicken	X-rays	29(4)			
	Tachycineta bicolor	Gamma	4(1)	*Tachycineta bicolor*	Gamma	1(1)	Chicken	Gamma	5(1)			
							Quelea quelea	X-rays	1(1)			
							Tachycineta bicolor	Gamma	3(1)			

Table 2-7 Summary effects data on birds based on the FASSET Radiation Effects Database (FRED).

Acute Birds Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
2.0-4.99	*Sialia sialis*	Gamma	11(1)	Chicken	Gamma	3(1)	Chicken	X-rays	176(9)			
	Chicken	Gamma	10(1)	Chicken	X-rays	6(1)	Chicken	Gamma	22(2)			
	Anas platyrhynchos	Gamma	1(1)	*Quelea quelea*	X-rays	2(1)	*Quelea quelea*	X-rays	4(1)			
	Tachycineta bicolor	Gamma	10(2)	*Anas platyrhynchos*	Gamma	4(1)	*Phasianus colchicus*	X-rays	1(1)			
	Troglodytes aedon	Gamma	8(1)	*Columba liva*	Gamma	6(1)	*Colinus virginanus*	Gamma	7(1)			
				Sturnus vulgaris vugaris	Gamma	2(1)	*C. coturnix*	Gamma	5(1)			
				Tachycineta bicolor	Gamma	3(2)	*Tachycineta bicolor*	Gamma	6(1)			
				Anas discolor & Anas crecca & Anas clypeata	Gamma	2(1)						
> 5.0	*Sialia sialis*	Gamma	23(1)	Chicken	Gamma	43(4)	*Sialia sialis*	X-rays	6(1)			
	Chicken	Gamma	17(1)	Chicken	X-rays	27(4)	Chicken	X-rays	72(9)			
	Chicken	X-rays	112(1)	*Quelea quelea*	X-rays	3(1)	Chicken	Gamma	79(8)			
	Anas platyrhynchos	Gamma	14(1)	*Gallus domesticus*	X-rays	32(1)	Duck	Gamma	2(1)			
	Troglodytes aedon	Gamma	4(1)	*Anas platyrhynchos*	Gamma	19(1)	*Quelea quelea*	X-rays	5(1)			
	Numerous species[1]	Gamma	7(1)	*Melopsittacus undulatus*	Gamma	16(1)	Goose	Gamma	4(1)			
				Melopsittacus undulatus	X-rays	18(1)	Gull	Gamma	4(1)			
				Columba liva	Gamma	19(1)	*Phasianus colchicus*	X-rays	16(2)			
				Columba liva	X-rays	4(1)	*Coturnix coturnix japonica*	Gamma	21(1)			
				Coturnix coturnix japonica	Gamma	18(1)	*Colinus virginanus*	Gamma	28(1)			
				Sturnus vulgaris vugaris	Gamma	11(1)	*C. coturnix*	Gamma	31(1)			
				Melospiza melodia & Junco hyemalis	X-rays	4(1)	*Tachycineta bicolor*	Gamma	4(1)			
				Anas discolor & Anas crecca & Anas clypeata	Gamma	31(1)	Numerous species[2]	Gamma	10(1)			

Table 2-7 Summary effects data on birds based on the FASSET Radiation Effects Database (FRED).

Acute Birds Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	388,438,552,554,734,735, 736,737,739			375,376,429,433,437,449,450,550,559, 680,727,728,729,731,733,736,737,738, 739,766			383,385,430,431,436,441,442,444, 446,448,451,524,680,694,725,727, 732,738,739,767			None		
Observations "rejected" (paper ID)[c]	2(388) [3]			None			18(430),6(431),4(442),3(448), 63(451)[3]			None		
Last paper published in:	1986			1986			1988			None		

a Number of data values in the dose rate interval. b Number of papers providing the data. c Data values omitted as not possible to estimate the dose or dose-rate.
1 *Passerina cyanea, Geothlypis trichas, Colinus virginanus, Thryothorus ludovicianus, Contopus virens, Vireo griseus, Vireo olivaceus*. *2 Somateria mollissima , Iuiscalus quiscula, Passer domesticus, Passer domesticus, Phalacrocorax auritas, Agelaius phoeniciuss*. 3 All references: dose at 0 Gy, but positive dose rate reported

Table 2-7 Summary effects data on birds based on the FASSET Radiation Effects Database (FRED).

Chronic Birds Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Hirundo rustica*	Mixed	11(1)				Chicken Gull *Tachycineta bicolor* Numerous species	Gamma Gamma Mixed Gamma	6(2) 1(1) 16(1) 3(1)			
< 99.9							*Iridoprocne bicolor* & *Troglodytes aedon* Numerous species	Gamma Gamma	6(1) 2(1)			
100-199.9							*Iridoprocne bicolor* & *Troglodytes aedon* Numerous species	Gamma Gamma	1(1) 4(1)			
200-499.9							Numerous species	Gamma	2(1)			
500-999.9							Numerous species	Gamma	4(1)	*Otis asio*	Mixed	1(1)
1,000-1,999.9							Numerous species	Gamma	2(1)			
2,000-4,999							*Iridoprocne bicolor* & *Troglodytes aedon* Numerous species	Gamma Gamma	5(1) 1(1)			
5,000-9,999							Numerous species	Gamma	5(2)			
> 10,000							Chicken Numerous species	Gamma Gamma	228(1) 8(2)			

Table 2-7 Summary effects data on birds based on the FASSET Radiation Effects Database (FRED).

Chronic Birds Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	377,726			None			384,432,434,435,439,448			445		
Observations "rejected" (paper ID)[c]	9(726),2(377)[1]			None			8(434),29(439),16(448) [1]			None		
Last paper published in:	1999			None			1993			2001		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

1 All references: dose rates at o microGy h^{-1}, but positive dose reported

2.7 Amphibians and reptiles

Frogs, toads and salamanders belong to the amphibian class of organisms while snakes, lizards and turtles are members of the reptile class of organisms. Although comprising a significant portion of the vertebrate species, relatively few studies exist on their radiosensitivity, especially after chronic irradiation. Undoubtedly, some aspects in the ecology of these species need consideration when determining the effects of radiation. For example, various life stages of amphibians and reptiles spend long periods of time in the sediment of lakes and wetlands. This shifting between aquatic and terrestrial ecosystems may display unique characteristics that affect the exposure to radioactive contaminants in the environment.

The amphibians are dependent on water for their reproduction and the immature life stages remain in water for extended period of time. As adult they shift from herbivorous to carnivorous diet and to nocturnal activities. The life span seems to be rather broad. The reptiles either lay egg or are viviparous. They can be found in various habitats while the habitat of snakes is predominantly terrestrial or wetland where they function as top predators. Reptiles have thick and dry skin, which may act as a shield against external radiation. However, the exoskeleton of turtles may accumulate radionuclides. Amphibians have moist skin with important respiratory and osmoregulation functions, which may be sensitive to adsorption of gases from the environment.

Both the amphibians and the reptiles are poikilothermic meaning they are unable to regulate their own body temperature but are dependent on the neighbouring temperature. They hibernate in burrows or in sediment. Hibernation may influence radiation sensitivity by altering the turnover of radionuclides in the body. The metabolic rate is low, especially during hibernation, which makes these organisms vulnerable in regard to potential biological effects from incorporated radionuclides. The biological half lives following uptake of ^{137}Cs varies from 24 to 430 days and of ^{90}Sr from 122 to 1386 days.

Table 2-8 summarises effects data on amphibians and reptiles, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). Too few data are included in the database to make generalisations on the effects of chronic irradiation, and the available data have been include in the discussion of the acute exposures. No effects data were recorded from transitory exposures.

2.7.1 The effects of acute and chronic irradiation

The experimental results presently in the database originate from 24 papers. There are results on the four umbrella endpoints for both the amphibians as well as the reptiles.

Morbidity

There are only five papers in the database related to this endpoint for the amphibians and two papers for the reptiles. Depigmentation and skin ulceration after high exposures has been reported for irradiated frogs and newts [273, 276].

Mortality

There are seven papers in the database related to this endpoint for the amphibians. They include data on mortality ratios for newt, salamanders and frogs. For the reptiles there appear


to be five papers in the database related to this endpoint. Studies on mortality have been performed on snakes, lizards and turtles.

There is a range of LD_{50} values reported depending on the length of the assessment period. Several studies have shown that the observation period after lethal doses must increase considerably compared to that for mammals. This is probably due to the low metabolic rate of these species. LD_{50} ranging between 2 and 22 Gy have been reported for a number of species of reptiles and amphibians. Extending the effect assessment period indicates LD_{50} values not different to mammals and birds. It has been argued that the size of the genome is an important determinant of radiation sensitivity and this assumption has also been used to estimate LD_{50} values for some species [281].

Juvenile stages are more sensitive to radiation as revealed by studies on toads showing $LD_{50/30}$ of 24, 10 and 7 Gy respectively [279]. Extending the observation period to 50 days yielded a LD_{50} of 0,1 Gy for juveniles and tadpoles. The irradiated tadpoles failed to metamorphose. Studies on frogs in contaminated areas close to the Chernobyl showed a decrease in male fertility the years after the accident. However the dose levels are unknown.

Reproduction

There is one paper on reproductive disturbances in the database for the amphibians and two papers for the reptiles. The female lizards chronically exposed to γ-radiation became sterile after total doses of 15 Gy (dose rates 0.06 Gy per day) [536]. Exposure of adult lizards to doses of 4.5 Gy resulted in 50 % decline in natality one year after irradiation [534].

Mutation

There are two papers in the database related to this endpoint for amphibians and only one paper for the reptiles. Chromosomal aberrations have been studied on frogs and turtles. Studies on turtles living in contaminated ponds at the Savannah River site have shown that greater genetic damage was induced compared with turtles living at an uncontaminated site [277]. Several studies on induction of chromosomal aberrations have been performed on populations of frogs inhabiting areas contaminated after the Chernobyl or EURT accidents. However, data on the irradiation effects are not accompanied by the information on doses accumulated by these species. Only levels of environmental concentrations of radionuclides are given in the reports, which impair the interpretation of the given data.

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Acute Amphibians Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Limnodynastes tasmaniensis* *Desmognathus fuscus, Necturus maculosus, Amphiuma means* *tridactylum, Taricha granulosa*	Gamma X-rays	3(1) 14(1)	*Bufo fowleri* *Bufo hemiophrys* *Rana pipiens* *Desmognathus fuscus, Necturus maculosus*	Gamma Gamma X-rays X-rays	10(1) 13(1) 3(1) 9(1)				*Bufo marinus, Bufo calamita, Bufo pardalis*	X-rays	12(1)
< 0.199												
0.2-0.499				*Desmognathus fuscus, Necturus maculosus*	X-rays	4(1)				*Bufo marinus, Bufo calamita, Bufo pardalis* *Rana temporaria, Rana arvalis*	X-rays X-rays	34(1) 6(1)
0.5-0.99	*Limnodynastes tasmaniensis*	Gamma	5(2)	*Desmognathus fuscus, Necturus maculosus*	X-rays	4(1)						
1.0-1.99	*Limnodynastes tasmaniensis*	Gamma	3(2)	*Taricha granulosa* *Bufo fowleri* *Desmognathus fuscus, Necturus maculosus*	Gamma Gamma X-rays	1(1) 8(1) 10(1)						

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Acute Amphibians Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
2.0-4.99	*Limnodynastes tasmaniensis* *Taricha granulosa*	Gamma Gamma	2(1) 2(1)	*Desmognathus fuscus, Necturus maculosus* *Taricha granulosa* *Rana pipiens, Notophthalmus viridescens, Hylla squirella, Necturus maculosus, Desmognathus fuscus*	X-rays Mixed X-rays	4(1) 2(1) 2(1)				*Bufo marinus, Bufo calamita, Bufo pardalis* *Rana temporaria, Rana arvalis*	X-rays X-rays	34(1) 6(1)
> 5.0	*Ambystama mexicaum* *Limnodynastes tasmaniensis* *Taricha granulosa*	X-rays Gamma Gamma	4(1) 18(2) 10(1)	*Taricha granulosa* *Bufo fowleri* *Bufo hemiophrys* *Desmognathus fuscus, Necturus maculosus, Amphiuma means tridactylum, Taricha granulosa* *Taricha granulosa* *Rana pipiens, Notophthalmus viridescens, Hylla squirella, Necturus maculosus, Desmognathus fuscus* *Rana pipiens*	Gamma Gamma Gamma X-rays X-rays X-rays X-rays	3(1) 63(1) 8(1) 26(1) 24(1) 4(1) 12(1)	Rana temporaria L	X-rays	5(1)	*Bufo marinus, Bufo calamita, Bufo pardalis*	X-rays	24(1)
Data relevant[c] to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Acute Amphibians Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Dbase paper ID	276,278,281,273,274			273,279,281,539,280,535,540			994			527,886		
Papers "rejected" (ID)[d]	None			None			None			None		
Last paper published in:	1986			1980			1963			2000		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Chronic Amphibians Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Rana arvalis* *Rana arvalis* *Rana temporaria*	Mixed Beta[2] Mixed	2(1) 18(1) 4(2)							*Rana arvalis* *Rana temporaria*	Mixed Mixed	31(4) 37(3)
< 99.9										*Rana arvalis* *Rana temporaria*	Mixed Mixed	12(1) 30(1)
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999												
> 10,000	*Limnodynates tasmaniensis*	Gamma	6(1)									
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	276,946,947,965,977,1008			None			None			955,966,977,1009		
Observations "rejected" (paper ID)[c]	4(946)[1],28(947)[1],18(965)[1], 14(977)[1],16(1008)[1]			None			None			10(955)[1],74(977)[1],23(1009)[1]		
Last paper published in:	2001			None			None			2002		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates, or doses. 2 Beta energy [965] not given.

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Acute Reptiles Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Uta stansburiana* *Uta stansburiana*	Gamma X-rays	4(1) 15(1)	*Terrapene carolina* *Uta stansburiana*	X-rays X-rays	1(1) 3(1)	*Uta stansburiana* *Crotaphytus wislizenii, Cnemidophorus tigris*	X-rays Gamma	15(1) 40(1)	*Trachemys scripta*	Gamma	5(1)
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99												
2.0-4.99	*Uta stansburiana*	Gamma	1(1)	*Terrapene carolina*	X-rays	2(1)				*Trachemys scripta*	Gamma	5(1)
> 5.0	*Uta stansburiana*	X-rays	19(1)	*Terrapene carolina* *Uta stansburiana* *Testudo horsfieldi*	X-rays X-rays Gamma	53 (2) 9(1) 10 (2)	*Uta stansburiana*	X-rays	15(1)	*Trachemys scripta*	Gamma	15(1)
Data relevant[c] to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper ID	525,541			528, 534, 538, 988, 1005			534,536			277		
Papers "rejected" (ID)[d]	None			None			None			None		
Last paper published in:	1986			1985			1963			2000		

[a] Indicates the number of data values available in the dose rate interval. [b] Indicates the number of papers providing the data. [c] Database paper IDs (Nº of data does not have much sense, usually a single RBE value is given in a paper). [d] Database paper IDs & reason to reject the study.

Table 2-8 Summary effects data on amphibians and reptiles, based on the FASSET Radiation Effects Database (FRED).

Chronic Reptiles Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background										*Trachemys scipta, & Chelydra serpentina* *Trachemys scipta & Chelydra serpentina*	Beta[2] Gamma	4(1) 6(1)
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999												
> 10,000												
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	272,526,530			None			None			531,532		
Observations "rejected" (paper ID)[c]	5(272)[1],1(526)[1],1(530)[1]			None			None			8(531)[1],10(532)[1]		
Last paper published in:	1993			None			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates or doses. 2 Beta energy not given [532]

2.8 Soil fauna and bacteria

The soil fauna consist of a large variety of species ranging from protozoa to earthworms and arthropods. This summary covers non-insect arthropods (*e.g.* woodlouse, scorpions, spiders, mites, millipedes, and springtails), nematodes and earthworms. The database contains 25 soil fauna references, but five of these [700, 144, 229, 249, 693] were excluded due to unspecified umbrella endpoints or no available data-points. 11 of the references concern the effects of acute irradiation, whereas 10 deal with chronic exposure. One review deals with both acute and chronic exposure. The most recent paper included in the database was published in 1992, though year of issue is not specified for all references. The largest amount of data is associated with the mortality endpoint.

In summary, based upon the references included in the database, the information on radiation effects on soil fauna seems to be rather limited, especially concerning low acute doses (no data at doses <5 Gy) and chronic exposure associated with other endpoints than mortality. There is also general lack of data suitable for RBE determination. Nevertheless, a few points can be made: acute radiosensitivity of soil fauna is largely dependent on type and developmental stage of organism considered (*i.e.* eggs, juveniles, adults). Generally, mortality is affected in the range of 100-1,000 Gy, whereas effects associated with morbidity and reproduction are evident at considerably lower doses (5-20 Gy). Concerning chronic exposure, decreased populations of sedentary animal groups (*e.g.* earthworms) have been reported in connection with increased background doses of ^{226}Ra. Earthworms utilise the soil as a direct source of nutrition and are thus particularly susceptible to internal exposure by α-radiation.

Table 2-9 summarises effects data on soil fauna and bacteria, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). No effects data were recorded from transitory exposures for these wildlife groups.

2.8.1 The effects of acute irradiation

The database does not contain effects data for acute doses lower than 5 Gy for soil fauna. The range of doses covered is 5-2,000 Gy.

Morbidity

Three papers concern various responses of the earthworm *Eisenia foetida* to acute irradiation: Body length of young worms treated with 100 Gy of γ-radiation remained shorter than the controls and the clitellum of the irradiated animals did not develop [755]. Posterior regeneration from the 50th segment (after cutting the animal) was blocked after a whole-body X-ray dose of 200 Gy. A general downward trend in the number of segments produced was observed in the range 20-100 Gy [758]. Using ^{3}H-thymidine autoradiography, labelling indices (LI) of epidermal cells were found to decrease following γ-irradiation at doses in the range 5-20 Gy. LI remained at a low level 10-20 days after irradiation with 5 and 10 Gy, and the damage caused by 20 Gy did not appear to have been repaired even 40 days after irradiation [652].

Mortality

A total of eight references associated with the mortality endpoint are included in the database. Of these, three are on earthworms, two refer to *Collembola* (springtails), one concerns


terrestrial isopods (pill bugs) and two are comparative studies of various soil invertebrates. In various ways, these studies focus on animal survival as a function of dose and time after irradiation, one example in this respect being LD_{50} values. The frequently used 30 day time period for assessing the expression of radiation-induced mortality (*i.e.* $LD_{50/30}$) is reported in several studies, however, lower lethal doses are observed for soil invertebrates at times greater than 30 days, *e.g.* in [764].

Susceptibility to acute radiation varies greatly both between and within soil invertebrate groups. Oribatid mites are reported to be most resistant, surviving up to 80 days after exposure to 2,000 Gy, whereas all isopods were dead after less than a day with the same treatment. Furthermore, there was a clear correlation between the activity and mobility of the animals and their susceptibility to radiation: More active animals, such as centipedes, wood lice, surface-dwelling *Collembola*, parasitic mites and symphylids were more radiosensitive than sluggish oribatid mites or deep soil-dwelling *Collembola*. Worms and nematodes are of intermediate activity and were also found to be moderately susceptible to acute γ-irradiation [765].

The population density of earthworms decreased fivefold when an experimental plot in birch forest was irradiated with gamma rays at a dose of 26 Gy. Counts were made four months after irradiation [759]. $LD_{50/30}$ of *Eisenia foetida* after γ-irradiation was reported to be 650 Gy, whereas LOED was estimated to be 390 Gy [755]. For *Lumbricus terrestris*, increased mortality was evident at about 600-700 Gy, but LD_{50} values were somewhat higher in reference [674] as compared with [760]. Nevertheless, both lethal doses are very high compared with doses relevant for natural ecosystems.

Concerning arthropods, a γ-dose of 750 Gy reduced the population of *Collembola* by 97% in 30 days; LOED was 150 Gy [90]. $LD_{50/30}$ for the springtail *Sinella curviseta* was 149 and 300 Gy for externally delivered γ– and β-radiation, respectively. Juveniles were more susceptible than adults to both types of radiation and (one day old) eggs were the most sensitive stage with $LD_{50/14}$ of 13.9 Gy for gamma and 14.9 Gy for beta. LOED with respect to egg mortality rates (averaged over a month) were 25 Gy for β and 50 Gy for γ. Survival values suggest an apparent RBE (β/γ) of 2 for adults and 1.1 for eggs [761]. The $LD_{50/30}$ of the terrestrial isopod *Armadillidium vulgare* was about 300 Gy and the animals were most sensitive during ecdysis. LOED was found to be 100 Gy, both for males and females [772].

Reproductive capacity

One database reference deals with earthworm fertility: Using ^{3}H-thymidine autoradiography, labelling indices (LI) of testicular cells of the earthworm *Eisenia foetida* were found to decrease following gamma-irradiation (5-20 Gy). For such cells the recovery was about 10 days for 5 and 10 Gy, whereas the damage was more long-lasting at 20 Gy (40 days or more) [652]. Two references associated with fecundity are also included in the database. Hatchability of cocoons of *Eisenia foetida* irradiated at various developmental stages was affected above 20 Gy. Especially in the early developmental stage, γ-doses of more than 40 Gy affected the hatchability strongly [755]. Fecundity rates (eggs per adult per day) of the springtail *Sinella curviseta* were increased by a dose of approximately 20 Gy of β-radiation. This was explained to be due to superovulation. At higher levels of radiation, fecundity rates were progressively reduced with a LOED of about 50 Gy. Gamma rays were more effective than beta in reducing fecundity rates with a LOED of 25 Gy. RBE may be estimated from dose-effect curves for fecundity (given for both gamma and beta exposure) [761].

Mutation

Two references concerning nematodes are included. A total X-ray dose of 50 Gy was applied to *Panagrellus redivivus* using a range of dose rates (0.23-10.49 Gy min^{-1}). The frequency of lethal X-chromosomes was determined and ranged from 1.6% at low dose rates to 4.3% at highest dose rates, indicating a dose rate dependency of mutation frequency in spermatogonia and oogonia of the nematode [756]. Basic findings in [748] were that at a γ dose of 15 Gy, at least 76% of the lethal recessive mutations induced in *Caenorhabditis elegans* were associated with chromosomal rearrangements. At higher doses rearrangements would be accompanied by additional chromosome breaks in the genome.

2.8.2 The effects of chronic irradiation

The experimental results presently in the database concern the effects of chronic irradiation on two umbrella endpoints; there were no direct dose-effects data on morbidity and reproductive capacity of soil fauna (comments related to those endpoints, however, are included in the mortality section). Several references on chronic exposure contain the same (or very similar) data sets, these being [639, 561, 754] and [763, 757], respectively. The data amount for chronic effects on soil fauna is thus more limited than the number of references imply.

Mortality, morbidity and reproduction

A total of nine references associated with the mortality endpoint are included in the database. Soil with elevated natural background levels of ^{226}Ra (1-2 μGy h^{-1}) contained less earthworms (*Eisenia nordenskioldi, Dendrobaena octaedra, Octolasium lacteum*) and insect larvae (*Dipterea*, *Elateridae*) compared with control areas. Earthworms, especially, proved sensitive to increased radium levels, possibly due to their close contact with soil. In the contaminated plots, earthworms were also smaller in size and showed reproductive disturbances; histological changes in the epithelium of integuments and mid-gut were also observed (cf. morbidity and reproduction) [639, 561, 754]. In experimental plots contaminated with ^{90}Sr and ^{90}Y, the soil was almost completely devoid of myriapods and contained far fewer spiders and earthworms than the control plots. The dose rate in upper parts of the contaminated soil was approximately 6,500 μGy h^{-1} and the number of soil invertebrates per m^2 was about 30% lower than the control [757].

Changes in soil arthropod biodiversity following chronic γ-irradiation were studied using an index of similarity at a range of dose rates (82,000 to 1,610,000 μGy h^{-1}) over time (0-400 days). These biodiversity indices have been characterised as assessing mortality because they reflect changes in the species composition resulting from the loss of individuals belonging to sensitive species [208].

Mutation

One reference was found in the database concerning the scorpion *Tityus bahiensis* [749]. This species exhibits a raised frequency of chromosomal damage when it receives a constant γ–radiation exposure up to 15 μGy h^{-1}. Such low dose rates of chronic irradiation clearly contribute to an increase in the frequency of chromosomal aberrations.

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Acute **Soil fauna** Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Eisenia foetida* *Lumbricus terrestris*	Gamma X-rays	3(2) 1(1)	*Sinella curviseta* *Sinella curviseta* *Eisenia foetida* *Eisenia foetida* *Eisenia foetida* *Armadillidium vulgare*	Gamma Beta[1] X-rays Gamma Beta[1] Gamma	2(2) 1(1) 3(1) 6(2) 1(1) 14(1)	*Eisenia foetida* *Sinella curviseta* *Sinella curviseta*	Gamma Gamma Beta[1]	1(1) 1(1) 1(1)			
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99												
2.0-4.99												
> 5.0	*Eisenia foetida* *Lumbricus terrestris* *Lumbricus terrestris* *Lumbricus terrestris*	Gamma Gamma Mixed X-rays	16(1) 5(1) 4(1) 14(1)	*Sinella curviseta* *Sinella curviseta* *Eisenia foetida* *Eisenia foetida* *Eisenia foetida* *Armadillidium vulgare* Soil fauna	Gamma Beta[1] X-rays Gamma Beta[1] Gamma Gamma	14(2) 8(1) 13(1) 22(3) 4(1) 32(1) 8(1)	*Eisenia foetida* *Sinella curviseta* *Sinella curviseta*	Gamma Gamma Beta[1]	15(1) 5(1) 5(1)	*Panagrellus redivivus*	Gamma	18(2)
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		752	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		752	Beta(<10keV) Beta(>10keV) Alpha Neutrons		
Dbase paper IDs	758,755,652			90,765,764,772,760,761,755,759			761,755			756,748		
Observations "rejected" (paper ID)[c]	None			3(764),6(772),1(759)			1(761)			None		

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Acute **Soil fauna** Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Last paper published in:		1987			1983			1983			1985	

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate. 1 No energy given [761]

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Chronic **Soil fauna** Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Mesofauna	Alpha	8(1)	*Octolasium lacterum* *Dendrobaena octaedae* *Eisenia nordenskioldi* Mesofauna	Alpha Alpha Alpha Beta[1]	1(1) 1(1) 1(1) 4(1)				*Tityus bahiensis* *Dero obtusa, Nais pseudobtusa, Nais pardalis*	Gamma Mixed	5(1) 6(1)
< 99.9				Soil community	Mixed	12(1)				*Tityus bahiensis* *Dero obtusa, Nais pseudobtusa, Nais pardalis*	Gamma Mixed	8(1) 2(1)
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9				Mesofauna Mesofauna	Mixed Beta[1]	1(1) 2(1)						
2,000-4,999												
5,000-9,999				Mesofauna	Beta[1]	2(1)						
> 10,000				*Octolasium lacterum* *Dendrobaena octaedae* *Eisenia nordenskioldi* Various fauna	Alpha Alpha Alpha Alpha	1(1) 1(1) 1(1) 5(1)						

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Chronic **Soil fauna** Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	752,759			208,639,561,754,762,763,757,759, 752			549			549,749		
Observations "rejected" (paper ID)[c]	(38)752,8(759)			12(754),3(759),2(757),1(763), 38(752),6(639),8(765),6(561)			None			4(549),7(749)		
Last paper published in:	1992			1992			None			1976		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate. 1 No energy given [761]

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Acute Bacteria Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Heterotrophic bacteria *Azotobacter chroococcum* *Azotobacter agille* Bacteria	Gamma Gamma Gamma Gamma	1(1) 6(1) 4(1) 1(1)									
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99												
2.0-4.99												
> 5.0	Heterotrophic bacteria *Azotobacter chroococcum* *Azotobacter agille* Bacteria	Gamma Gamma Gamma Gamma	1(1) 27(1) 12(1) 3(1)	*Tetrahymena pyriformis*	Gamma	4(1)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	551,1062			650			None			None		
Observations "rejected" (paper ID)[c]	None			None			None			None		
Last paper published in:	1977			1979			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates, or doses

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Chronic Bacteria Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Bacteria *spp.*	alpha	2(1)									
< 99.9												
100-199.9	Microbial community	Gamma	5(1)									
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999	Microbial community	Gamma	5(1)									
5,000-9,999	Microbial community *Euglena gracilis &* *Tetrahymena & Thermophilia* *& Escherichia coli*	Gamma Gamma	5(1) 3(1)									
> 10,000	Microbial community *Euglena gracilis &* *Tetrahymena & Thermophilia* *& Escherichia coli*	Gamma Gamma	49(1) 12(1)									
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	130,643,673,691			None			None			None		

Table 2-9 Summary effects data on soil fauna and bacteria, based on the FASSET Radiation Effects Database (FRED).

Chronic Bacteria Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Observations "rejected" (paper ID)[c]	30(130) [1],1(691)[1]			None			None			None		
Last paper published in:	1998			None			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

1 Paper describes effects but without giving any dose rates, or doses

2.9 Insects

There were no collated data in the "transitory" type of exposure, and no data from the acquired literature relevant to the derivation of RBE or weighting factor values. The latest reported date was 1974, so the UNSCEAR [1996] review still prevails.

Overall there were not enough data available to draw concluions on dose-effect relationships.

Table 2-10 summarises effects data on insects, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). No effects data were recorded from transitory exposures.

2.9.1 The effects of acute irradiation

Most results centre on gamma radiation, using Co-60. Mortality information was the most common endpoint studied. There are few data for doses below 1 Gy.

Morbidity

A total of five references were recorded, with studies on wasps, mud daubers and *Collembolla*. Observations were reported of comparisons of the percentage of parasite host cocoons, longevity, population growth, and respiration rates.

LOED were reported at 2 Gy for wasps (gamma exposure) and 3 Gy for mud daubers (under X-ray).

Mortality

Experiments centred on LD_{50}, life expectancy and percentage survival rates for a wide range of insects. LOED were recorded at greater than 5 Gy for gamma and X-ray exposures [244, 199, 226, 90, 188, 214].

Reproductive capacity

References indicate studies on mites, wasps, yellow fever mosquitoes and German cockroaches. Results have been expressed in terms of: number of eggs laid, % androgenesis, sterility (% hatch), mean number of females produced, reproductivity (% of non-reproductive females), viability following introduction of sterile males (%), and fertility of females (% viability).

LOED as low as 1 Gy delivered through X-ray exposure to mosquitoes egg, pupa and adult stages resulted in significant reductions in the viability of non stored eggs [245]. LOED of greater than 5 Gy were reported on cockroach reduced reproductive capacity under X-ray and gamma exposures [34,245].

Mutation

Data were reported from a total of four references, all dealing with wasps. Experiments considered mutation frequencies in females, % parasite host cocoons, and frequencies % of eye colour mutations.

Wasps exhibited increases in mutation frequencies at LOED of 2.5 Gy under gamma exposure [152,184].

2.9.2 The effects of chronic irradiation

Most results centre on gamma radiation, using Cs-137 and on occasion X-ray. Morbidity information was the most common endpoint studied, with no information on reproductive capacity. No data were reported for chronic exposure studies concentrating on mortality and reproduction as endpoints.

There are a few data for dose rates below 500 μGyhr^{-1} for morbidity, otherwise there is no reported information below 10 000 μGyhr^{-1}.

Morbidity

Researches have been carried out on ants, arthropods, aphids, leafminers, bark beetles and grasshoppers. Results were reported in terms of behavioural changes in an ant colony, percentage cambial utilisation by beetles or changes in population densities or index of taxa composition.

Whilst a total of seven references were found, only two described effects under gamma exposures for wide ranging dose rates, but above 1 250 μGy h^{-1} [408, 741]. One of the studies related to controlled field experiments where behavioural changes in ant colony were potentially not directly attributable to increased radiation exposure because of other environmental changes associated with radiation, *e.g.* changes in plant structure and cover [345].

Mortality

Three references were reported, looking at survival rates of ants, termites and bark beetles in field experiments, under gamma exposures.

Reproductive capacity

A total of four references were compiled on wasps and termites, looking at egg laying, feeding, nest structures. One experiment resulted in sterility in wasps, under beta exposure, but as the data were related to counts per seconds no conversion to dose rates was possible [181].

Mutation

Four references were reported in this category, all looking at wasps. Few mutations were reported in controls, and mutation frequency observations were sought in oocytes and eye colour.

LOEDR were recorded at 24,000 μGy h^{-1} [152,184] with gamma exposures, but corresponded to the first tested dose rate in the experiments.

Table 2-10 Summary effects data on insects, based on the FASSET Radiation Effects Database (FRED).

Acute Insects Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Proisotoma minuta* *Dahlbominus* *Habrobracon*	Gamma Gamma X-rays	8(1) 1(1) 2(2)	*Neoparasitidae & Rhizoglyphus* *Attagenus piceus* *Tribolium confusum* *Melanolus sanguinipes* *Dermestes ater* *Rhyzopertha dominica* *Habrobracon & Bracon hebetor*	Gamma Gamma Gamma Gamma Gamma Gamma X-rays	2(1) 12(1) 14(1) 19(1) 12(1) 8(1) 3(2)	*Blattella germanica* *Caloglyphus mycophagus & Fuscuropoda marginata* *Aedes aegypti* *Habrobracon juglandis*	Gamma Gamma X-rays X-rays	2(1) 14(1) 2(1) 11(2)	Dahlbominus Dahlbominus	X-rays Gamma	5(2) 2(2)
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99	*Sceliphron caementarium*	X-rays	1(1)	*Musca domestica*	Gamma	1(1)	*Blattella germanica* *Aedes aegypti*	Gamma X-rays	1(1) 1(1)			
2.0-4.99	*Sceliphron caementarium* *Dahlbominus*	X-rays Gamma	2(1) 1(1)	*Drosophila melanogaster* *Melanolus sanguinipes*	X-rays Gamma	1(1) 21(1)	*Blattella germanica* *Aedes aegypti*	Gamma X-rays	3(1) 1(1)	Dahlbominus	Gamma	3(2)

Table 2-10 Summary effects data on insects, based on the FASSET Radiation Effects Database (FRED).

Acute Insects Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Proisotoma minuta*	Gamma	24(1)	*Neoparasitidae & Rhizoglyphus*	Gamma	10(1)	*Blattella germanica*	Gamma	5(1)	*Dahlbominus*	Gamma	8(2)
	Sceliphron caementarium	X-rays	1(1)	*Crematogaster lineolata*	Gamma	10(1)	*Caloglyphus mycophagus, & Fuscuropoda marginata*	Gamma	28(1)	*Dahlbominus*	X-rays	8(2)
	Dahlbominus	Gamma	1(1)	*Monomorium pharaonis*	Gamma	4(1)						
	Habrobracon	X-rays	22(1)	*Cimex lectularius*	Gamma	6(1)	*Habrobracon juglandis*	X-rays	42(2)			
				Periplaneta americana	Gamma	16(2)	*Aedes aegypti*	X-rays	13(2)			
				Blattella germanica	Gamma	26(3)						
				Blatta orientalis	Gamma	9(1)						
				Periplaneta americana	Beta > 10 keV	40(1)						
				Attagenus piceus	Gamma	44(2)						
				Acheta domesticus	Gamma	50(2)						
				Pediculus humanus humanus	Gamma	18(1)						
				Lasioderma serricorne	Gamma	19(1)						
				Thermobia domestica	Gamma	15(1)						
				Tribolium confusum	Gamma	36(2)						
				Drosophila melanogaster	X-rays	13(1)						
				Melanolus sanguinipes	Gamma	97(1)						
				Harpalus pennsylvanicus	Gamma	10(1)						
				Musca domestica	Gamma	9(1)						
				Dermestes ater	Gamma	39(1)						
				Oncopeltus fasciatus	Gamma	10(1)						
				Rhyzopertha dominica	Gamma	29(1)						
				Sceliphron caementarium	Gamma	4(1)						
				Sitophilus oryzae	Gamma	14(1)						
				Armadillidium vulgare	Gamma	8(1)						

Table 2-10 Summary effects data on insects, based on the FASSET Radiation Effects Database (FRED).

Acute Insects Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0 (continued)				*Nasutitermes costalis, & Nasutitermes nigricpes, & Parvitermes discolor*	Gamma	12(1)						
				Habrobracon & Bracon hebetor	X-rays	12(2)						
				Trogoderma granarium, & Sitophilus granarius & Tribolium castaneum	Gamma	60(2)						
				Numerous beetles[1]	Gamma	60(1)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	157,184,195,214,424			34,67,90,154,188,191,199,214,221,226,244, 254,647,660			34,162,181,245,634,687			152,182,183,184		
Observations "rejected" (paper ID)[c]	None			14(67),12(199),14(221),9(226)[2]			None			None		
Last paper published in:	1968			1974			1969			1970		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 *Rhizopertha dominica, Sitophilus granarius, Tribolium castaneum, Trogoderma granarium*. 2 All references: dose at 0 Gy, but positive dose rate reported

Table 2-10 Summary effects data on insects, based on the FASSET Radiation Effects Database (FRED).

Chronic Insects Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Formica integra* *Dahlbominus* *Myzocallis discolor*	Gamma Gamma Gamma	1(1) 1(1) 1(1)	*Ips grandicollis* *Nasulitermes costalis*	Gamma Gamma	1(1) 6(1)	*Habrobracon juglandis*	Beta	10(1)	*Dahlbominus* *Dahlbominus*	Gamma X-rays	2(2) 1(1)
< 99.9												
100-199.9												
200-499.9												
500-999.9	Arthropods[1]	Gamma	1(1)									
1,000-1,999.9	*Cameraria hamadryadella*	Gamma	20(1)									
2,000-4,999	*Cameraria hamadryadella*	Gamma	6(1)									
5,000-9,999	Arthropods[2] *Cameraria hamadryadella*	Gamma Gamma	9(2) 6(1)									
> 10,000	*Pogonomyrmex occidentalis* *Ips grandicollis* *Cameraria hamadryadella* *Dahlbominus*	Gamma Gamma Gamma Gamma	4(1) 48(1) 6(1) 2(1)	*Pogonomyrmex occidentalis* *Ips grandicollis & calligraphus* *Nasulitermes costalis*	Gamma Gamma Gamma	1(1) 5(1) 6(1)				*Dahlbominus* *Dahlbominus*	Gamma X-rays	6(2) 2(2)
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		

Table 2-10 Summary effects data on insects, based on the FASSET Radiation Effects Database (FRED).

Chronic Insects Dose-rate ($\mu Gy\ h^{-1}$)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Dbase paper IDs	184,345,408,409,741,750,751			164,196,251			181, 196,197			152,182,183,184		
Observations "rejected" (paper ID)[c]	4(409)[3]						15(181)[4],4(196), 5(197)[3]			1(182)[3]		
Last paper published in:	1974			1973			1970			1970		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 78 taxa. 2 *Carabidae, Phalacridae, Simuliidae, Kolla bifida, Poduridae, Sminthuridae, Aphidiae, Trombibculidae*, & 78 taxa in another paper. 3 All references: dose rate at 0 microG/hy, but positive dose reported. 4 Results in counts per seconds, so can't translate into dose rates

2.10 Fish

The study of the responses of fish to irradiation has a long history. X-ray exposures of developing lamprey eggs were carried out by Tarkhanov [1896] soon after the discovery of the radiation. The major part of the available literature, however, dates from the mid-1940s when it was recognised that the applications of nuclear energy for either military or peaceful purposes would be likely to result in the release, either deliberate or adventitious, of man-made radionuclides to lakes, rivers, seas and oceans. This literature has been reviewed, more or less comprehensively in a number of publications [Blaylock and Trabalka, 1978; IAEA, 1976, 1988, 1992; NCRP, 1991; UNSCEAR, 1996; Woodhead, 1984], and new studies continue to be published, although at a low rate. The radiation effects database contains 167 references to publications on the responses of fish to irradiation, of which 151 contain potentially useful information (*i.e.* the paper was not rejected because it was not possible to estimate the dose rate for chronic exposures). Table 2-11 provides a summary of the fish data that have been entered into the database. A majority of the papers give data for acute radiation exposures (118) as compared with chronic irradiation (34); and for both irradiation regimes, reproductive capacity is the most frequently studied umbrella endpoint. In part, this latter focus arises from the ease with which fertile fish eggs can be obtained and the development of the embryo followed visually until hatching, but it also stems from the expectation that the developing embryo would be one of the radiosensitive stages of the life-cycle. The most recent paper on the response to acute irradiation is 1992, and for chronic irradiation is 1999.

The species that have been studied for the publications included in the database are almost entirely from the class Osteichthyes, *i.e.* the bony fishes; there are very few examples from the class Chondrichthyes, *i.e.* the cartilaginous sharks and rays.

The data relating to the responses to acute irradiation are primarily for freshwater species, with the Japanese ricefish or medaka (*Oryzias latipes*) being the favoured subject for study, followed by the rainbow trout (*Salmo gairdnerii*). Anadromous (*i.e.* those that mature in the sea and return to river headwaters to spawn) and marine species are almost equally represented; there are no data for catadromous species (*i.e.* those that mature in freshwater and return to the sea to spawn, *e.g.* the European eel).

The data relating to the responses to chronic irradiation are more evenly distributed between freshwater, anadromous and marine species, but again, there are no data for catadromous species. As before, the medaka is the favoured organism for study from the freshwater environment; the two pacific salmon species, *Oncorhyncus kisutch* and *O. tshawytscsha*, provide essentially all the available data for anadromous species; and, the European plaice (*Pleuronectes platessa*) has yielded about half the available data for marine species.

2.10.1 The effects of acute irradiation

For the acute irradiations, exposures to X-rays are in a small majority as compared with sealed sources of γ-rays; one study employed a sealed external source of β-particles. There are no data relating to responses to high LET radiations, *i.e.* neutrons or α-particles, so there is no possibility of estimating RBE values. There are data available for the umbrella effects in all acute dose ranges except for morbidity at doses of 2 - 4.99 Gy; the majority of the data relate, however, to acute exposures greater than 5 Gy. The last paper was published in 1992.

Morbidity

A variety of biological endpoints has been studied that may be included under this umbrella heading. The lowest doses at which effects have been seen can be summarised as follows (unless specifically noted, these were also the lowest doses used in the studies, *i.e.* it is not possible to give any estimate of the highest no effect dose).

The most data are available for the medaka (*Oryzias latipes*). The mitotic activity (cell division) in, and the volume of, the thymus was significantly affected by exposure to doses greater than 1 Gy but lower doses of 0.1 and 0.25 Gy had little apparent effect [36]. An exposure of 10 Gy at critical times was found to suppress the primary and secondary rejection responses to allogenic scale grafts [4]. The lipid metabolism of hepatocytes, and the gonadotrophin release by the pituitary, were found to be inhibited by a 20 Gy radiation exposure [49].

In the tench (*Tinca vulgaris*) the leucocytes in the blood are reduced to 50% of control values by an exposure of 1 Gy, but the numbers of, and ^{59}Fe incorporation into, erythrocytes is only affected at the higher dose of 11 Gy [57]. The numbers of thrombocytes and leucocytes in the circulating blood of the pinfish (*Lagodon rhomboides*) were reduced by a radiation dose of 20 Gy but the thrombocytes recovered to control values by 35 days post-irradiation whereas the leucocytosis persisted [41].

Exposure of the goldfish (*Carassius auratus*) to 80 Gy reduced the number of cells in the intestinal epithelium as compared with the controls. If the fish were maintained at a low temperature of 4°C the post-irradiation cellular depletion of the intestinal epithelium was delayed and survival was extended as compared with fish maintained at the normal temperature of 22°C, but this apparent protective effect disappeared if they were returned to the normal maintenance temperature of 22°C [77, 78]. Exposure of goldfish to 10 - 20 Gy of X-rays induced hypertrophy of the interrenal glands; as this response was also induced by exposure of the head alone, and by the injection of ACTH (adrenocorticotrophic hormone) into un-irradiated fish, it was concluded that the irradiation exposure stimulated the secretion of the hormone from the pituitary gland [39].

Thyroid and haematological lesions were induced in all amazon mollies (*Poecilia formosa*) following the injection of isogenic thyroid cells that had been irradiated with a dose of 2.5 Gy [155].

Ancestral paternal irradiation with 5 Gy increased the incidence of spinal deformities in the F_2 generation of an inbred guppy (*Poecilia reticulata*) line; 10 Gy to both sexes increased the incidence in both the F_1 and F_2 generations. These effects did not, however, persist into the subsequent generations [5].

The growth of rainbow trout (*Salmo gairdnerii*) over a two year period was not affected by exposure to doses of 0.21, 0.83 or 2.03 Gy at the eyed embryo stage [111]. Exposure of rainbow trout (*Salmo irideus*) fry to 1 Gy depressed their feeding activity significantly in the period 3 - 7 days post-irradiation [217].

In conclusion, it appears, from the data presented above, that acute doses below 1 Gy are unlikely to have any significant influence on the general health (morbidity) in fish.

Mortality

While mortality might appear to be an unambiguous biological endpoint, it has actually been assessed in a number of different ways, *e.g.* as a function of time, or as mean survival time,


after irradiation, as a function of age at irradiation, etc., thus the available data are not easily comparable.

Total doses of Cs-137 γ-rays in the range 900 – 1,100 Gy induce some mortality of medaka (*O. latipes*) within 24 hours, although there is dependence on the dose rate (28 Gy min^{-1} is more effective than either 0.2 or 1 Gy min^{-1}) [38]. All male medaka irradiated with doses of 40 and 80 Gy died within 11 days [36, 103], whereas all males exposed to 20 Gy, and the controls, survived to 60 days [103]; similarly, all males and females exposed to 40 Gy died within 19 days, whereas the death rate at doses of 5 and 10 Gy was not significantly different from that of the controls [102]. Irradiation of medaka embryos with doses of X-rays less than 10 Gy at any stage of development did not appear to affect the subsequent survival up to day 30 post-irradiation [21].

Of 22 guppies (*Poecilia reticulata* (this is a taxonomic revision of the original species name - *Lebistes reticulatus*)) irradiated with X-rays to a dose of 15 Gy, only one survived at 8 months post-exposure [135]. Ancestral exposure of either male or female guppies in a hybrid line with 10 Gy of X-rays increased the incidence of neonatal deaths (*i.e.* within 90 days of birth) in the F_2 generation, but this treatment did not have any significant effects in the F_1 generation, or in an inbred line [5].

The injection of isogenic thyroid cells that had been irradiated with doses of 2.5 or 5 Gy of Co-60 γ-rays had no influence on the survival of amazon mollies (*P. formosa*)[155].

All goldfish (*C. auratus*) exposed to 80 Gy of X-rays died within about 10 days at 22°C but all survived for 110 days at a maintenance temperature of 4°C although 75% subsequently died between 150 and 200 days post-irradiation; there were no control deaths within the 200 day period [77]. The exposure of the medaka (*O. latipes*) to 28 Gy of X-rays resulted in 100% mortality at 23 °C, whereas maintenance at a temperature of 4°C provided apparent protection until the temperature was raised back to the normal 23°C [40, 42]. In this latter study, the prior administration of cysteamine mitigated the lethal effects of irradiation at both of the maintenance temperatures.

Total X-ray doses in the range 3 - 12 Gy appeared to have little effect on the mortality of 3-month old rainbow trout fry (*Salmo irrideus*) as compared with the controls [217]. There is no effect on the subsequent survival of eyed rainbow trout embryos (*Salmo gairdnerii*) exposed to 0.21, 0.83 and 2.03 Gy of X-rays [111].

Irradiation of three month old chinook salmon fingerlings (*Oncorhynchus tschawytscha*) with 1 Gy of X-rays did not increase the cumulative mortality at 90 days post-exposure, but 2.5 Gy had a significant effect. The LD50 at 90 days can be estimated to be in the range 12.5 - 20 Gy [65]. Exposure of eyed embryos of the chinook salmon to 10 Gy of X-rays arrested the development of the hatched larvae and 51 % died during a 125 day post-hatch period. At lower doses of 5 and 2.5 Gy the mortalities were slightly, but not significantly greater than the controls [213]. The radiosensitivity of the developing embryo was found to vary over time with LD_{50} values for the survival of the larval fish to 107 days after fertilisation of 3.4, 2.9, 9.8 and 10.0 Gy for irradiation with X-rays at the 1-cell, 32-cell, epiboly and eyed embryo stages, respectively [29]. The 1-cell stage in silver salmon embryos (*Oncorhynchus kisutch*) had previously been found to have a rather variable radiosensitivity with the very early part (0.17% of embryonic development) showing the lowest LD50 at 150 days post-fertilisation of 0.16 Gy [131].


A limited study of two shark species (*Triakis scyllia* and *Heterodontus japonicus*) found that a Cs-137 γ-ray exposure of 20 Gy was lethal within 20 days (no control deaths occurred) due to intestinal and haematopoietic damage, and it was concluded that sharks show a similar radiosensitivity to acute radiation exposure to that of the teleost fish [48].

Juvenile and post-larval individuals of 6 species of marine teleosts (*Micropogon undulatus*, *Fundulus heteroclitus*, *Mugil cephalus*, *Paralichthys lethostigma, Lagodon rhomboides* and *Eucinostomus spp*) showed $LD_{50/30}$ values in the range 10.5 - 55.5 Gy, but it was observed that at later times the LD_{50} values were lower (9.25 - 30.8 Gy at 40 days (6 species), and 10.8 - 22.5 Gy at 50 days (4 species)). Thus it may be concluded that the 30 day assessment period usually used for homeothermic mammals is not appropriate for the poikilothermic fish [267]. Aoki *et al*. showed that the $LD_{50/30}$ of the goldfish (*C. auratus*) was between 10 and 20 Gy of X-rays [39].

In conclusion, in terms of subsequent survival, it is clear that the fish embryo is much more radiosensitive than the free swimming larvae, the juveniles and the adults - acute exposures as low as 0.16 Gy could have significant effects if delivered at critical times in the early 1-cell stage of development and the consequent mortality is scored over long periods. At all other times, however, exposures less than 2 Gy are likely to have little effect on mortality. In making any comparisons of radiosensitivity between fish and other vertebrate groups, due account must be taken of their poikilothermic (as opposed to homeothermic) nature, and of the finding that fish show a wide range of LD_{50} values for a given determination period.

Reproductive capacity

This umbrella category includes the effects of radiation on the production of germ cells - spermatogenesis and oogenesis (here called fertility), and on the development of the embryo up until the time that it begins to lead an existence independent of direct physiological support provided by the parents, *i.e.* at the time of hatching for fish eggs that are released into the environment to develop, and at the time of birth for ovo-viviparous species, *e.g.* the guppy (*Poecilia reticulata*) - the fecundity.

Exposure of reproductively active male and female medaka (*Oryzias latipes*) to about 4.9 Gy increased the number of deformed and dead embryos resulting from subsequent matings; the incidence returned to normal levels by 20 days post-irradiation. It was determined that the process of spermatogenesis was 3 - 4 times more radiosensitive than oocyte maturation, and took twice as long to recover to normal levels [159]. The loss of male fertility after exposure to 5 Gy has been shown to be due to the radiation-induced reduction in the numbers of the differentiating spermatogonia and the spermatocytes, and that the recovery is due to the compensating activation of the more radio-resistant primary spermatogonia [101, 102, 105]. Even a dose as low as 1 Gy has some slight effect on the sensitive stages of spermatogenesis, and 2.5 Gy to either the male or female can temporarily reduce the hatchability of the eggs laid [16, 103]. During the recovery period to normal spermatogenesis, oocyte-like cells have been observed in the medaka testes [103]. An exposure of 20 Gy to the female medaka prevents the normal process of oocyte maturation (ovarian growth) when the fish are transferred from water at 10 °C where they are sexually inactive to water at 26 °C [107], but an exposure of 10 Gy had no effects [102]. Exposure of the developing medaka embryo to 20 Gy at 3 days after fertilisation of the egg interrupts the normal development of the gonads. At about 5 days post-hatching, the ovary appears to resume normal development in terms of cell numbers, but there is residual damage to intra-cellular organelles detectable in electron micrographs; the testes do not resume development [118]. The testes in the embryo show increasing radiosensitivity during development with an exposure of 5 Gy increasing the

proportion of ovo-testes and the incidence of sterility [112]. Exposure of the meiotic oocytes in 3-day old fry to 10 Gy causes cell death and no regeneration of the ovary is possible because there are no oogonia remaining in the earlier mitotic stage of development [94]. The mean survival times of medaka embryos irradiated at five different stages of development was not significantly affected, as compared with the controls, by exposures up to 10 Gy [21]. An exposure of 20 Gy at a dose rate of 0.25 Gy min^{-1} at times of increasing embryonic development showed that there were particular stages of higher radiosensitivity as determined by the percentage hatch of the eggs; a similar variation in embryo sensitivity was found for pike (*Esox lucius*) eggs exposed to 2 Gy at 0.26 Gy min^{-1} [116], and for silver salmon (*Oncorhynchus kisutch*) in terms of the resultant LD_{50} at hatching when exposed at different stages of development to X-rays at a dose rate of 1 Gy min^{-1} [131]. From 5 days post-fertilisation, the 20 Gy exposure had no significant effect on hatching success. This variation in stage sensitivity disappeared, however, when the same total dose was delivered at the lower dose rate of 0.017 Gy min^{-1} (~1x10^6 μGy h^{-1}), and the hatching success was almost the same as for the controls; in part, this changed response is due to the fact that the radiosensitive stages do not accumulate sufficient total dose to induce the differential effect at the lower dose rate [266]. X-ray exposure of the ovary alone to 20 Gy had no effect on the subsequent egg-laying activity of female medaka, but the same exposure of the whole body, or with just the ovary shielded resulted in a substantial reduction in egg-laying from 5 days post-irradiation [178]. Exposure of the anterior or posterior half, or the whole, body of the loach (*Misgurnus anguillicaudatus*) to 10 Gy had no significant effect on the weight or histological appearance of the ovary [205]. Importantly, different laboratory strains of the medaka have been shown to have differing radiosensitivities in terms of effects on both fertility and fecundity [16].

Eggs of the tench (*Tinca tinca*) irradiated with X-rays at 30 minutes post-fertilisation showed a reduction in hatch rate and an increase in the number of deformed larvae at the lowest exposure used (0.25 Gy); their survival over the 10 day post-hatch period was, however, greater than either the controls or the fish that had received 2.5 Gy. In addition, the prior exposure of the embryos to 0.25 Gy (and, to a lesser extent, to 0.5 and 1 Gy) provided some protection, as indicated by their 10 day survival, to an exposure to 40 Gy of X-rays at age 2 days [113].

For male and female hybrid (outbred) guppies (*Poecilia reticulata*) each exposed to 10 Gy and mated with unirradiated partners, there were no significant differences in the sizes of the first four broods in the F_1 generation as compared with the controls, or between treatments. For an inbred line, there were no significant effects in the F_1 generation for males exposed to 5 Gy and mated to unirradiated females, or for matings between males and females that each had been receiving a dose of 10 Gy. No effects were observed concerning the numbers of stillborn fish, the incidence of postnatal mortality, or in the sex ratio in the F_1 generation for any combination of treatments [5]. An exposure of male guppies to 5 Gy of X-rays significantly reduced the numbers of spermatogonia, spermatocytes, spermatids and, ultimately, spermatozoa [99].

In vitro exposure of loach (*Misgurnus fossilis*) sperm to X-rays to doses at and above 1 Gy induces progressive detrimental changes in the incidence of fertilised eggs, embryo death, normal embryos at hatching and chromosome bridges in dividing cells at gastrulation [174].

An 8 Gy exposure to Co-60 γ-radiation (0.0083 Gy min^{-1}) to newly-fertilised goldfish (*Carassius auratus*) eggs increased the number of abnormalities and the embryo mortality [31].

Developing carp (*Cyprinus carpio*) embryos showed increasing resistance to the effects of irradiation with Co-60 γ-rays (3.83 Gy min^{-1}). At 30 minutes post-fertilisation, 5 Gy reduced the hatching success to 50%, and 36 % of the resulting larvae were abnormal. The same dose at 1 hour post-fertilisation, or later, had no significant effects on either endpoint as compared with the controls [27]. An intercomparison of the effects of Co-60 γ-rays (4.26 Gy min^{-1}) and $^{90}Sr/^{90}Y$ β-radiation (0.84 Gy min^{-1}) delivered at 30 minutes post-fertilisation yielded estimated LD_{50} values for hatching success of 6 and 5 Gy, respectively. Although there is some indication that the β-radiation is more effective than the γ-radiation, *i.e.* the RBE is greater than unity, it must be noted that the exposure period for the β-dose is extended by a factor of 5 relative to the γ-dose at a time when it is to be expected that the radiosensitivity of the developing embryo is varying [Blaylock and Griffith, 1971].

The LD_{50} for silver salmon (*Oncorhynchus kisutch*) embryos at hatching varied between 0.3 and 18.7 Gy of X-rays (1 Gy min^{-1}) depending on the embryonic stage irradiated. The induced mortality did not cease at hatching and the LD50 at 150 days was estimated to be 0.16 Gy [131]. No significant effects on the cumulative mortality of rainbow trout (*Salmo irrideus*) eggs from parents each irradiated with 1 Gy of X-rays (0.0825 Gy min^{-1}) although the subsequent mortality of the fry was significantly increased at all doses greater than, or equal to, 0.5 Gy [150]. Exposure of 4-month old rainbow trout fry to 1 and 5 Gy of X-rays (0.33 Gy min^{-1}) produced a dose-dependent increase in the incidence of necrotic cells in the developing testes, but the organ recovered and the irradiated fish tended to mature earlier than the unirradiated controls [104]. In the females, the ovary weight relative to the body weight was significantly reduced at 4 and 6 months after irradiation at both doses, but by 9 months the ovaries in the 1 Gy group had recovered to control values [169]. Low doses (0.25 and 0.5 Gy) of Co-60 γ-radiation (0.64 Gy min^{-1}) to rainbow trout (*Salmo gairdnerii*) sperm have been shown to increase the fertilisation rate of eggs [61] and the survival of the resulting embryos [202], but the number of abnormal embryos was increased at both doses [153]; higher doses are unconditionally harmful. Thus, the low doses appear to induce both “benefits” and “harm” [141]. X-ray exposures of 0.21, 0.83 and 2.03 Gy to rainbow trout (*S. gairdnerii*) eyed embryos have no effects on their subsequent fecundity [111].

An acute X-ray exposure of 5 Gy to a marine goby (*Chasmichthys glosus*) caused significant damage to both the ovaries (in the 4 - 19 day post-irradiation period) and the testes (4 - 24 days post-irradiation). In both cases, however, regeneration of the organs was under way towards the end of the study. The ovaries showed some differential radiosensitivity as a function of the season, *i.e.* the actively developing oocytes in the spring are more sensitive than the resting oocytes in the winter [100, 106, 175].

Developing eggs of the killifish (*Fundulus heteroclitus*) exposed to 1 Gy of X-rays (1 Gy min^{-1}) at the 8-cell stage and then at 24 hour intervals for 5 days (giving a total dose of 6 Gy) showed delayed development and hatch, but the embryo survival and the cumulative hatch were not significantly different from the controls [72].

Irradiation of plaice (*Pleuronectes platessa*) embryos at 22 h post-fertilisation, *i.e.* at their estimated time of maximum sensitivity, with doses of X-rays (0.291 Gy min^{-1}) between 0.3 and 1.5 Gy produced a clear sigmoid response curve for survival to larval metamorphosis (*i.e.* when the larvae transform to the “flat” morphology and adopt a benthic habit) with an estimated LD_{50} of 0.9 Gy. A total dose below about 0.3 Gy would have no significant effect on survival to metamorphosis [28]. In this study the LD_{50} at hatching would have been greater than 1.5 Gy, in reasonable agreement with the data of Templeton [33] from which a value of 2.1 Gy may be estimated. Again, it may be estimated that doses less than about 0.5 Gy would


have little effect on the mortality at hatching although the incidence of abnormalities would be increased above control levels [33].

In conclusion it is clear from the available experimental results that the developing fish embryo is very sensitive to the effects of acute irradiation, particularly at the very early stages just prior to, or immediately after the actual fertilisation (*i.e.* the conjugation of the male and female pronuclei), and during the process of division of the single cell. Irradiation of silver salmon embryos at this stage gave an estimated LD_{50} of 0.16 Gy when assessed at 150 days post-irradiation. At this time, the response is likely to be stochastic in nature, and it may be reasonably assumed that any acute (or chronic) exposure would have a low, but non-zero, probability of affecting the outcome of the subsequent embryonic development. Apart from this critical time interval in embryonic development, however, it appears unlikely that significant effects will follow doses below 0.5 Gy. It also appears that an acute dose of this magnitude at any later stage of development will be unlikely to have any significant influence on adult male and female fertility.

Mutation

A variety of endpoints, including specific locus mutations, dominant and recessive lethal mutations, polygenic characters, and chromosome aberrations, has been used to assess the possible mutagenic impact of irradiation of fish. Because the mutagenic effects of radiation are of a stochastic nature, it is to be expected that the induced incidence would be linear with dose at low acute doses; the main question to be considered is the relative sensitivity of fish as compared with the more intensively studied mouse.

X-irradiation of male and female guppies (*Poecilia reticulata*) with doses of 10 and 20 Gy confirmed the possibility of mutations at Y-linked genes for specific body colour patterns (the colour pattern polymorphism complex) [3, 5, 135]. Exposure of the male partner in an inbred line to 5 Gy, and both partners to 10 Gy, showed on increase in anomalous individuals in the F_1 and F_2 generations - and indication of recessive mutations [5, 9]. In specific locus tests, the phenotypic segregation ratios in the F_2 generation after exposure of wild-type parental generation stem cell spermatogonia or oogonia, or spermatozoa (to 10, 10 and 2 x 5 Gy of X-rays, respectively) were significantly altered from the control values (also significantly different from the theoretical Mendelian expectation). It was concluded that heterozygosity for radiation-induced recessive mutations in the wild-type gene constitution were having differential deleterious effects on the viability of the F_2 offspring depending on the particular complement of test alleles present [13]. The induction of specific locus mutations in the zebra fish (*Brachydanio rerio*) increases linearly (at 4×10^{-3} Gy^{-1}) with dose from 0.9 Gy of Co-60 γ-rays, the lowest dose employed. Recessive lethal mutations, at a rate of 4×10^{-1} Gy^{-1}, were detected by the quantification of embryo viability in eggs fertilised with UV-inactivated sperm and then made homozygous through the application of a heat-shock [17]. Later studies showed that specific locus and recessive lethal mutations could be induced in the pregonial cells in early cleaving embryos and recovered in subsequent offspring [18]. The induction of specific locus mutations in the developing gametes of the male medaka (*Oryzias latipes*) was found to increase from spermatogonia through spermatids and be greatest in the mature sperm. A dose of 0.64 Gy (0.95 Gy min^{-1}) of Cs-137 γ-rays to sperm was found to increase the incidence of specific locus mutations by more than 10-fold relative to the controls [19].

Dominant lethal mutations are most often quantified by comparing the reduced brood/litter size from irradiated animals relative to the controls. In the medaka, the immediate mating of irradiated females with unirradiated males produces a dose-dependent reduction in the hatching success (*i.e.* the increased induction of dominant lethal mutations) for eggs produced


1 - 4 days post-irradiation, *i.e.* there is no threshold for effect above 2.5 Gy of X-rays. For eggs produced 6 - 10 days post-irradiation, there was some evidence for a threshold extending up to 10 Gy and some recovery from the exposure. Variation of the dose rate between 0.014 and 2.5 Gy min^{-1} for a 20 Gy dose to oocytes had no effect on the relative hatching success of the resulting eggs. The reverse mating of irradiated males with unirradiated females showed greater reductions (as compared with the response of irradiated females) in hatching success at a given dose for eggs fertilised with sperm irradiated as sperm or late spermatids; the early spermatids and spermatocytes showed somewhat lesser radiosensitivity. There was evidence of a dose rate sparing effect for lower dose rates when spermatocytes and spermatogonia were exposed, but this was not apparent for the later stages of spermatogenesis [16]. The general magnitude of the induction rate of dominant lethal mutations, and the relative radiosensitivities of the stages of spermatogenesis in medaka, were confirmed in an independent study [19]. The dominant lethal mutations induced in mature medaka sperm, and scored as inviable embryos, have been shown, in part, to correlate with the loss of paternal bands in DNA fingerprints developed using an arbitrarily primed polymerase chain reaction (AP-PCR) [82]. An X-ray dose of 2 Gy to either the ova or sperm of the rainbow trout (*Salmo gairdnerii*) resulted in a significant increase in the number of anomalous embryos that did not survive. It was assumed that this outcome was the consequence of dominant lethal mutations involving the loss of chromosomal material in the irradiated gametes and the resulting aneuploidy in the zygote. Assuming a linear dose response relationship, together with the spontaneous incidence of anomalies in the control eggs, it was estimated that the doubling dose for the induction of dominant lethal mutations was about 0.26 Gy [206].

Exposure of developing embryos of one strain of the platyfish (*Platypoecilus maculatus*) to 15 Gy of X-radiation, and subsequent breeding tests with a second non-irradiated strain, revealed the induction of mutations in a highly polygenic repression gene system responsible for melanophore gene control (and melanophore expression). This polygenic system was found to be distributed throughout the chromosome complement [8]. A 10 Gy X-ray exposure of either parent guppy (as neonates) showed mutation effects on quantitative traits in F_1 and F_2 offspring (number of vertebrae and relative body proportions) that are controlled by a polygenic system [10, 264].

Chromosome aberrations (dicentrics, centric rings and acentric fragments) were induced in cultured cells derived from embryos of *Ameca splendens* as a linear function of the dose from Co-60 γ-rays; the lowest dose used - 0.75 Gy - produced an increase in aberration frequency relative to the controls [11]. An *in vitro* X-ray dose of 0.48 Gy induced a significant increase in the incidence of dicentric chromosomes, as compared with the controls, in cultured lymphocytes from the mudminnow (*Umbra limi*) [14]. *In vivo* irradiation of mudminnows (3.25 Gy X-rays) induced a 300-fold increase in the incidence of chromosome gaps and breaks in mitotic cells sampled from kidneys, gills, stomach and intestines; no increases in the numbers of translocations or inversions were seen [15]. X-irradiation (10 Gy) of stem cell spermatogonia in neonatal male guppies increases the incidence of exchanges of chromosomal material between the X and Y chromosomes as revealed by the resultant appearance of specific, sex-linked, colour patterns in the offspring derived from breeding tests with unirradiated females. The later stages of differentiating spermatogonia (the so-called “early” spermatogonia) did not show this response [12]. The conservation of chromosome damage in embryos and larvae produced from either ova or sperm irradiated with 5 Gy of X-rays has been demonstrated in the groundling (*Misgurnus fossilis*), the Russian sturgeon (*Acipenser güldenstädti*) and the sterlet (*A. ruthenus*) with the observation of anaphase and telophase bridges (indicative of the presence of dicentric chromosomes) in dividing cells. The incidence of radiation-induced damage was consistently above control levels, but there was


great variation between individuals. In addition, the incidence of chromosome damage was higher in visibly deformed than apparently normal larvae [172].

In conclusion, all forms of mutagenic damage (specific locus mutations, dominant and recessive lethal mutations, polygenic characters, and chromosome aberrations) have been observed at all radiation doses used in the relevant studies. This is not an unexpected result for a stochastic response to acute radiation exposure. A possible exception is the apparent absence of dominant lethal mutations in medaka embryos developing from eggs spawned later than 6 days post-exposure for which a threshold (*i.e.* a highest no effect dose) of 10 Gy might be deduced for the data given, with no effect apparent at the lowest dose of 2.5 Gy [16]. For the rainbow trout, and on the assumption of a linear dose-response relationship, a doubling dose of 0.26 Gy was estimated for the induction of dominant lethal mutations in either ova or sperm [206]. Where comparisons of relative radiosensitivity have been made, it has been concluded that fish show a sensitivity similar to, and most often less than, that of the mouse [3, 5, 19, 135]; there is a single example of apparently greater sensitivity - for specific locus mutations induced in medaka sperm [19].

Although there are no data relating to radiation-induced mutagenesis in marine fish, there is no reasonable basis for expecting them to respond any differently, in general terms, to their freshwater counterparts.

2.10.2 The effects of chronic irradiation

A majority (~66%) of the chronic irradiation studies employed external sealed sources of γ-rays and almost all of the remainder used β-emitting radionuclides added to the water and taken up by, or adsorbed onto, the experimental organism. In this case, the methods of estimating the dose rate and its spatial distribution in relation to the specific targets of interest are crucial to the interpretation of the resulting data concerning radiation effects. A few of the available data relate to exposure to mixed β- / γ-sources, and even fewer to exposures to ^{3}H and α-emitters. There are, therefore, very limited data to form a basis for estimates of RBE values. As may be seen from Table 2.11, there are data in all dose rate ranges for the umbrella endpoints of morbidity and reproductive capacity, but there are substantial gaps for mortality and the induction of mutations.

Morbidity

The endpoints that have been studied include body weight and length, and measures of immune response.

For male guppies (*Poecilia reticulata*) that had been irradiated with ^{3}H (as tritiated water) as developing embryos, a dose rate of 4.7 10^{3} μGy h^{-1} (total dose 2 Gy) had no significant effect on body weight at either 16 or 43 weeks of age. Pooled data on the body weight at 14 weeks at higher dose rates in the range (9.4 - 18.8) 10^{3} μGy h^{-1} showed a significant reduction, but this had disappeared by 43 weeks; also exposed females showed no significant weight changes at 43 weeks. Fish irradiated as week-old juveniles were less sensitive [73]. Irradiation as embryos at 9.4 x 10^{3}, or as juveniles at 4.7 x 10^{3} μGy h^{-1} did not affect the survival time of the guppies when exposed to a heat shock [73]. Irradiation of medaka (*Oryzias latipes*), as embryos and until 2 months of age, at dose rates of 1.17 x 10^{4} and 2.21 x 10^{4} μGy h^{-1} (total accumulated doses of 14.6 and 27.6 Gy, respectively) did not have any significant effect on male or female body weight at an age of 385 days [91].

No significant effects on mean eye diameter were seen in sticklebacks (*Gasterosteus aculeatus*) that had been exposed at a dose rate of 580 μGy h^{-1} from tritiated water as developing embryos [75].

Exposure of developing chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon embryos to Co-60 γ-rays at a dose rate of ~200 μGy h^{-1} (total dose 0.33 - 0.4 Gy) had no significant effects on growth as indicated by parr length; the weight of the coho parr was not significantly different from the controls, but the exposed chinook parr were significantly heavier than the controls. In the exposed coho salmon parr, individuals had significantly fewer vertebrae, and there was a significantly greater incidence of truncated opercles exposing the posterior edge of the gill filaments, as compared with the controls [265].

Exposure of rainbow trout (*Salmo gairdnerii*) embryos to ^{3}H (as tritiated water) during embryogenesis has been found to influence the immune response of juveniles and yearlings to a natural *Chondrococcus columnaris* infection. The estimated dose rates were 2.1 x 10^{3} and 2.1 x 10^{4} μGy h^{-1} (total doses of 1 and 10 Gy). For the juveniles, the exposure to the two different concentrations of ^{3}H significantly suppressed the immune response in the late summer, relative to the controls, but there was no significant difference between the two irradiation levels; for the yearlings, the lower dose rate induced a significant suppression, again in the late summer [189]. In a second study, a greater range of lower dose rates (0.83, 8.3, 83, and 830 μGy h^{-1} (for total doses of 4 x 10^{-4}, 4 x 10^{-3}, 0.04 and 0.4 Gy)) were employed to determine the influence on the primary immune response in juvenile rainbow trout to a vaccination with heat-killed cells of *Flexobacter columnaris*. At 9 and 11 weeks post-vaccination there was significant variation between radiation treatments in the specific serum agglutinin titres. It was concluded that the lowest dose rate had had no significant influence at either 9 or 11 weeks, and that 8.3 μGy h^{-1} had had no effects at 11 weeks [84]. In a continuation of this study, the response of yearlings to a second challenge of inactivated *F. columnaris* cells was investigated. At 7 and 10 weeks post-vaccination it was concluded that the lowest dose rate had had no significant effect on the serum agglutinin titre; for each of two replicates there was a significant linear dependence of the immune response suppression (as % of control) on the logarithm of the dose (and dose rate) [86]. A fourth study investigated the influence of external irradiation with Cs-137 γ-rays during embryonic development (experiment I), and from fertilisation for 246 days, *i.e.* well into the juvenile period (experiment II) for the rainbow trout (*Oncorhynchus mykiss*). In experiment I the dose rates were 1.9 x 10^{3}, 3.7 x 10^{3} and 9.0 x 10^{3} μGy h^{-1} (total doses 0.83, 1.66 and 4.01 Gy). The immune response was tested at 5 months of age by means of an intra-peritoneal injection of dinitrophenol conjugated keyhole limpet haemocyanin (DNP-KLH) antigen. All groups raised antibodies to the antigen, and the response of the irradiated fish was not significantly different from the controls. In exp. II, the irradiation of the embryos was as for exp. I, and then the fish continued under irradiation (at lower mean dose rates: 9.9 x 10^{2}, 1.9 x 10^{3} and 4.66 x 10^{3} μGy h^{-1}) for an additional 225 days (total accumulated doses: 5.43, 10.53 and 25.43 Gy). The immune response to the DNP-KLH antigen challenge was significantly depressed at the highest dose rate as compared with the controls and the lower dose rate; there was no significant difference between the controls and the two lower dose rates. The overall trend of the response appears, however, to indicate a suppression dependent on the total accumulated dose (and, therefore, the dose rate) from a threshold at around 10^{3} μGy h^{-1} [85].

Irradiation of a marine fish (the eelpout - *Zoarces viviparus*), as adults, with Cs-137 γ-rays from an external source at a dose rate of 2 x 10^{3} μGy h^{-1} had no effect on the immune response to a trinitrophenol keyhole limpet haemocyanin (TNP-KLH) antigen. When the first antigen challenge was given, the fish had accumulated 18.2 Gy; at the first sampling point (15


weeks post-injection), they had accumulated an additional 4.6 Gy (total 22.8 Gy), and there was no significant difference in the specific humoral antibody response between the control and irradiated fish. At 17 weeks they were given a second antigen challenge, and when the immune response was measured at 23 weeks (total accumulated dose - 25.3 Gy), there was again no significant difference between control and irradiated fish [87].

The effects of radiation (8.3×10^3 and 12.8×10^3 $\mu Gy\ h^{-1}$) in combination with different levels of environmental temperature and salinity (a 3^3 factorial experimental design) have been investigated for the euryhaline pinfish (*Lagodon rhomboides*) exposed at the post-larval - juvenile stage. In total, 8 body dimensions and the weight were measured after 45 days of exposure (8.7 and 13.4 Gy). From an analysis of variance, it was determined that temperature significantly affected all 9 measures, with lesser influences for salinity (5) and irradiation (2). There were significant first order interactions between radiation and temperature (8 measures) and between radiation and salinity (4 measures); the second order interaction between all three environmental variables affected 7 measures [35].

In conclusion, it appears that chronic dose rates up to about 4×10^3 $\mu Gy\ h^{-1}$ to developing fish eggs (the most sensitive stage in the life cycle) will not have any significant influence on subsequent growth (length and weight). Minor anomalies of growth, *e.g.* the opercular defects in coho salmon parr, are significantly increased at ~200 $\mu Gy\ h^{-1}$, however, and these could have an influence of subsequent survival in the wild. The interpretation of the available data on the effects of irradiation on the immune system is particularly difficult. The data from the embryonic irradiation of rainbow trout with ^3H indicate a threshold for effects between 0.83 and 8.3 $\mu Gy\ h^{-1}$ (for total doses of 4×10^{-4} and 4×10^{-3} Gy); irradiation of embryos of another species of rainbow trout with Cs-137 γ-rays from an external source had no effect at a dose rate of 9.0×10^3 $\mu Gy\ h^{-1}$ (total dose - 4.01 Gy); this ~1000-fold difference in apparent sensitivity to the two radiation regimes could only be reconciled in small part by taking account of differences in RBE. As is to be expected, chronic irradiation interacts with other environmental variables to influence the degree of response, although the irradiation appears to be a minor contributor.

Mortality

There are rather few data concerning the effects of radiation accumulated at low dose rates in adult fish; the effects of radiation on embryonic survival are considered under reproductive capacity in the following section.

Exposure of developing chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon embryos to Co-60 γ-rays at a dose rate of ~200 $\mu Gy\ h^{-1}$ (accumulated total dose 0.33 - 0.4 Gy at hatching) had no significant effects on the post-hatch survival up to about one year of age when the parr were released to migrate to sea [265].

Exposure of guppy embryos (*Poecilia reticulata*) to Cs-137 γ-rays at dose rates of 1.7×10^3, 4.0×10^3 and 12.7×10^3 $\mu Gy\ h^{-1}$ from fertilisation to birth (approximate total accumulated doses of 1.1, 2.6 and 8.4 Gy) had no significant effects on their subsequent survival to maturity at ~3 months of age [74].

The irradiation of adult male and female medaka (*Oryzias latipes*) with Co-60 γ-rays had no effects on survival at dose rates below 4.2×10^3 $\mu Gy\ h^{-1}$ (no data given on the irradiation period and, therefore, on the total accumulated dose) [46].

In conclusion these very limited data relating to irradiation from external sources indicate that dose rates below 12 x 10^3 μGy h^{-1} during embryonic development, and below about 4 x 10^3 μGy h^{-1} during post-hatch life, are unlikely to have any significant effects on survival.

Reproductive capacity

The umbrella endpoint of "reproductive capacity" includes a range of responses including, but not restricted to, the fertility of the irradiated parents; the viability of the resulting embryos, whether irradiated or not; the effects of radiation on the developing embryo in terms of the production of viable individuals; and, the fertility of offspring that had been irradiated as developing embryos.

The effects of long-term (*i.e.* over many generations) chronic irradiation on the fecundity of the mosquito fish (*Gambusia affinis*) in the contamination White Oak Lake on the Oak Ridge site in Tennessee have been investigated on a number of occasions. A major problem has been the estimation of the dose rates likely to have been received by the fish, sampled from the population at different times, from internal and external sources. The following summary of the work is based on the dose rate estimates given in [83]. In 1965, when the external dose rate (by far, the major source) was estimated to be about 150 μGy h^{-1} (and perhaps a factor of 10 higher 5 years earlier), the females in the irradiated population were found to be producing more viable embryos, when normalised for length, than in the control population; the incidence of dead and abnormal embryos was, however, significantly greater [110]. The apparent increase in fecundity, originally attributed to the influence of the chronic irradiation, was later ascribed to the more eutrophic nature of White Oak Lake as compared with the control [83]; the greater incidence of dead and abnormal embryos remained attributable to the irradiation, however, and the 1973 incidence was maintained at the 1966 level despite the fall in the estimated dose rate to 75 μGy h^{-1} by 1971. Overall, it was concluded that the persistent increase in non-viable embryos relative to the controls was a consequence of radiation-induced recessive lethal mutations [83]. A later study, in 1992, of mosquito fish from White Oak Lake and from another waste holding pond that had been stocked with fish in 1977 when the dose rate at mid-depth was about 450 μGy h^{-1}, showed a general increase in DNA strand breaks relative to the controls, and a positive correlation between the level of DNA damage and the incidence of abnormal embryos; in addition, at the second site, the fecundity was negatively correlated with the incidence of DNA double strand breaks [20].

The appearance of secondary sex characteristics in guppies (*Poecilia reticulata*) that had been exposed to tritium during embryonic development showed one significant instance (replicate) of earlier development at a dose rate of 2.3.x 10^3 μGy h^{-1}, but no other consistent, significant differences in timing relative to the controls at dose rates up to 1.9 x 10^4 μGy h^{-1}. Young fish exposed for 21 or 30 days from 7 days of age showed no significant effects on secondary sex character development at dose rates up to 9.4 x 10^3 μGy h^{-1}. One replicate of fish exposed as embryos showed a significant increase in the relative number of male offspring at 2.3.10^3 μGy h^{-1}, but at all other dose rates up to 4.7 x 10^4 μGy h^{-1} there were no significant differences; a comparison of pooled data for all irradiated fish and the pooled data for all the controls did, however, show a significantly increased proportion of male offspring. The courting activity of males that had been irradiated as either embryos or young fish was not significantly at dose rates below 1.4 x 10^4 μGy h^{-1} [73]. The total lifetime fecundity of pairs of guppies was markedly reduced at all dose rates between 1.7 x 10^3 and 1.3 x 10^4 μGy h^{-1}, but the neonatal death rate, incidence of abnormalities, and the survival and sex ratio of the offspring (not irradiated after birth) were unaffected [74].

A substantial amount of work has been carried out to determine the response of the reproductive capacity of the medaka (*Oryzias latipes*) to irradiation. the exposure of developing medaka embryos to tritium at dose rates of 1.79 x 10^4 and 3.54 x 10^4 μGy h^{-1}, and to Cs-137 γ-rays at dose rates of 1.83 x 10^4 and 4.33 x 10^4 μGy h^{-1} had no significant effects on their hatching success, but there is evidence that their subsequent survival to age 1 month at the lower dose rates is reduced with marginal significance, with an increase in the incidence of vertebral malformations. It was concluded that the RBE for these endpoints was not significantly different from unity [76]. In newly hatched fry, the logarithm of the total number of germ cells (male and female cells could not be differentiated) declined linearly with accumulated dose, *i.e.* there appeared to be no dose (or dose rate) from tritium or Cs-137 γ-rays that had no effects, although there was a radioresistant sub-population amounting to ~20% of the total; the data provided an estimate of 1.8 for the RBE value of tritium relative to the Cs-137 γ-rays. In female fry produced by phenotypic manipulation, the female germ cells in the developing embryo were found to be slightly more radiosensitive, and an RBE value of 2.2 was estimated from the data [97]. In medaka irradiated with Cs-137 γ-rays for 52 days during embryonic and early post-natal development, there were slight quantitative changes in the numbers of male and female germ cells over the period of irradiation at dose rates of 1.2 x 10^4 and 2.2 x 10^4 μGy h^{-1}, but in the surviving adults there were no significant differences, compared with the controls, in the gonadosomatic indices (GSI) for either the males or the females [91]. The subsequent fertility and fecundity of fish irradiated as embryos with tritium and Cs-137 γ-rays has also been determined. When irradiated females were mated with unirradiated males, the total number of ovipositions and number of eggs per female decreased with increasing dose rate (*i.e.* the accumulated dose during embryogenesis) for all dose rates used (*i.e.* > than 3.5 x 10^3 and 2.5 x 10^3 μGy h^{-1} for ^{3}H and ^{137}Cs, respectively). Although ^{3}H β-radiation appears to be more effective than the Cs-137 γ-radiation, no estimate of the RBE value is given. For irradiated males mated with unirradiated females, the number of ovipositions was hardly affected, but the number of fertilised eggs declined with increasing dose rate; there was no significant difference in the degree of response between the β- and γ-radiation [95, 260]. Adult male medaka exposed to tritiated water showed dose rate dependent reductions in the number of spermatogonia 1b at all ^{3}H concentrations tested (*i.e.* at dose rates above 4.2 10^2 μGy h^{-1}), but recovery was under way by 30 days at dose rates less than 8.4 10^2 μGy h^{-1}, and essentially complete (*i.e.* not significantly different from the controls) at 120 days [96, 192]. When the adults males were also exposed to Cs-137 γ-rays, after 10 days of exposure the RBE relative to tritium β-radiation was unity for the gonadosomatic index and 2.2 for the reduction in spermatogonia 1b; when assessed after 30 days of exposure, the corresponding RBE values were 1.7 and 2.4, respectively [192].

The effects of α-particles from ^{238}Pu(IV) citrate have been investigated with developing eggs of the carp (*Cyprinus carpio*) and the fathead minnow (*Pimephales promelas*); the former were exposed from fertilisation, and the latter between the one cell and early blastula stages. Estimates of the absorbed dose rates were made using data obtained on the uptake of the radionuclide onto the surface of, and into, the egg. No effects were found in hatching rate, number of abnormalities or larval survival for carp at dose rates below 4.7 x 10^4 μGy h^{-1}, or for fathead minnow below 8.9 x 10^3 μGy h^{-1} [58].

Brown trout (*Salmo trutta*) eggs exposed to ^{90}Sr/^{90}Y at estimated dose rates of 2.9 x 10^1, 2.8 x 10^2 and 1.3 x 10^3 μGy h^{-1} showed significant heterogeneity in the variation in the hatch rate, with the lower two dose rates producing a significant decrease and increase, respectively, relative to the control, and the highest dose rate no significant difference; the proportions of abnormal embryos were also variable with no significant differences from the controls at any dose rate [33, 68, 193].

An increase in the number of anomalous peled (*Coregonus peled*) larvae at an accumulated dose of 0.031 Gy was observed in the developing embryo, from C-14 accumulated from the water (dose rate estimated to be ~ 20 μGy h^{-1}), although the supporting data are not given; it is also difficult to interpret the information provided concerning the accumulated doses [203]. Overall, this interesting result, interpreted as being the consequence of the incorporation of the biologically significant ^{14}C radionuclide, must be treated with some caution until it is confirmed.

The biggest study of the effects of chronic irradiation on the developing fish embryo is that carried out with chinook and coho salmon (*Oncorhyncus tsawytscha* and *O. kisutch*) at the College of Fisheries on the University of Washington campus [121, 123, 149, 170, 265]. Not all the reports providing the experimental data are included in the database. A summary of the major findings of this series of studies, utilising all the available published data, has been given in [241], and this will be used here. The salmon embryos were irradiated with Co-60 γ-rays through the ~80 day development period at dose rates of 2.1 x 10^2, 5.4 x 10^2, 1.2 x 10^3, 2.1 x 10^3, 4.2 x 10^3, 8.3 x 10^3, and 7.1 x 10^3 to 2.1 x 10^4 μGy h^{-1}. Consistently deleterious effects on the first generation individuals were not observed at dose rates below 2.1 x 10^3 μGy h^{-1}. When adult males and females that had been irradiated at 2.1 x 10^2 μGy h^{-1} as embryos returned, they were mated together and, if not further exposed, the offspring generally out-performed the corresponding controls; if, however, the developing embryos from irradiated parents were given additional exposure at the same dose rate, there was some evidence of cumulative damage relative to the controls.

Exposure of flounder (*Paralichthys olivaceus*) eggs from the 16 - 32 cell stage and puffer (*Fugu niphobles*) eggs from the two cell stage to tritiated water had no effects on hatch rate at dose rates up to 1.2 x 10^3 μGy h^{-1}; for the puffer, there was some indication of a threshold for a decline in hatch rate at 1.2 x 10^5 μGy h^{-1} [23].

Exposure of developing plaice (*Pleuronectes platessa*) eggs to $^{90}Sr/^{90}Y$ at estimated absorbed dose rates of 1 x 10^2, 5 x 10^2, 5.3 x 10^2 and 5.3 x 10^3 μGy h^{-1} showed inconsistent variation in the hatch rate - the second highest and the highest dose rates produced significant reductions whereas at 53 μGy h^{-1} it was no different than the controls; there were no significant effects on the proportions of abnormal larvae [33, 68, 193]. Because of the difficulties in being sure of the dose rates from the $^{90}Sr/^{90}Y$ contamination in the water, the experiment was repeated with irradiation from external ^{137}Cs sources. Again, there was significant heterogeneity in the variations in hatch rate and the proportions of abnormal larvae, but there were no significant differences from the controls at any dose rate below 1.1 x 10^4 μGy h^{-1} [33, 68, 193]. Male plaice exposed to Cs-137 γ-rays (at 2.5 x 10^2, 5.0 x 10^2 and 1.2 x 10^3 μGy h^{-1}) for 73 days showed no significant effects on GSI at any dose rate; the relative proportions of cells at the different stages of spermatogenesis were, however, significantly affected at all dose rates. A second, longer experiment (197 days) showed that the testis weight, normalised for body weight, was significantly reduced at a dose rate of 2.4 x 10^2 μGy h^{-1}, and that there would have been some effect of irradiation at lower dose rates; the dose rate at which this effect would have become insignificant could not, however, be determined [207].

Prolonged chronic exposure of male eelpout (*Zoarces viviparus*) to Cs-137 γ-rays at mean dose rate of 2 x 10^4 μGy h^{-1} had a significant effect on the GSI in the late winter after 540 days of irradiation, but 2 months later, when spermatogenesis was under way in preparation for the August breeding season, the GSI was reduced, but the difference from the control value was not significant [87].


In conclusion, there appears to be little consistent, significant evidence for radiation-induced effects on the reproductive capacity of fish at dose rates below 2 x 10^2 μGy h^{-1}. Available dose-response relationships do indicate, however, that there probably is not a threshold for some endpoints, *e.g.* the gonadosomatic index and the number of gametogenic cells in fish irradiated as developing embryos.

Mutation

As mutation induction is a stochastic response to irradiation, it is to be expected that any dose rate above the relevant ambient background would yield an increase in incidence that could be detected provided that the experimental design had sufficient statistical power. The interesting question is whether fish are any more susceptible to radiation-induced mutation than other taxonomic groups.

As noted in the previous section above, the irradiation of the mosquito fish (*Gambusia affinis*) appears to increase the incidence of double strand breaks in DNA. The only information that is available concerning the radiation exposure of the fish in 1992 is that, in the two lakes, it is probably less than the dose rates of 50 and 450 μGy h^{-1} that were estimated some 15 years previously [20].

On the assumption that the decrease in the life-time mean brood size produced by guppies (*Poecilia reticulata*) irradiated at dose rates of 1.7 x 10^3, 4.0 x 10^3 and 1.27 x 10^4 μGy h^{-1} is indicative of dominant lethal mutations induced in the maturing gametes, mutation rates of 8.7 x 10^{-2}, 3.1 x 10^{-2} and 3.5 x 10^{-2} per gamete per Gy of accumulated exposure have been estimated. Given the number of uncertain assumptions underlying these estimates, these three values are probably not significantly different. It was also indicated that it would be unwise to conclude more than that the radiation-induced dominant lethal mutation rate in the guppy is unlikely to be greatly different than that determined for other vertebrates [74].

In conclusion, there are very limited data on the mutagenic effects of chronic irradiation in fish. It is apparent that radiation-induced genetic damage occurs, probably at all dose rates, and that fish have a similar radiation sensitivity to other vertebrates, at least in terms of the induction of dominant lethal mutations.

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Acute **Fish** Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Carassius auratus*	X-rays	6(1)	*Carassius auratus*	X-rays	10(2)	*Misgurnus fossilis*	X-rays	1(1)	*Lebistes reticultus*	X-rays	8(4)
	Pleuronectes platessa	X-rays	2(1)	*Carassius auratus*	Gamma	7(1)	*Salmo gairdnerii*	Gamma	5(1)	*Umbra limi*	X-rays	3(2)
	Salmo irrideus	X-rays	1(1)	*Oryzias latipes*	Gamma	1(1)	*Salmo gairdnerii*	X-rays	8(1)	*Umbra limi*	Gamma	2(1)
	Lebistes reticulatus	X-rays	2(2)	*Oryzias latipes*	X-rays	3(2)	*Tinca tinca*	Gamma	3(1)	*Oryzias latipes*	Gamma	1(1)
	Oryzias latipes	Xrays	1(1)	*Gambusia affinis*	Gamma	4(1)	*Esox lucius*	Gamma	3(1)	*Acipenser ruthenus*	X-rays	2(1)
	Oryzias latipes	Gamma	9(4)	*Poecilia formosa*	Gamma	1(1)	*Brachydanio rerio*	Gamma	1(1)	*Misgurnus fossilis*	X-rays	4(1)
	Salmo salar	Gamma	1(1)	*Oncorhynchus tschawytscha*	X-rays	21(4)	*Oryzias latipes*	X-rays	20(7)	*Salmo gairdnerii*	X-rays	5(1)
	Salmo gairdnerii	Gamma	1(1)	*Salmo irrideus*	X-rays	1(1)	*Oryzias latipes*	Gamma	7(3)	*Carassius auratus*	Gamma	1(1)
	Salmo gairdnerii	X-rays	1(1)	*Misgurnus fossilis*	X-rays	1(1)	*Lebistes reticulatus*	X-rays	8(3)	*Ameca splendens*	Gamma	4(1)
	Lagodon rhomboides	Gamma	6(1)	*Lebistes reticulatus*	X-rays	2(1)	*Chasmichthys glosus*	X-rays	7(2)			
				Salmo gairdnerii	X-rays	15(3)	*Salmo irrideus*	X-rays	6(2)			
				Micropogon undulatus	Gamma	2(1)	*Misgurnus anguillicaudatus*	X-rays	1(1)			
				Fundulus heteroclitus	Gamma	1(1)	*Cyprinus carpio*	Gamma	11(2)			
				Mugil cephalus	Gamma	2(1)	*Cyprinus carpio*	beta	6(1)			
				Lagodon rhomboides	Gamma	1(1)	*Salmo trutta*	Gamma	2(1)			
				Eucinostomus sp	Gamma	1(1)	*Pleuronectes platessa*	Gamma	3(1)			
				Heterodontus japonicus	Gamma	1(1)	*Pleuronectes platessa*	X-rays	6(2)			
				Triakis scyllia	Gamma	1(1)	*Fundulus heteroclitus*	X-rays	4(2)			
							Carassius auratus	Gamma	1(1)			
							Tilapia zilli	Gamma	1(1)			
< 0.199	*Oryzias latipes*	Gamma	4(2)	*Oncorhynchus tschawytscha*	X-rays	2(1)	*Salmo gairdnerii*	Gamma	1(1)	*Salmo gairdnerii*	X-rays	5(1)
				Salmo gairdnerii	X-rays	4(1)	*Tinca tinca*	Gamma	1(1)			

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Acute **Fish** Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
0.2-0.499	*Poecilia formosa* *Oryzias latipes* *Salmo gairdnerii* *Salmo gairdnerii*	Gamma Gamma X-rays	1(1) 2(1) 1(1)	*Oncorhynchus tschawytscha* *Salmo gairdnerii*	X-rays X-rays	13(2) 1(1)	*Salmo gairdnerii* *Salmo gairdnerii* *Tinca tinca* *Pleuronectes platessa*	X-rays Gamma Gamma X-rays	3(1) 5(3) 3(1) 10(2)	*Umbra limi* *Umbra limi* *Salmo gairdnerii*	X-rays Gamma Gamma	1(1) 4(1) 2(1)
0.5-0.99	*Salmo gairdnerii*	X-rays	1(1)	*Oncorhynchus tschawytscha* *Salmo gairdnerii*	X-rays X-rays	14(2) 1(1)	*Salmo gairdnerii* *Salmo gairdnerii* *Tinca tinca* *Cyprinus carpio* *Cyprinus carpio* *Pleuronectes platessa*	X-rays Gamma Gamma Beta Gamma X-rays	13(2) 5(3) 3(1) 3(1) 3(1) 10(2)	*Umbra limi* *Umbra limi* *Salmo gairdnerii* *Oryzias latipes* *Ameca splendens*	X-rays Gamma Gamma Gamma Gamma	1(1) 2(1) 2(1) 2(1) 4(1)
1.0-1.99	*Oryzias latipes* *Salmo irrideus* *Lebistes reticulatus*	Gamma X-rays X-rays	3(2) 1(1) 1(1)	*Oncorhynchus tschawytscha* *Salmo gairdnerii*	X-rays X-rays	20(3) 4(1)	*Salmo gairdnerii* *Salmo gairdnerii* *Tinca tinca* *Brachydanio rerio* *Salmo irrideus* *Cyprinus carpio* *Cyprinus carpio* *Pleuronectes platessa*	X-rays Gamma Gamma Gamma X-rays Beta Gamma X-rays	14(2) 5(3) 3(1) 1(1) 6(2) 3(1) 3(1) 9(2)	*Umbra limi* *Salmo gairdnerii* *Salmo gairdnerii* *Ameca splendens*	X-rays X-rays Gamma	2(1) 5(1) 2(1) 4(1)
2.0-4.99				*Poecilia formosa* *Salmo irrideus* *Oncorhynchus tschawytscha* *Carassius auratus* *Salmo gairdnerii*	Gamma X-rays X-rays X-rays X-rays	2(1) 1(1) 16(3) 3(1) 1(1)	*Salmo gairdnerii* *Salmo gairdnerii* *Tinca tinca* *Brachydanio rerio* *Cyprinus carpio* *Cyprinus carpio* *Pleuronectes platessa* *Oryzias latipes*	X-rays Gamma Gamma Gamma Beta Gamma X-rays X-rays	15(2) 10(3) 3(1) 3(2) 3(1) 3(1) 4(1) 6(1)	*Salmo gairdnerii* *Umbra limi* *Oryzias latipes* *Fundulus heteroclitus* *Ameca splendens*	Gamma X-rays Gamma X-rays Gamma	4(1) 2(1) 3(1) 1(1) 4(1)

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Acute Fish Total absorbed dose (Gy)	MORBIDITY			MORTALITY			REPRODUCTIVE CAPACITY			MUTATION		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Oryzias latipes*	X-rays	15(4)	*Carassius auratus*	X-rays	35(2)	*Misgurnus fossilis*	X-rays	15(2)	*Lebistes reticulatus*	X-rays	19(4)
	Oryzias latipes	Gamma	23(5)	*Carassius auratus*	Gamma	35(1)	*Salmo gairdnerii*	X-rays	61(2)	*Oryzias latipes*	Gamma	2(1)
	Carassius auratus	X-rays	5(1)	*Oryzias latipes*	Gamma	17(3)	*Oryzias latipes*	Gamma	57(5)	*Acipenser ruthenus*	X-rays	6(1)
	Tinca vulgaris	Gamma	6(1)	*Oryzias latipes*	X-rays	45(5)	*Oryzias latipes*	X-rays	139(10)	*Misgurnus fossilis*	X-rays	10(1)
	Poecilia formosa	Gamma	1(1)	*Gambusia affinis*	Gamma	24(1)	*Acipenser stellatus*	X-rays	1(1)	*Misgurnus fossilis*	Gamma	1(1)
	Salmo irrideus	X-rays	4(1)	*Poecilia formosa*	Gamma	2(1)	*Tinca tinca*	Gamma	4(1)	*Oryzias latipes*	Gamma	3(1)
	Salmo gairdnerii	Gamma	3(1)	*Salmo irrideus*	X-rays	3(1)	*Esox lucius*	Gamma	60(1)	*Fundulus heteroclitus*	X-rays	2(1)
	Lebistes reticulatus	X-rays	6(2)	*Lebistes reticulatus*	X-rays	8(2)	*Brachydanio rerio*	Gamma	1(1)	*Platypoecilia maculata*	X-rays	3(2)
	Lagodon rhomboides	Gamma	10(1)	*Misgurnus fossilis*	X-rays	2(1)	*Lebistes reticulatus*	X-rays	18(3)	*Salmo gairdnerii*	X-rays	5(1)
				Oncorhynchus tschawytscha	X-rays	41(3)	*Salmo irrideus*	X-rays	6(2)	*Carassius auratus*	Gamma	5(1)
				Salmo gairdnerii	X-rays	4(1)	*Cyprinus carpio*	Gamma	35(1)	*Ameca splendens*	Gamma	8(1)
				Paralichthys lethostigma	Gamma	5(1)	*Cyprinus carpio*	Beta	12(1)			
				Micropogon undulatus	Gamma	3(1)	*Cyprinus carpio*	Gamma	19(1)			
				Fundulus heteroclitus	Gamma	4(1)	*Salmo trutta*	Gamma	3(1)			
				Mugil cephalus	Gamma	3(1)	*Pleuronectes platessa*	Gamma	6(1)			
				Lagodon rhomboides	Gamma	4(1)	*Pleuronectes platessa*	X-rays	3(2)			
				Eucinostomus sp	Gamma	4(1)	*Fundulus heteroclitus*	X-rays	8(1)			
				Triakis scyllia	Gamma	2(1)	*Carassius auratus*	Gamma	5(1)			
				Heterodontus japonicus	Gamma	2(1)	*Tilapia zilli*	Gamma	3(1)			

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Acute Fish Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	4,5,23,36,41,45,47,49,53,56, 57,60,71,75,78,84,85,86,89, 92,93,98,111,124,135,136, 137,143,147,148,155,179, 189,217,259,268			5,21,29,30,31,36,38,39,40,42,48,65,77, 82,88,102,103,111,134,135,155,172, 200,213,217,267			5,6,10,16,17,18,21,23,27,28,31,33,52,61, 69,72,84,94,97,99,100,101,102,103,104, 105,106,107,109,112,113,116,118,131, 141,142,150,153,159,169,174,175,176, 178,186,187,194,201,202,205,206,260, 266			7,8,9,11,12,13,14,15,17,18,19,30,31,66, 70,79,82,135,151,172,185,186,215,216		
Observations "rejected" (paper ID)[c]	1(4),1(5),6(23),2(41), 1(47),1(56),1(57),16(75), 1(78),3(84),4(85),5(86), 11(137),3(148),1(189), 60(268)			8(29)			14(23),1(52),9(72),10(84),1(94),8(97), 11(100),4(102),1(176),1(186),1(187), 20(201),1(202),25(260)			2(17),1(18),1(30),18(79)		
Last paper published in:	1992			1992			1985			1992		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Chronic Fish Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Zoarces viviparus*	Gamma	8(1)	*Misgurnus fossilis*	Beta	2(1)	*Oryzias latipes*	Gamma	6(2)	*Poecilia reticulata*	Gamma	2(1)
	Pleuronectes platessa	Gamma	4(1)	*Esox lucius*	Gamma	1(1)	*Oryzias latipes*	H-3	4(2)	*Poecilia reticulata*	Beta	1(1)
	Pleuronectes platessa	Beta	2(1)	*Salmo salar*	Gamma	1(1)	*Gambusia affinis*	Mixed	6(3)	*Oryzias latipes*	Gamma	1(1)
	Gambusia affinis	Mixed	1(1)	*Onchorhyncus kisutch*	Gamma	5(1)	*Pleuronectes platessa*	Beta	10(3)	*Oryzias latipes*	H-3	1(1)
	Oryzias latipes	Gamma	1(1)				*Pleuronectes platessa*	Gamma	15(3)	*Gambusia affinis*	Mixed	1(1)
	Salmo trutta	Beta	2(1)				*Pleuronectes platessa*	X-rays	1(1)	*Onchorhynchus kisutch*	Gamma	9(2)
	Salmo trutta	Beta	2(1)				*Onchorhyncus tshawytscha*	Gamma	2(2)			
	Onchorhyncus kisutch	Gamma	6(1)				*Salvelinus lepechini*	Beta	1(1)			
	Lagodon rhomboides	Gamma	2(1)				*Poecilia reticulata*	Gamma	5(1)			
							Pimephales promelas	Alpha	1(1)			
							Salmo trutta	Beta	4(2)			
< 99.9	*Pleuronectes platessa*	Gamma	4(1)				*Pleuronectes platessa*	Beta	12(2)			
	Pleuronectes platessa	Beta	8(1)				*Pleuronectes platessa*	Gamma	4(2)			
							Salmo trutta	Beta	3(2)			
100-199.9	*Pleuronectes platessa*	Gamma	4(1)	*Onchorhyncus kisutch*	Gamma	5(1)	*Pleuronectes platessa*	Gamma	4(2)	*Onchorhynchus kisutch*	Gamma	1(1)
	Onchorhyncus kisutch	Gamma	6(1)									
200-499.9	*Salmo trutta*	Beta	2(1)				*Pleuronectes platessa*	Gamma	9(1)			
							Salmo trutta	Beta	5(2)			
							Onchorhyncus tshawytscha	Gamma	2(2)			

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Chronic Fish Dose-rate (μGy h^{-1})	MORBIDITY			MORTALITY			REPRODUCTIVE CAPACITY			MUTATION		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
500-999.9	*Pleuronectes platessa*	Gamma	4(1)				*Pleuronectes platessa* *Onchorhyncus tshawytscha*	Gamma Gamma	13(3) 4(2)			
1,000-1,999.9	*Salmo trutta*	Beta	2(1)				*Pleuronectes platessa* *Salmo trutta* *Onchorhyncus tshawytscha* *Poecilia reticulata*	Gamma beta Gamma Gamma	9(1) 4(2) 4(2) 5(1)			
2,000-4,999	*Zoarces viviparus* *Gambusia affinis* *Oryzias latipes*	Gamma Mixed Gamma	8(1) 1(1) 1(1)				*Onchorhyncus tshawytscha* *Gambusia affinis* *Poecilia reticulata*	Gamma Mixed Gamma	8(2) 3(1) 5(1)	*Poecilia reticulata*	Gamma	2(1)
5,000-9,999	*Pleuronectes platessa* *Lagodon rhomboides*	Beta Gamma	2(1) 2(1)				*Oryzias latipes* *Oryzias latipes* *Pleuronectes platessa* *Onchorhyncus tshawytscha*	Beta Gamma Beta Gamma	3(1) 1(1) 4(2) 4(2)	*Poecilia reticulata* *Oryzias latipes*	Gamma Beta	2(1) 1(1)
> 10,000	*Pleuronectes platessa* *Lagodon rhomboides* *Oryzias latipes*	Gamma Gamma Gamma	4(1) 2(1) 7(2)				*Oryzias latipes* *Oryzias latipes* *Pleuronectes platessa* *Onchorhyncus tshawytscha* *Poecilia reticulata* *Pimephales promelas*	Gamma Beta Gamma Gamma Gamma Alpha	31(3) 6(1) 4(2) 4(2) 5(1) 3(1)	*Poecilia reticulata* *Oryzias latipes* *Oryzias latipes*	Gamma Gamma Beta	3(2) 3(1) 2(1)

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Chronic Fish Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	35,68,73,87,91,110,122,168, 265			37,91,146,265			20,33,51,58,64,74,76,83,91,95,110,149, 161,170,171,177,192,193,203,204,207, 210,265			3,20,76,117,121,265		
Observations "rejected" (paper ID)[c]	1(122),22(73),4(168)			1(37),1(91),10(146)			1(20),24(33),1(51),16(58),4(64),1(76), 2(83),16(95),1(110),1(149),1(171), 1(177),2(192),2(203),1(204),3(207), 14(210),1(265)			23(3),1(117),1(20),8(121)		
Last paper published in:	1995			1981			1999			1993		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-11 Summary effects data on fish, based on the FASSET Radiation Effects Database (FRED).

Transitory **Fish** Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Oncorhychus tshwytscha* *Oryzias latipes*	Gamma Beta	4(1) 1(1)				*Heteropneutes fossilis* *Cyprinus carpio* *Oryzias latipes*	Gamma Alpha X-ray	1(1) 1(1) 1(1)			
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999												
> 10,000												
Data relevant to RBE determination for:	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	96,120,123,257			None			108,163,198,258			None		
Observations "rejected" (paper ID)[c]	24(120)[1],8(123)[2],16(96)[2],1(257)[3]			None			1(108),1(258)			None		
Last paper published in:	1977			None			1980			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Effects described for micro Ci levels, but no dose or dose rates recorded. 2 effects described but no dose rates reported. 3 no data.

2.11 Crustaceans

As is the case for fish, the published information concerning the effects of radiation on aquatic crustaceans and molluscs has been reviewed on a number of occasions [*e.g.* Blaylock & Trabalka, 1978; IAEA, 1976, 1988, 1992; NCRP, 1991; UNSCEAR, 1996; Woodhead, 1984]. The FRED contains 19 accessible references, and one paper was rejected. (It should be noted that, due to the lack of precise criteria defining crustaceans and molluscs (Section 2.12), and the over-arching categories of aquatic invertebrates and zooplankton (Section 2.13) on the other, there is some mis-attribution of papers between these four categories.)

A large majority of relevant studies concerning crustaceans (15) relate to acute exposures. Apart from a somewhat increased interest in the effects of acute irradiation on crustacean mortality and reproductive capacity and the apparent total lack of data for the induction of mutations, the available data are fairly evenly distributed between the umbrella endpoints. On the basis of the evidence accumulated in the database, there has been no recent research with latest publication dates ranging from 1967 - 1977.

With the arbitrary inclusion of the brine shrimp (*Artemia salina*) in the marine category (populations can exist in salinities up to 5x normal seawater), there are 2, 7 and 2 distinct species representing, respectively, the marine, estuarine and freshwater environments. All of the studies employed low LET radiation (X- and γ-rays); one study additionally exposed the experimental organisms (*Artemia salina*) to neutrons and generated RBE values [301]. There are no data for acute absorbed doses less than 1 Gy and for chronic absorbed dose rates less than 10^4 μGy h^{-1} for any of the umbrella endpoints.

Table 2-12 summarises effects data on crustaceans, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). No effects data in these two wildlife groups were recorded from transitory exposures.

2.11.1 The effects of acute irradiation

It appears, from the information available from the database, that significant acute effects are not likely to be expressed in crustaceans exposed to acute (*i.e.* high dose rate) doses less than 1 Gy.

Morbidity

The two studies included in the database, both for the brine shrimp (*Artemia salina*), examined the influence of irradiation on respiration rate [300], and the damage repair capacity together with its dependence on strain and ploidy [307]. In neither case were there any significant effects of irradiation at absorbed doses below 10 Gy.

Mortality

The primary measure of the mortality response to acute radiation has been the $LD_{50/30}$; the values determined for a number of post-juvenile crustacean species vary between 8 Gy for the grass shrimp (*Palaemonetes pugio*) and 510 Gy for the blue crab (*Callinectes sapidus*). It has also been found that the LD_{50} continues to decline with the extension of the assessment period beyond the 30 days found to be appropriate to mammals [314, 315, 316] - a probable expression of the influence of metabolic rate in poikilothermic organisms on radiosensitivity. In addition, for the estuarine species that are adapted to a range of salinities and temperatures,


these factors interact to influence the radiosensitivity as indicated by the LD_{50} [147]. The sigmoid nature of the mortality response relationship also means, however, that there is likely to be significant mortality at lower doses than the LD_{50} - the mean survival time of adult female freshwater calanoid copepods (*Diaptomus clavipes*) was significantly reduced at a dose of 10 Gy as compared with the approximate $LD_{50/30}$ of 100 Gy [309] and also at a dose of 1 Gy [310]. The long-term (20 week) survival of adult female amphipods (*Gammarus duebeni*) was not affected by an acute exposure of 3.3 Gy [312].

Reproductive capacity

The long-term (20 weeks) fertility and fecundity of irradiated female amphipods (*Gammarus duebeni*) mated to unirradiated males was affected at an absorbed dose of 2.2 Gy but not at 1.5 Gy [312]. Similarly, the percentage hatch of egg clutches carried by irradiated ovigerous female calanoid copepods (*Diaptomus clavipes*) was significantly reduced at 5 Gy but not at 1 Gy [310]. The radiosensitivity of brine shrimp (*Artemia salina*) "eggs" (strictly, these are desiccated cysts containing partially developed, but metabolically arrested embryos) varies with the degree of rehydration at irradiation. The $LD_{50/3}$ (% hatchability at 3 days) of the desiccated eggs depends on the precise experimental conditions for the rehydration of the eggs, but is high - between 2.3×10^3 [302] and 5×10^3 Gy [305], and post-irradiation storage of the eggs in ambient humidity at room temperature reduces the hatchability of the eggs [302]. A diploid strain showed greater radiosensitivity (2.1×10^3 Gy) as compared with a tetraploid strain (2.5×10^3 Gy) [308].The irradiation delays hatching, and partial rehydration of the eggs prior to irradiation decreased, but total rehydration increased, the radiosensitivity [302].

Mutation

There are no experimental results in the database for this umbrella endpoint.

2.11.2 The effects of chronic irradiation

The great majority of the data in FRED indicate that there is unlikely to be any observable impacts to crustaceans at dose rates up to 10^3 μGy h^{-1} and that a dose rate of ~10^4 μGy h^{-1} is probably the lower limit for the onset of significant effects. The clear exception is the study of the effects of tritium irradiation on the development of the goose barnacle in which there were apparent responses at dose rates of 0.7, 6.5 and 64 μGy h^{-1}. There is a clear requirement for such experiments to be repeated to confirm the results and to investigate the mechanisms by which this response is activated. (Although there is no parallel study of the effects of low LET radiation, it might be inferred that, for this particular endpoint, a high RBE value could be expected.)

Morbidity

Irradiation of juvenile (< 1 year) blue crabs (*Callinectes sapidus*) at dose rates of 3.2×10^4 and 7.3×10^4 μGy h^{-1} non-significantly increased moulting frequency as compared with the controls; crabs exposed at 2.9×10^5 μGy h^{-1} moulted least, and none achieved a third moult. The growth rate (% increase in carapace width) of the crabs at the lowest dose rate was significantly greater than the controls but non-significantly reduced at the higher dose rates [314]. In small populations of water fleas (*Daphnia pulex*) maintained on a constant *per capita* supply of food, the individual growth in length, relative to the controls, was not affected by irradiation at dose rates up to 2.55×10^5 μGy h^{-1}. At higher dose rates, the growth was greater than for the controls and this was interpreted as being due to the availability of

energy that, at the lower dose rates, was diverted to egg production [1065]. When the *Daphnia* populations were given a constant total food supply (*i.e.* there was a possibility of intra-population competition for food), the net production or total yield of biomass to consumers was unaffected by irradiation. Although the number of individuals produced by each population reduced with increasing dose rate (3.5×10^4 to 2.2×10^5 μGy h^{-1}), this was almost exactly balanced by the increased mean weight of the individuals at a given age arising from the increase in the food supply to each individual [490]. Thus irradiation at these dose rates appears to have little net effect on the basic metabolic and anabolic functions. In similar populations additionally subjected to exploitation (*i.e.* the periodic, random harvesting of set percentages of individuals), this stress reduced the relative impact of increasing dose rate on both the population size and the individual weight. Overall, exposures up to 1.1×10^5 - 1.6×10^5 μGy h^{-1} had little influence on the weekly biomass yield from exploitation at either 15 or 40 % per week [Marshall, 1967].

Mortality

Although dose rates of 3.2×10^4 and 7.3×10^4 μGy h^{-1} over a period of 70 days had no effect on the cumulative mortality of young blue crabs (*C. sapidus*), the proportion of total deaths at moulting was significantly higher than was the case for the controls; a higher dose rate of 2.9×10^5 μGy h^{-1} resulted, however, in 95% mortality with a smaller proportion of the total deaths associated with moulting [314]. In populations of water fleas (*D. pulex*) maintained with a constant *per capita* supply of food, irradiation at dose rates above 2.3×10^5 μGy h^{-1} had little effect on survival until 16 days of age; from this age it was progressively compromised at dose rates above about 3.7×10^5 μGy h^{-1} resulting in a slight reduction in average life span and increases in the population death rate[1065]. In populations given a constant total food supply, irradiation at dose rates in the range 3.5×10^4 to 2.2×10^5 μGy h^{-1} had no effect on the estimated mean population death rate per capita per week over the 55 week experimental period [490].

Reproductive capacity

In populations of water fleas (*D. pulex*) maintained with a constant *per capita* supply of food, irradiation at all dose rates above 2.3×10^5 μGy h^{-1} had a profound impact on the age-specific fertility rate (m_x, the number of female offspring produced per female in a given age interval, x) - m_x was reduced at all ages, and the reproductive life span was truncated. In total, these effects resulted in monotonic declines with increasing dose rate in both the population birth rate and the intrinsic rate of natural increase. At the highest dose rates, (~ 7×10^5 μGy h^{-1}) the intrinsic rate of natural increase was around zero and the populations would have had no reserve reproductive capacity to survive additional environmental stress; the maximum dose rate that the populations could tolerate under these conditions was about 5.4×10^5 μGy h^{-1}. The cumulative dose at which the average female ceased reproduction, approximately 100 Gy, was independent of dose rate [1065]. In populations given a constant total food supply, this constraint places an effective upper limit on the population size. Chronic irradiation at dose rates in the range 3.5×10^4 to 2.2×10^5 μGy h^{-1} resulted in significant dose-dependent reductions in the mean population sizes that became relatively stable after about 20 weeks of the 55 week experiment. Although the value of the population birth rate varied over time, the mean value was not significantly dependent on the radiation dose rate. Given the resource constraint on the population size, it was not unexpected to find that the mean value of the intrinsic rate of natural increase was close to zero and, except for the highest dose rates (1.8×10^5 - 2.2×10^5 μGy h^{-1}) at which 3 populations went extinct, not dependent on the dose rate. Thus the population death rate was not significantly different from the birth rate. The maximum tolerable dose rate for these conditions was about 1.8×10^5 μGy h^{-1} [490]. In


populations given a constant total food supply, but subjected to exploitation, there was a very significant increase in the mean brood size with increasing exploitation. This arose from the availability of an increased *per capita* food supply and the consequent increased growth rate even though the mean individual weight declined with a corresponding shift in the age distribution to younger animals and a lower average age. In this case the maximum tolerable dose rate was about 2.6 x 10^5 μGy h^{-1} [Marshall, 1967]. It is clear from these three seminal studies that environmental variables, including chronic irradiation, interact with the demographic properties of the exposed population is a complex way, and that the other environmental stresses reduce the population tolerance to irradiation. Nonetheless, it may be concluded from all the evidence presented that dose rates up to 10^3 μGy h^{-1} in a contaminated freshwater environment would be unlikely to have a significant detrimental effect on *Daphnia* populations.

One interesting paper [404], excluded as ther was no estimates of dose rate, relates to the exposure of developing embryos of the goose barnacle (*Pollicipes polymerus*) to tritiated water. Using the data supplied in the paper, and some reasonable assumptions about the uptake of the tritiated water by the eggs, it is possible to estimate the radiation dose rate to the developing embryos. For the six tritium concentrations used (0.26 x 10^4 - 2.0 x 10^4 Bq ml^{-1}), the dose rates are estimated to be from 8 x 10^{-4} to 64 μGy h^{-1} over the 32 day embryonic development period, *i.e.* they bracket the natural background. The response of the embryos to irradiation was assessed in terms of the transition of the newly hatched stage-I nauplii, through moulting, to post-stage-I nauplii. It was concluded that there had been a response to irradiation at all dose rates even though at the lower three tritium concentrations, these were substantially lower than, or of the same order as, the natural background. Even if the possibility of a real radiation response is discounted at the lower concentrations (it may be simply demonstrated that, depending on the size of the eggs, many would have completed the whole of their development without any tritium decays occurring in the egg at these concentrations), the apparent responses at the higher dose rates of 0.7, 6.5 and 64 μGy h^{-1} require consideration (see also the apparent sensitivity of the developing immune system in fish to tritium irradiation).

Mutation

There are no experimental results in the database for this umbrella endpoint.

Table 2-12 Summary effects data on crustaceans, based on the FASSET Radiation Effects Database (FRED).

Acute Crustaceans Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Artemia salina*	Gamma	7(1)	*Gammarus duebeni* *Palaemonetes pugio* *Uca pugnax* *Uca minax* *Uca pugilator* *Callinectes sapidus* *Diaptomus clavipes* *Artemia salina* *Artemia salina*	X-rays Gamma Gamma Gamma Gamma Gamma Gamma Gamma Neutrons	5(1) 7(1) 7(2) 1(1) 1(1) 6(1) 12(2) 7(1) 7(1)	*Artemia salina* *Diaptomus clavipes* *Gammarus duebeni*	X-rays Gamma X-rays	1(1) 13(2) 20(1)			
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99				*Diaptomus clavipes*	Gamma	1(1)	*Diaptomus clavipes*	Gamma	7(1)			
2.0-4.99	*Artemia salina*	X-rays	4(1)	*Palaemonetes pugio* *Gammarus duebeni*	Gamma X-rays	1(1) 10(1)	*Diaptomus clavipes* *Gammarus duebeni*	Gamma X-rays	2(1) 40(1)			

Table 2-12 Summary effects data on crustaceans, based on the FASSET Radiation Effects Database (FRED).

Acute Crustaceans Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Artemia salina* *Artemia salina*	X-rays Gamma	3(1) 32(1)	*Gammarus duebeni* *Gammarus zaddachi* *Gammarus salnus* *Palaemonetes pugio* *Uca pugnax* *Uca minax* *Uca pugilator* *Callinectes sapidus* *Diaptomus clavipes* *Artemia salina* *Artemia salina*	X-rays X-rays X-rays Gamma Gamma Gamma Gamma Gamma Gamma Gamma Neutrons	2(1) 1(1) 1(1) 25(1) 26(2) 5(1) 5(1) 34(2) 30(2) 46(1) 30(1)	*Diaptomus clavipes* *Artemia salina* *Artemia salina*	Gamma X-rays Gamma	46(2) 11(2) 62(4)			
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		90 (1)	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	300,307			301,309,310,312,313,314,315,316			299,302,303,305,306,307,308,309, 310,312			None		
Observations "rejected" (paper ID)[c]	None			19(303)			44(303)			None		
Last paper published in:	1968			1977			1977			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-12 Summary effects data on crustaceans, based on the FASSET Radiation Effects Database (FRED).

Chronic Crustaceans Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Daphnia pulex, Callinectes sapidus*	Gamma	9(2)	*Daphnia pulex, Callinectes sapidus*	Gamma	18(3)	*Daphnia pulex*	Gamma	5(2)			
< 99.9												
100-199.9												
200-499.9												
500-999.9												
1,000-1,999.9												
2,000-4,999												
5,000-9,999												
> 10,000	*Daphnia pulex, Callinectes sapidus*	Gamma	53(3)	*Daphnia pulex, Callinectes sapidus*	Gamma	60(3)	*Daphnia pulex*	Gamma	23(2)			
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	314, 490, 1065			314, 490, 1065			490, 1065			None		
Observations "rejected" (paper ID)[c]	1(404)			None			None			None		
Last paper published in:	1967			1967			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate

2.12 Molluscs

There are 17 papers relating to aquatic molluscs in the database - 15 giving data for acute exposures and 4 for chronic irradiation. All of the acute exposure data relate to low LET X- or γ-radiation; apart for reproductive capacity, there are no data at total doses less than 5 Gy. Studies on marine species are in the majority, and there are decreasing numbers of observations for morbidity, mortality and reproductive capacity, respectively, with none at all for mutation.

The chronic exposures were mainly delivered by external sources of γ-radiation, but one study employed either ^{3}H or ^{65}Zn, initially in solution, as the source of the low LET radiation. Marine and freshwater species are equally represented and there are rather more data for reproductive capacity than either morbidity or mortality with, again, no data for mutation.

Table 2-13 summarises effects data on molluscs, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). No effects data in these two wildlife groups were recorded from transitory exposures. The most recent work dates from 1986.

2.12.1 The effects of acute irradiation

From the available information, the molluscs appear to be less radiosensitive than the crustaceans, and it is reasonable to conclude that an acute exposure of less than 1 Gy is unlikely to induce a significant acute response in any of the umbrella endpoints (excluding mutation for which no data are available).

Morbidity

Mitotic activity in the ascending limb of the oyster (*Crassostrea gigas*) gut was inhibited by all doses upwards from 10 Gy; the mitotic index recovered to control values by 59 days post-irradiation at 10 and 50 Gy, but at doses greater than 100 Gy there was no sign of mitotic activity. At the higher doses, the permanent loss of mitotic activity led to a slow degeneration of the tissue, and at 750 Gy the oysters died between 120 -180 days after irradiation (two other tissues with cell renewal systems - the digestive tubules and the gills - were also showing signs of degeneration) [295]. Larvae of the slipper limpet (*Crepidula fornicata*) showed a dose-dependent reduction in growth at all doses from 5 Gy that became statistically significant ($p<0.01$) at 20 Gy over a post-irradiation period of 20 days; the shell length specific biomass was not affected by a dose of 50 Gy. The cumulative percentage of larval metamorphosis was reduced at all doses from 5 Gy [321]. Doses of 30 - 40 Gy had little effect on the growth of a freshwater snail (*Australorbis glabratus*) at an age of either 2-7 days or 44-97 days; irradiation at higher doses was more effective, per unit of exposure, in reducing the growth of the younger, as compared with the older, snails [405].

Mortality

The $LD_{50/30}$ for the mud snail (*Nassarius obsoletus*) has been determined to be 375 Gy, and considerably lower than the quoted values of around 10^3 Gy for a clam (*Mercenaria mercenaria*) and an oyster (*Crassostrea gigas*). More importantly, these low radiosensitivities were shown to be unrealistic when the observation period was extended to allow a greater proportion of the lethal damage to be expressed. At 50 days, the LD_{50} values had reduced to about 140, 800 and 90 Gy for the three species, respectively; and the value for the clam


continued to decline until at 80 days it had reached about 420 Gy [267]. A second study with the mud snail [322] showed a more complex response to acute irradiation. The survival at 60 days was a biphasic function of the dose, and it was not possible to estimate a unique value for the median lethal dose (LD_{60}).

Studies with a freshwater snail (*Australorbis glabratus*) indicate that the median lethal dose depends on the age at irradiation. The $LD_{50/30}$ increases from about 76 Gy at age 2-3 days to about 250 Gy for individuals older than 55 days. As the observation period increases, however, the LD_{50} values decline, and to a greater extent for the older than the younger animals thus reducing the apparent differences in radiosensitivity with age. Size at a given age also appears to influence radiosensitivity with the $LD_{50/30}$ values being generally lower for the smaller specimens [770]. For the pond snail (*Physa acuta*), the $LD_{50/80}$ has been estimated to be about 400 Gy with no significant lethal effects being observed within the 80 day period at doses below 80 Gy [325]. A previous history of chronic radiation exposure in a contaminated environment (a dose rate of 270 $\mu Gy\ h^{-1}$ at the time of sampling and higher at earlier times) had no significant effect on the $LD_{50/30}$ value (480 Gy) determined for the pond snail (*Physa heterostropha*) [326].

Reproductive capacity

A low dose of 1.8 Gy to developing embryos of the pond snail (*Radix japonica*) had a significant effect on development in terms of reduced growth of the embryonic shell [286]. Irradiation of a freshwater snail (*Australorbis glabratus*) to 60 Gy (or more) at ages between 2 and 44 days had no effects on the growth of subsequent offspring as assessed by mature shell diameter [405]. A dose of 20 Gy significantly reduced the numbers of eggs produced by the hermaphroditic pond snail (*Physa acuta*) and their hatching success; exposure at a higher than normal temperature accentuated the damage [323]. A dose of 5 Gy one day after oviposition reduced the survival of pond snail (*Physa acuta*) embryos (an LD_{50} of 20 Gy). In adults, given a dose of 100 Gy, there was an immediate reduction in the rate of oviposition and the hatchability of the eggs, but the former recovered to control values 60 days after exposure, and the latter approached 70% of the control value by day 50 [325]. The various early stages of the developing embryos of the marine snail (*Ilyanassa obsoleta*) show varying radiosensitivity. An X-ray dose of 10 Gy at the pronuclear interphase stage induces a slight delay in the first cleavage division and, although the eggs form blastulae after 24-36 hours, they proceed no further in development; higher doses are more damaging. Later stages in development show variable, but lower radiosensitivity [320].

Mutation

There are no experimental results in the database for this umbrella endpoint.

2.12.2 The effects of chronic irradiation

It appears likely that dose rates above $10^2\ \mu Gy\ h^{-1}$ to developing mollusc embryos will affect the incidence of developmental abnormalities but not the subsequent overall survival of the resulting larvae. Significant detrimental effects are to be expected at dose rates greater than $10^3\ \mu Gy\ h^{-1}$.

Morbidity

Increasing dose rates of Co-60 γ-rays in the range 1.6 x 10^5 to 3.7 x 10^5 μGy h^{-1} progressively reduced the growth rates (weight) of juvenile clams (*Mercenaria mercenaria*), but dose rates lower than 10^4 μGy h^{-1} had no significant effects as compared with the controls over an exposure period of 60 days. In contrast, even the highest dose rates had no effects on the growth of scallops (*Argopecten irradians*) [296]. Developing oyster larvae (*Crassostrea gigas*) have been exposed from either the one cell, two cell or rotating blastula stages to either tritiated water or ^{65}Zn in solution and the proportions of abnormal larvae scored after 48 h. In one experiment, dose rates of 0.13 - 13 μGy h^{-1} from tritium had no effects, but 130 μGy h^{-1} significantly increased the abnormality rate; in a second experiment, only a higher dose rate of 1.3 x 10^3 μGy h^{-1} produced a significant effect. For the ^{65}Zn exposures, dose rates of 1.7 - 17 μGy h^{-1} did not significantly affect the abnormality rate, but 167 μGy h^{-1} significantly increased the rate. Maintenance of the developing larvae at different temperatures showed that there were no interactive effects with the irradiation [298]. The growth of young pond snails (*Physa heterostropha*) exposed to ^{60}Co γ-rays over a 120 day period was not significantly affected at a dose rate of 10^4 μGy h^{-1}, but was significantly increased at 10^5 μGy h^{-1} [326].

Mortality

Significant mortality of juvenile clams (*M. mercenaria*) attributable to their exposure to ^{60}Co γ-rays over a period of 425 days was not observed at dose rates up to 10^4 μGy h^{-1}, but progressively increasing mortality occurred from 120 days at dose rates in the range 1.6 x 10^5 - 3.7 x 10^5 μGy h^{-1}; in this group it was estimated that the cumulative dose for 50% mortality was about 1300 Gy. The juvenile scallops (*A. irradians*) showed no mortality attributable to the irradiation at any dose rate over a period of 84 days [296]. Dose rates up to 1.3 x 10^3 μGy h^{-1} and 1.7 x 10^4 μGy h^{-1}, respectively, from tritium and ^{65}Zn in the water had no influence on the survival of oyster larvae at 48 h after fertilisation, and there were no interactions between irradiation and rearing temperature [298]. The cumulative mortality of pond snails (*P. heterostropha*) irradiated at 10^4 μGy h^{-1} over 25 weeks was not significantly different from the controls but was increased at dose rates above 10^5 μGy h^{-1} [326].

Reproductive capacity

Irradiation of pond snails (*P. heterostropha*) with ^{60}Co γ-rays at dose rates in the range 10^4 to 2.5 x 10^5 μGy h^{-1} significantly impaired both egg capsule and total egg production per female over the first 12 weeks of exposure; in the period 12 - 24 weeks, both measures of fertility at 10^4 μGy h^{-1} became the same as for the controls but declined progressively at dose rates greater than 10^5 μGy h^{-1}. At 10^4 μGy h^{-1}, the hatchability of the eggs was not significantly different than for the controls, but was progressively impaired at dose rates of 10^5 μGy h^{-1} and greater [326]. Field studies of a population of that had a history of chronic irradiation (a dose rate of 270 μGy h^{-1} at the time of sampling and higher over at least some of the previous 30 generations) showed that, as compared with a control population, the pond snails had a lower frequency of egg capsule production, but also that the number of eggs per capsule was increased so that the total egg production in each population was similar. It was suggested that this apparent compensation had been brought about by natural selection [324, 326].

Mutation

There are no experimental results in the database for this umbrella endpoint.

Table 2-13 Summary effects data on molluscs, based on the FASSET Radiation Effects Database (FRED).

Acute Molluscs Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Cardita antiquata*, *Anadara granosa* *Crassostrea gigas* *Australorbis glabratus* *Crepidula fornicata*	Gamma Gamma X-rays X-rays	2(1) 19(1) 9(1) 15(2)	*Crepidula fornicata* *Physa acuta* *Physa acuta* *Physa heterostropha*	X-rays X-rays Gamma Gamma	6(1) 7(1) 4(1) 2(1)	*Ilyanassa obsoleta* *Physa acuta* *Crassostrea gigas*	X-rays X-rays X-rays	1(1) 9(1) 3(1)			
< 0.199							Crassostrea *gigas*	X-rays	10(1)			
0.2-0.499												
0.5-0.99							*Crassostrea gigas*	X-rays	3 (1)			
1.0-1.99							*Crassostrea gigas*	X-rays	3 (1)			
2.0-4.99												

Table 2-13 Summary effects data on molluscs, based on the FASSET Radiation Effects Database (FRED).

Acute Molluscs Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Cardita antiquata, Anadara granosa*	Gamma	14(1)	*Cardita antiquata*	Gamma	5(1)	*Ilyanassa obsoleta*	X-rays	7(1)			
	Crassostrea gigas	Gamma	34(1)	*Anadara granosa*	Gamma	6(1)	*Physa acuta*	X-rays	23(1)			
	Australorbis glabratus	X-rays	19(1)	*Mercenaria mercenaria*	Gamma	1(1)	*Physa acuta*	Gamma	16(1)			
	Crepidula fornicata	X-rays	51(2)	*Crassostrea virginica*	Gamma	1(1)						
				Nassarius obsoletus	Gamma	2(1)						
				Physa heterostropha	Gamma	10(1)						
				Crepidula fornicata	X-rays	32(1)						
				Physa acuta	X-rays	19(1)						
				Physa acuta	Gamma	24(1)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	294,295,321,405,504			294,321,322,323,325,326			298,320,323,325			None		
Observations "rejected" (paper ID)[c]	1(297)			None			None			None		
Last paper published in:	1986			1986			1984			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

Table 2-13 Summary effects data on molluscs, based on the FASSET Radiation Effects Database (FRED).

Chronic Molluscs Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Mercenaria mercenaria* *Physa heterostropha*	Gamma Gamma	5(1) 2(1)	*Mercenaria mercenaria* *Physa heterostropha*	Gamma Gamma	3(1) 1(1)	*Crassostrea gigas* *Crassostrea gigas* *Physa heterostropha*	Beta Gamma Gama	3(1) 3(1) 5(1)			
< 99.9				*Mercenaria mercenaria*	Gamma	3(1)	*Crassostrea gigas* *Crassostrea gigas* *Physa heterostropha*	Beta Gamma Gama	6(1) 6(1) 2(1)			
100-199.9							*Crassostrea gigas* *Crassostrea gigas*	Beta Gamma	3(1) 3(1)			
200-499.9												
500-999.9	*Mercenaria mercenaria*	Gamma	5(1)	*Mercenaria mercenaria*	Gamma	3(1)						
1,000-1,999.9												
2,000-4,999												
5,000-9,999				*Mercenaria mercenaria*	Gamma	3(1)						
> 10,000	*Mercenaria mercenaria* *Physa heterostropha*	Gamma Gamma	5(1) 6(1)	*Mercenaria mercenaria* *Physa heterostropha*	Gamma Gamma	3(1) 3(1)	*Physa heterostropha*	Gamma	18 (1)			

Table 2-13 Summary effects data on molluscs, based on the FASSET Radiation Effects Database (FRED).

Chronic Molluscs Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	296,326			296,326			298,326			None		
Observations "rejected" (paper ID)[c]	None			None			None			None		
Last paper published in:	1976			1976			1971			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rat

2.13 Aquatic invertebrates and zooplankton

Some of the data now included in the database have not been fully discussed in existing reviews, in part because they are from recent publications - the latest is from 1997. A wide range of invertebrate types is covered, but the greatest amount of information is available for species of small marine polychaete worms and mosquitoes (*i.e.* insects that spend their larval development in freshwaters and that should, strictly, be included in the insect category); and marginally more of the available data relate to freshwater species. A total of 28 papers is entered onto the database and these are fairly evenly distributed between studies of responses to acute and chronic radiation exposure. The great majority of studies employed low LET X- and γ-rays (including a field study with mixed β- / γ-radiation), with one each relating to the responses to neutrons and tritium.

Table 2-14 summarises effects data on aquatic invertebrates and zooplankton, resulting from acute and chronic exposures, based on the FASSET Radiation Effects Database (FRED). No effects data were recorded from transitory exposures.

2.13.1 The effects of acute irradiation

Although doses up to 1 Gy had no significant impacts on the majority of aquatic invertebrates for which data are included in the database, acute doses as low as 0.5 Gy can significantly decrease the percentage of live embryos in broods of the particularly radiosensitive polychaete worm *Neanthes arenaceodentata*; this radiosensitivity is confirmed by the finding of an increased incidence of radiation-induced sister chromosome exchanges in juvenile worms exposed at total doses greater than 0.17 Gy.

Morbidity

X-irradiation of hydra (*Pelmatohydra robusta*) with 100 or 400 Gy induced progressively more severe morphological changes. At the higher dose, no new buds were formed, the body size reduced slowly, no new nematocysts were distributed to the tentacles, which became shorter, and, by 10 days post-irrradiation, the organism collapsed into a small cell mass; histological preparations showed that certain cell types had disappeared and that there were no mitotic figures in those that remained. At the lower dose, the appearance of damage after a few days was variable between individuals but became clear, including a shortening of the tentacles, at about 8 days post-irradiation; after a further 7 days, regeneration was in progress [290].

Mortality

X-irradiation of hydra (*Pelmatohydra robusta*) at doses of 4 - 100 Gy had no lethal effects over the ensuing 60 day period, whereas 400 Gy was 100% lethal by day 15 at 25 °C and by day 52 at 10 °C [290]. The published LD_{50} values for protozoans (*Paramecium spp.*) show a wide variation of 750 - 3750 Gy. It has been demonstrated, however, that much of the mortality may be caused indirectly by the extra-cellular radiolytic generation of H_2O_2 in the surrounding water and that the reduction of the response depends on the presence of bacteria that are capable of metabolising the hydrogen peroxide [690]. The apparent radiosensitivity of the sea urchin (*Arbacia punctulata*), as indicated by the LD_{50}, increases as the assessment period is increased from 20 to 40 days, and then stabilises at about 80 Gy [267]. Exposure of polychaete larvae (*Neanthes arenaceodentata*) to ^{60}Co γ-radiation for 24 h at dose rates of


either 2.2 x 10^4 or 1.2 x 10^5 μGy h^{-1} (total doses of 0.52 and 2.8 Gy) had no effects on survival over a period of 17 days [368]. Doses up to 8.4 Gy of ^{137}Cs γ-rays to juvenile, or adult male or female worms (*N. arenaceodentata*) did not significantly influence their subsequent survival or mean life span [357]. A thermal neutron exposure of amoebae (*Amoebae proteus*) to an absorbed dose of 2.4 x 10^3 Gy appeared to have no effect on their survival to 15 days [685].

Reproductive capacity

A ^{137}Cs γ-radiation dose of 4 Gy produced a significant reduction in the fecundity of the terminal spawning polychaete worm, *N. arenaceodentata*, and for adults worms the time to spawning was delayed at all doses up to 8.4 Gy [357]. In a second, more extensive study, all doses from 0.5 - 5 Gy had no significant effects on the number of embryos in a brood when the worms were irradiated at the stage that the oocytes became visible in the female, *i.e.* the fertility of the worms and the fertilisation rate were unaffected at these doses. It was established, however, that doses as low as 0.5 Gy caused significant decreases in the percentages of live embryos in the broods; the derived, highly significant, dose-response relationship indicated that a dose of 1 Gy would result in no live embryos in worms of average radiosensitivity. The radiation exposure also increased the percentage of abnormal embryos, but this only became significant at a dose of 2 Gy or greater; again, a highly significant dose-response relationship was developed, and this showed that a dose of 0.75 Gy would produce an abnormality rate of 100% in the worms of average radiosensitivity. The survival of the embryos to hatching was also significantly dependent on dose, and it was estimated that a zero hatch for the worms of average radiosensitivity would require an exposure of 0.6 Gy. It is clear from these three measures of the effects of gamete irradiation in the adult worms that low acute doses of <<1 Gy can have a significant effect on reproductive performance, and it was concluded that the response was due to the induction of dominant lethal mutations in the gametes [359].

Mutation

An acute dose of 2.3 Gy (^{60}Co γ-rays) significantly increased the number of abnormal metaphase cells harvested from juvenile polychaete worms (*N. arenaceodentata*) to 48% from the <1% observed in the controls [366]. A later study, using improved methods, showed a lower incidence of abnormal cells at a dose of 2 Gy, but a dose-dependent increase in the frequency of aberrations (chromatid and chromosome deletions and interchanges) per cell and percentage abnormal metaphase cells [357]. Similarly, a 3.1 Gy dose of ^{137}Cs γ-rays significantly increased the incidence of single strand DNA breaks [367]. The induction of sister chromosome exchanges (SCE) detectable by harlequin staining of bromodeoxyuridine (BrdU)-labelled metaphase chromosome spreads is, however, a more sensitive indicator of nuclear DNA damage. The response is largely due to an increase, relative to the controls, in the number of cells showing large numbers of SCE per chromosome and is apparent in cells exposed for 12-24 h at dose rates from 5 x 10^3 to 2.5 x 10^4 μGy h^{-1} (total doses of 0.12 - 0.7 Gy) [365, 368]. Although these responses cannot be interpreted in terms of mutation rates in specific genes, they are directly indicative of the presence of radiation-induced damage, at low doses, in nuclear DNA.

The larvae produced by adult male mosquitoes (*Chironomus riparius*) given an acute dose of 20 Gy of ^{60}Co γ-rays and mated to unirradiated virgin females had a significantly increased incidence of chromosome aberrations in their salivary glands and an induction rate of 1.8 x 10^{-2} per larva per Gy was determined [1060].

2.13.2 The effects of chronic irradiation

Significant effects of chronic irradiation (on invertebrate reproductive capacity) have been observed at dose rates down to 1.9 x 10^2 μGy h^{-1}; a similar dose rate was the presumed cause of an increase in chromosome aberrations in a wild population of mosquitoes. A lower dose rate of 14 μGy h^{-1} in a contaminated environment appeared to be a possible cause of an alteration in the reproductive behaviour of one of three species of oligochaete worms. However, even lower dose rates (*i.e.* small multiples of the background) to populations of protozoans appeared to stimulate their growth relative to the controls, whereas a reduction of the background reduced the growth rate. Two experiments provide somewhat contrary evidence for the RBE of tritium β-radiation - values of unity for worm reproduction, and 1.6 - 1.9 for mosquito chromosome aberration induction.

Morbidity

None of the references recovered from the database under this heading relates strictly to morbidity. References [311, 638] provide data on the growth of *Paramecium* populations (reproductive capacity); [1059] relates to a cytogenetic study (mutation); and, [675] concerns the numbers of species present in ponds and streams, with varying dose rates, on the Hanford site in the US. Reference [361] (not recovered by the search), however, shows that exposure to ^{137}Cs γ-rays at dose rates of 1.7 x 10^3 - 1.4 x 10^4 μGy h^{-1} over a period of 35 days had no significant effects on the growth of a polychaete worm (*Ophryotrocha diadema*).

Mortality

The survival of polychaete worms (*O. diadema*) has been assessed at days 50 and 62 in generations 1, 2, 3 and 7 maintained under chronic ^{137}Cs γ-ray exposure at dose rates between 1.7 x 10^3 - 1.4 x 10^3 μGy h^{-1} (in this study, each generation lasted 50 days, *i.e.* a new, synchronised, population was started at this time interval). In the first generation, the irradiation produced no significant mortality as compared with the controls; in the second generation, the survival to day 50 was affected by the irradiation and at day 62 it appeared to be dose rate-dependent; in the third generation, the survival was less strongly correlated with the dose rate; in generation 7, the irradiation had no significant effects on the mortality at either 50 or 62 days [361].

Reproductive capacity

A number of studies have shown that the reproductive potential of populations of single cell protozoans, *Paramecium spp*. is influenced by chronic radiation dose rates of the order of the natural background. The use of 5 and 10 cm thick lead shields to reduce the natural radiation background dose rate to clonal populations of *P. aurelia* and *P. caudatum* resulted in reduced population growth rate and maximum population size, and increased generation time. These effects of the reduced irradiation could be mitigated by the addition of a small thorium source inside the lead shields to increase the dose rate above the normal background. [638; Planel *et al*., 1976]. Similar results have been obtained with another protozoan species (*Tetrahymena pyriformis*), and it has been demonstrated that populations cultured in a reduced background environment (~0.06 μGy h^{-1}) grow at consistently slower rates with ^{39}KCl in the culture medium than with either natural KCl or ^{40}K-enhanced KCl [645]. The growth of *P. tetraurelia* populations was found to be stimulated, relative to comparable unirradiated controls, by irradiation with ^{60}Co γ-rays at a dose rate of 2.3 μGy h^{-1} if either the concentration of bacteria


(the food source) in the culture was high, or catalase were added to the culture medium. If the bacterial concentration were low, or a catalase inhibitor were added to the medium, then the population growth was temporarily inhibited but then stimulated. It was concluded that the added catalase activity, or that from the bacteria, was counteracting a toxic effect from the radiolytic production of H_2O_2 in the water of the culture medium. Stimulated growth eventually occurred even in the cultures with a low initial bacterial concentration, and it was suggested that the radiation-generated H_2O_2 could be oxidising some substrate to a product that was essential to growth and, otherwise, rate limiting [311].

Exposure of the developing embryos of the marine polychaete worm *N. arenaceodentata* to ^{60}Co γ-rays at dose rates between 1.9 x 10^2 to 1.7 x 10^4 μGy h^{-1} had no significant effects on the number of larvae that hatched. These larvae were allowed to develop and reproduce under irradiation, and the mean number of embryos in their broods was significantly reduced at 1.7 x 10^4 μGy h^{-1} but not at the lower dose rates, *i.e.* only the highest dose rate influenced gamete production and fertilisation rate. At all dose rates, however, there were significant reductions in the numbers of live embryos and increases in the numbers of abnormal embryos, and it was suggested that this was a consequence of the induction of lethal mutations in the gametes. [358]. Exposure of the gametes of a second species of polychaete (*O. diadema*) in the parent from the juvenile stage to spawning, and of the developing embryos, to ^{137}Cs γ-rays at a dose rate of 1.4 x 10^4 μGy h^{-1} significantly reduced the number of larvae produced; lower dose rates had no effects [361]. Thus the results from these two studies are consistent. The second study [361] followed the reproductive performance of the irradiated worms over 7 generations (at 50 days per generation). In generations 2 and 3, there were dose rate dependent reductions in the numbers of egg sacs, eggs and larvae produced, and at the highest dose rate the populations became extinct; but by generation 7 the damaging effects of the irradiation, although still present, were less pronounced. A second study with *O. diadema* [360] compared the influence on reproductive capacity of ^{137}Cs γ-rays and tritium β-radiation at a single dose rate of 7.3 x 10^4 μGy h^{-1} from the egg stage to the old adult. Although the γ-irradiated worms showed significant reductions in egg production but not in egg survival to larvae, and the converse was the case for the β-irradiation, both radiations caused similar, significant reductions in the numbers of larvae produced as compared with the controls. Thus, the results do not indicate an RBE for low energy β-radiation significantly different from unity for this endpoint.

Oligochaete worms of the family *Naididae* can reproduce either asexually or sexually, but predominantly by the former mode. An increased radiation exposure from low-level contamination from the Chernobyl accident (~ 14 μGy h^{-1} as compared with a natural background of 0.7 μGy h^{-1}) appeared to increase the asexual reproductive activity in one species (*Dero obtusa*) but not in two others (*Nais pseudobtusa* and *N. pardalis*) for samples taken in 1995. In 1996 there were no significant differences between the exposed animals and the controls for any of the species.

Mutation

The incidence of chromosome aberrations in the larval salivary glands of mosquitoes (*C. riparius*) whose parents had been exposed from the egg stage to adulthood to either tritiated water or external ^{60}Co γ-irradiation was increased in comparison with the controls. The induction rates were 2.1 x 10^{-3} per larva per Gy for ^{60}Co irradiation (16.5 Gy at 3 x 10^4 μGy h^{-1}) and 3.9 x 10^{-3} and 2.7 x 10^{-3} per larva per Gy for two concentrations of tritiated water (30.5 Gy at 5.3 x 10^4 μGy h^{-1} and 15.3 Gy at 2.7 x 10^4 μGy h^{-1}, respectively). These results indicate that the dose from the low energy β-rays from tritium is 1.6 - 1.9 times as effective in producing aberrations as the same dose of ^{60}Co γ-rays. The data also show that the chronic

^{60}Co γ-ray exposure is less effective, by a factor of about 15, than the acute exposure (taking account of the fact that both males and females were exposed to the chronic irradiation as compared with only the males for the acute exposure, and assuming equal gender sensitivity) [1060]. The mosquito larvae inhabiting White Oak Creek on the Oak Ridge site in the US were estimated to receive a dose rate of about 2.6×10^{2} μGy h^{-1} from contaminant radionuclides in the creek sediments. Although larva from both these mosquitoes and those from uncontaminated control sites had a fairly stable incidence of identifiable endemic chromosome aberrations (paracentric inversions), the irradiated sample had 10 aberrations that were unique to this population and presumed to be radiation-induced [369, 1059].

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Acute Aquatic Invertebrates Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Corophilum volutator*	Gamma	6(1)	*Pelmatohydra robusta* *Arbacia punctulata* *Neanthes arenaceodentata*	X-rays Gamma Gamma	1(1) 1(1) 15(2)	*Neanthes arenaceodentata*	Gamma	12(2)	*Chironomus riparius* *Chironomus riparius* *Neanthes arenaceodentata* *Neanthes arenaceodentata*	Gamma Beta[1] X-rays Gamma	2(2) 2(2) 4(1) 13(4)
< 0.199										*Neanthes arenaceodentata* *Neanthes arenaceodentata*	X-rays Gamma	3(1) 7(2)
0.2-0.499										*Neanthes arenaceodentata* *Neanthes arenaceodentata*	X-rays Gamma	7(1) 3(2)
0.5-0.99				*Neanthes arenaceodentata*	Gamma	2(1)	*Neanthes arenaceodentata*	Gamma	5(1)	*Neanthes arenaceodentata* *Neanthes arenaceodentata*	X-rays Gamma	4(1) 4(2)
1.0-1.99							*Neanthes arenaceodentata*	Gamma	6(2)	*Neanthes arenaceodentata* *Neanthes arenaceodentata*	X-rays Gamma	3(1) 2(2)
2.0-4.99	*Pelmatohydra robusta*	X-rays	1(1)	*Neanthes arenaceodentata*	Gamma	14(2)	*Neanthes arenaceodentata*	Gamma	7(2)	*Neanthes arenaceodentata* *Neanthes arenaceodentata*	X-rays Gamma	15(1) 10(5)

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Acute Aquatic Invertebrates Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 5.0	*Pelmatohydra robusta* *Corophilum volutator*	X-rays Gamma	4(1) 6(1)	*Pelmatohydra robusta* *Arbacia punctulata* *Neanthes arenaceodentata*	X-rays Gamma Gamma	12(1) 4(1) 49(1)	*Arbacia punctulata* *Neanthes arenaceodentata*	Gamma Gamma	2(1) 30(2)	*Chironomus riparius* *Chironomus riparius* *Neanthes arenaceodentata*	Gamma Beta[1] Gamma	2(2) 4(2) 15(3)
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		Possibly[1]: 371,1060
Dbase paper IDs	290, 1062			267,290,357,368			289,357,359			357,365,366,367,368,371,1060		
Observations "rejected" (paper ID)[c]	None			None			None			None		
Last paper published in:	1977			1990			1994			1990		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Beta – energy not given on papers 371 and 1060

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Chronic Aquatic Invertebrates Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	Invertebrates	Mixed	7(1)	*Ophryotrocha diadema*	Gamma	9(1)	*Neanthes arenaceodentata* *Ophryotrocha diadema* *Ophryotrocha diadema* *Dero obtusa*	Gamma Beta[1] Gamma Mixed	14(1) 5(1) 25(2) 1(1)	*Neathes arenacedentata* *Chironomus tentans* *Chironomus tentans*	Gamma Mixed Gamma	2(1) 7(1) 2(1)
< 99.9	*Astrangia danae* *Chironomus tentans* *Hymenacidon heliophila*	Gamma Mixed Gamma	2(1) 1(1) 2(1)				*Neanthes arenaceodentata* *Physa heterostropha* *Dero obtusa*	Gamma Mixed Mixed	15(1) 27(1) 1(1)			
100-199.9												
200-499.9	*Chironomus tentans*	Mixed	1(1)							*Chironomus tentans*	Mixed	4(1)
500-999.9	*Astrangia danae* *Hymenacidon heliophila*	Gamma Gamma	1(1) 1(1)									
1,000-1,999.9	*Astrangia danae* *Hymenacidon heliophila*	Gamma Gamma	1(1) 1(1)	*Ophryotrocha diadema*	Gamma	6(1)	Ophryotrocha diadema	Gamma	21(1)			
2,000-4,999	*Astrangia danae* *Hymenacidon heliophila*	Gamma Gamma	1(1) 1(1)	*Ophryotrocha diadema*	Gamma	6(1)	Neanthes arenaceodentata Ophryotrocha diadema	Gamma Gamma	15(1) 12(1)	*Neathes arenacedentata*	Gamma	2(1)
5,000-9,999	*Astrangia danae* *Hymenacidon heliophila*	Gamma Gamma	1(1) 1(1)	*Ophryotrocha diadema*	Gamma	6(1)	*Ophryotrocha diadema* *Ophryotrocha diadema*	Beta[1] Gamma	5(1) 17(2)	*Neathes arenacedentata* *Chironomus tentans*	Gamma Gamma	2(1) 2(1)

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Chronic Aquatic Invertebrates Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
> 10,000	*Astrangia danae* *Hymenacidon heliophila* *Molgula manhattensis* *Invertebrates*	Gamma Gamma Gamma Mixed	4(1) 4(1) 1(1) 1(1)	*Ophryotrocha diadema*	Gamma	3(1)	*Neanthes arenaceodentata* *Physa heterostropha* *Ophryotrocha diadema*	Gamma Mixed Gamma	15(1) 24(1) 6(1)			
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		Possibly (360[1])	Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		Possibly[2] 371,1060
Dbase paper IDs	675,1059,1064			361			324,358,360,361, 549			366,369,371,1060		
Observations "rejected" (paper ID)[c]	none			none			4(549)			none		
Last paper published in:	1980			1994			1997			1981		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

1 Beta – on paper 360 not given on database. 2 Beta energies are mentioned in the two papers, but without energies

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Acute Zooplankton Total absorbed dose (Gy)	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Tetrahymina pyriformis* *Vorticella & Telotrochidium*	Gamma Gamma	4(1) 2(1)									
< 0.199												
0.2-0.499												
0.5-0.99												
1.0-1.99												
2.0-4.99												
> 5.0	*Paramecium tetraurelia* *Spirostomum ambiguum* *Tetrahymina pyriformis* *Vorticella & Telotrochidium*	Gamma Gamma Gamma Gamma	56(1) 3(1) 11(1) 4(1)	*Amoebae proteus*	Mixed	5(1)						
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	642,644,646,690			685			None			None		
Observations "rejected" (paper ID)[c]	None			5(685)[1]			None			None		
Last paper published in:	1982			1973			None			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.
1 Paper describes effects but without giving any dose rates, or doses

Table 2-14 Summary effects data on aquatic invertebrates and zooplankton, based on the FASSET Radiation Effects Database (FRED).

Chronic Zooplankton Dose-rate (μGy h^{-1})	**MORBIDITY**			**MORTALITY**			**REPRODUCTIVE CAPACITY**			**MUTATION**		
	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]	Species	Radiation type	Data[a] (paper)[b]
Control-background	*Paramecium aurelia*	Gamma	17(1)									
< 99.9	*Paramecium aurelia* *Paramecium tetraurelia*	Gamma Gamma	7(1) 12(1)				*Tetrahymena pyriformis*	Gamma	4(1)			
100-199.9												
200-499.9							*Tetrahymena pyriformis*	Gamma	1(1)			
500-999.9												
1,000-1,999.9							*Tetrahymena pyriformis*	Gamma	1(1)			
2,000-4,999												
5,000-9,999												
> 10,000							*Tetrahymena pyriformis*	Gamma	3(1)			
Data relevant to RBE determination for: Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons				Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons			Beta (< 10 keV) Beta (> 10 keV) Alpha Neutrons		
Dbase paper IDs	311,638			None			645			None		
Observations "rejected" (paper ID)[c]	None			None			none			None		
Last paper published in:	1982			None			1986			None		

[a] Number of data values in the dose rate interval. [b] Number of papers providing the data. [c] Data values omitted as not possible to estimate the dose or dose-rate.

3. The relative biological effectiveness of radiations in the context of environmental exposures

The definition of relevant quantities, and the selection of their associated units, is fundamental to any branch of scientific endeavour and, most crucially, underlies the communication of ideas and data between practitioners and the practical application of scientific knowledge. In the radiological sciences (including radiological protection), the required quantities relate to the ionising radiations, their interactions with matter, and the later biological effects.

Radiation transfers energy through the interactions between the radiation flux and the electrons of biomolecules causing damage to them and, consequently, to cells, tissues, organs or the whole-body. In the course of these interactions, the atomic structure of the molecules may be disrupted due to excitations (the translation of orbital electrons to higher energy levels in the atoms) or ionisation (the separation of orbital electrons from the parent atoms), provided the transferred energy is high enough. The time scales differ greatly between the initial excitation and ionisation events, and the final expression of the induced biological damage.

Radiations induce a wide spectrum of molecular damage in the cell depending on dose but not all of these types of damage are relevant for the umbrella endpoints. Complex damage in DNA and in the chromatin, as a result of the production of clusters of ionisation events, is assumed to be the major cause of cell killing, mutation and carcinogenesis [Goodhead *et al*., 1993]. Theoretical analyses, as well as experimental evidence, have revealed that high LET radiation is more effective than low LET radiation in inducing complex damage in nucleosomes and chromatin - presumably the sizes of the ionisation clusters produced by α-radiation in DNA-related volumes encompass larger chromosome domains. This greater effectiveness is usually particularly marked at low doses even though the number of individual radiation tracks is smaller. Clusters of damage present an increased challenge to the repair processes operating in the cell, and have been postulated to be largely responsible for the difference in biological effectiveness of different radiation qualities [Goodhead, 1994].

It has long been known that the biological effectiveness differs for different radiation qualities. For example, there is a very substantial body of evidence to indicate that the absorbed dose from α-particles required to produce a given biological effect is less than for the electrons generated by γ-rays. The influence of radiation quality on biological systems is usually quantified in terms of the relative biological effectiveness - RBE. The RBE for a specific type of radiation, X, is defined as:

$$\text{RBE (X)} = \frac{\text{absorbed dose of reference radiation required to produce a given biological response}}{\text{absorbed dose of radiation X required to produce an equal response}}$$

In human radiation protection practice, the empirical observations relating to the RBE phenomenon are taking into account by applying dimensionless radiation-weighting factors, w_R, to the contributions to the absorbed dose (Gy), averaged over a tissue or organ, from the different radiation types, and summing to give an aggregate quantity called the *equivalent dose* (Sv). The use of this concept has been recognised as a convenient administrative approach to "adding up" amounts of different radiations having different effectiveness values per unit of absorbed dose. The w_R factor applies to all tissues and organs in the body irrespective of the variation of biological response for different stem cells to a given radiation. Consequently the generalisation to single values of w_R for each radiation type has been questioned but the simplification may be justified for practical applications in radiation


protection [ICRP, 1991]. Organisms in the environment are also exposed to ionising radiations differing in biological effectiveness, but no accepted radiation weighting factors, corresponding to w_R, have yet been accepted for general application to the dosimetry of non-human organisms.

The RBE values determined experimentally vary markedly, depending on the biological specimen use, the endpoint of interest and the conditions of exposure. The main effects of potential concern for humans are the induction of either tumours or germ cell mutations, *i.e.* stochastic effects. The current w_R factors have, therefore, been chosen on the basis of RBE values for biological endpoints relevant to stochastic late effects and for humans. Although numerous RBE values for these endpoints have been obtained for single cells in culture, only data from investigations of tumour induction and life shortening in animals have been regarded as relevant in the context of human radiation protection.

For a determination of appropriate w_R for biota, the RBE values relevant to the endpoints of concern are probably different than for humans. Furthermore, the values of RBE for the four umbrella endpoints may also be different due to the physical features of the radiation and the consequent cellular response in each case. The complex dependence of RBE on dosimetric and environmental factors, as well as on the endpoint considered, indicates that the derivation of generally acceptable w_R values, applicable in the context of environmental exposures, is likely to be a difficult issue to resolve at the present time.

3.1 Influence of radiation quality

The insult to cells, irrespective of their origin, from virtually all radiations is in the form of individual tracks of ionisation from charged particles. The capacity of radiation to cause permanent change to cells, ultimately leading to one of the four umbrella endpoints, is dependent on how effectively these individual radiation tracks induce multiple damages in DNA. This is determined by the probability of a radiation track passing through the cell volume and the conditional probabilities of the quantity and micro-distribution of the energy deposition. On logical grounds, therefore, the observed differences in biological effectiveness of different types of ionising radiations of different quality must originate from differences in track structures [Barendsen, 1979]. In an environment contaminated by radionuclides from authorised activities, low doses and low dose rates are to be expected, and the exposures are chronic rather than acute. Both these factors play a significant role in the interpretation of RBE relationships [Goodhead, 1992]. It seems highly unlikely that individual tracks should overlap, and interact, with one another at any doses and dose rates of interest for exposures of biota in a contaminated environment.

The linear energy transfer (LET) is commonly used as a description of radiation quality, and characterises the rate of energy transfer per unit distance along a charged-particle track. The LET is often expressed in units of keV/μm of water. For human radiation protection purposes, the radiation weighting factors (w_R), derived from experimental RBE values, are currently considered to be a function of radiation quality, as expressed in terms of LET.

X- and γ- rays (strictly, the secondary electrons that they generate) are considered to be low-LET radiations, while α-particles are a high-LET radiation. This qualitative difference in energy transfer between the α-particles and the secondary electrons arises primarily from the lower velocity of an α-particle relative to an electron at a given energy (due to its greater mass) and, therefore, its longer interaction time with the orbital electrons; the greater charge of the α-particle is also a contributory factor. A high LET radiation, such as an α-particle, is


capable not only of directly ionising the atoms along its path, but also of ejecting δ-rays (low energy electrons), *which* may act independently at a distance from the primary particle track. It is important to appreciate, however, that a radiation field is likely to consist of primary or secondary ionising particles with widely differing initial energies and that the energy of any individual particle will vary along its path. It follows, therefore, that the individual particles comprising a specific type of radiation can have a wide range of LET in tissue, and that any quoted value is an average. Nevertheless, typical LET values for different types of radiation broadly reflect their capacity to produce damage; the more effective radiations, such as α-particles, have higher LET (~100 keV per μm on average) than less damaging radiations such as the recoil electrons generated by X- or γ-rays (on average, about 2 and 0.3 keV per μm respectively).

The random distribution, relative to cell dimensions, of the individual ionisation events along the particle track is more pronounced for low than for high LET radiations. Many of the secondary electrons generated by low LET radiation have ranges great enough to traverse many tens of cells. Track structure analysis has confirmed the formation of ionisation clusters, equivalent to those commonly formed by high LET radiations, at the ends of secondary electron tracks as their velocity decreases and the interaction times increase [Nikjoo *et al.*, 2001]. Such clusters are assumed to be the prime determinant of radiation effectiveness for different radiation types.

The LET dependence of RBE has often been demonstrated although it is generally acknowledged that RBE is not a unique function of LET [Blakely and Kronenberg, 1998]. A common feature of many of these RBE-LET displays is the tendency towards increasing RBE with increasing LET, up to maximum at about 100 keV/μm, followed by a decrease at very high LET. The numerical values of RBE for a given LET can vary considerably, depending not only on cell-types and tissues but also on features of radiation tracks not adequately described by the LET concept. The RBE tend to be greater for mutation than for cell killing, and radioresistant cells generally show higher RBE than radiosensitive cells [NCRP, 1990]. There are, however, many exceptions from these generalities, and this makes it difficult to predict an RBE value for a given situation with any certainty. Commonly, X- or γ-rays are used as the reference radiation in experimental studies. However, the choice of reference radiation influences the RBE. X-rays for example, seem to have slightly higher biological effectiveness than γ-rays. For low doses applied at low dose rates it might be important to consider whether X- or γ-rays have been taken as the standard for the derivation of RBE values.

A dose of about 1 mGy delivered by γ-rays produces, on average, one electron track crossing each cell nucleus of diameter 8 μm, corresponding to an energy deposition generating about 60-80 ionisations in the nucleus [Bond *et al*., 1988]. For α-particles (at an initial energy of 5.5 MeV), an average of one track crossing each nucleus (at 8 μm diameter) is reached when the dose is about 370 mGy with an average energy deposition generating ~ 2.4 10^4 ionisations in the nucleus [Goodhead, 1992]. Accordingly, a mean dose of 3 mGy from α-radiation results in only ~ 1 % of the cells being hit - and essentially all hit cells will have experienced the passage of just one α-particle, with extremely few cells being hit by two or more particles. The microscopic distribution of ionisation in an organ may affect RBE significantly since not all cells in the target organ receive a dose, equal to the average organ absorbed dose. For low dose rate environmental exposures, a heterogeneous distribution of energy deposition prevails implying that microdosimetric analysis, taking into account target size, radiation source distribution at the cellular level, hit probability etc., is needed to obtain a better understanding of the RBE values.

3.2 Influence of dose rate

Data for a hypothetical experiment to determine the RBE of α-radiation are shown in Figure 3-1. In this illustration, the effects of α- and γ-irradiation on a stochastic endpoint (induction of chromosomal aberrations) are indicated at a range of doses. The dose response for the α-radiation is shown as being approximately linear ($f(D)=\alpha D$), and that for the γ-radiation as linear-quadratic ($f(D)=\alpha D+\beta D^2$) (as is usually found experimentally). It follows, therefore, that the RBE value depends on the dose at which the biological effect is measured and, in this example, the RBE decreases as the dose increases. For practical reasons, much of the available data relates to high, acute doses rather than the low dose rate chronic exposures relevant to a contaminated environment.

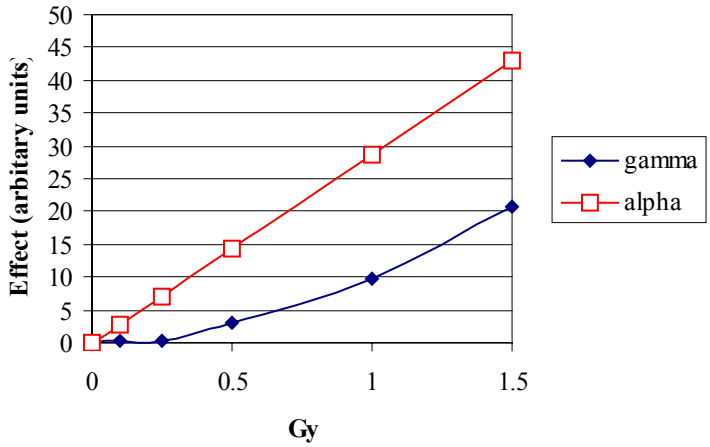


Figure 3-1 Effect of gamma and alpha irradiation at different doses on a hypothetical stochastic endpoint. The RBE at effect value 3.0 (gamma dose, 0.5 Gy/alpha dose, 0.1 Gy) is 5.0, whereas the RBE at effect value 10 (gamma dose, 1.0 Gy/alpha dose, 0.35 Gy) is 2.9.

The phenomenon of local clusters of initial damage is a biologically significant feature of ionising radiation. There seems to be no *a priori* reason to assume that these early events would differ amongst organisms. The proportions, as well as the complexity, of this damage within a single track are higher for high LET than for low LET radiation, and by assuming that the repair will be least efficient for this complex damage, the RBE will be enhanced. The much larger number of sparsely-distributed ionisation produced by low LET radiation is assumed to play a minor role in regard to the induction of late biological effects as compared with the random production of ionisation clusters at the end of the particle tracks.

It will have become apparent from this brief description of the distribution of ionisation events along the track of a particle that the dose rate is likely to influence the biological response, *i.e.* the higher incidence of interactions between multiple tracks at higher dose rates could increase the probability of inducing severe biological effects (see Figure 3-1). Yet, experiments performed with ultrasoft X-rays or radionuclides incorporated into DNA, have provided evidence that chromosome exchanges can be induced by radiation damage to one chromosome (simple exchanges) [Anderson *et al*., 2002]. The dose response for simple exchanges (*i.e.* two exchanges points in either one or two chromosomes) has been found to be


linear with dose. This situation also applies to low LET radiation in the low dose range where the probability of interaction between induced breaks in DNA from several radiation tracks could occur only if the dose rate and the total dose are high enough. Such interaction events will cause the complex chromatin damage that is assumed to be the source of the D^2 (quadratic) component of the dose response curve for low LET radiation and for induction of chromosomal aberrations. Accordingly, few examples of complex damage to chromatin will be induced when the dose and dose rate of low LET radiation are reduced, simply due to the fact that a single electron track is more or less unable to produce interacting lesions in the chromatin. By contrast, high LET radiation, has a much higher probability to produce high incidence of complex damage in chromatin. The induction of chromosome damage, including complex as well as simple exchanges, follows essentially a linear dose dependence, irrespective of dose rates, as shown in Figure 3-1. Obviously, the higher ionisation density along the single track of an α-particle has a proportionately greater probability of damaging multiple chromosomes with the corollary that there should be no dose rate effect for high LET radiations, including α-particles.

A crucial question in regard to long-term biological effects in biota is how viable the cells are after the induction of chromosomal damage. Only cells that survive long enough after irradiation can cause effects arising from mutation, or resulting in morbidity. Stem cells that have lost their capacity for proliferation cannot give rise to any genetic effects. Presumably, induced complex breaks are more difficult to repair and the cells are more prone to die. Hence, the viability of cells carrying these types of complex aberrations are low, and they may, therefore, not live long enough to cause any late effects of radiation. It should also be emphasised that the dose and dose rates in the environment are expected to be very low, implying that the probability of interacting events is negligible. For that reason, the dose response for those umbrella endpoints caused by damage to a single cell is expected to be linear (single track event) and independent of dose rate, even after low LET radiation.

The basic processes of cell survival are probably rather similar to those for the survival of the whole animal after irradiation. It is to be expected, therefore, that mortality is due to death of cells, probably as a consequence of the induction of the more complex damage in the chromatin. There is a large number of proliferating cells in sensitive organs and tissues of different organisms and, apparently, a large fraction (many millions) of these cells must be killed before the organism will be seriously affected (the deterministic effect). The RBE values obtained in studies using high LET radiation, such as α-particles, are usually rather low - between 3 and 5 for both survival of cells *in vitro* and for the mortality of animals [NCRP, 1990]. The present lack of data makes it more difficult to predict RBE values for the other umbrella endpoints. An increase in the yield of severe clustered damage in DNA, accentuated by inaccuracies in repair and the production of correlated damage along the track, may lead to an expectation for high RBE values for high LET radiations. Conversely, the complex damage may be more lethal for the cells and tend to reduce RBE values for long-term effects in viable cells. Taken together, these factors indicate that the RBE may vary considerably amongst cell types and tissues. For reproduction, the situation may become even more complicated. For example the β^--particles from tritium decays have been shown to be effective in killing primary oocytes in mice. Administration of tritium to mice from day 19 to 33 after conception can result in a dose of 3 mGy per day that causes a 50 % reduction in the number of cells. The range of a β^--particle from a tritium decay in water is less than the size of the oocyte, and the dose to the cell nucleus (8 μm diameter) induced by one decay within the cell will be in the order of 2.8 mGy. Evidently some structure(s) in the DNA of the oocytes of mice may be very sensitive to such highly localised irradiation, and probably result in a high RBE value.

It has been noted that a total absorbed dose of ~ 10^{-3} Gy of low LET radiation results in each cell nucleus in tissue being traversed, on average, by one track of an ionising secondary particle. In principle, therefore, the effects of dose rate should only be apparent above total absorbed doses of 10^{-3} Gy of low LET radiation. From experimental radiobiology and epidemiological studies of tumour induction in the atomic bomb survivors, it has been concluded [UNSCEAR, 1993b] that low doses and low dose rates of low LET radiation (β-particles and γ-rays) are less than 0.2 Gy and 6.10^{3} μGy h^{-1}, respectively. Below these levels, it is to be expected that the dose - response relationship for stochastic effects (cancer and genetic effects) would be linear with dose, *i.e.* the effects of both the interactions between individual particle tracks - the D^2 component that tends to increase the response, and the induction of cell killing - a deterministic effect that tends to reduce the response - are minimal.

It must be emphasised that these doses and dose rates are operational definitions, and simply indicate the dose and dose rate regions across which extrapolations should be made with both caution and due consideration of the biological effect and species being examined. In the low dose rate domain, *i.e.* below ~10^{4} μGy h^{-1} (also the region of primary concern for environmental exposures), a "chronic" exposure is taken to mean that it is continuous over all, or at least, a significant fraction, of the life stage of interest. It should be also be noted that in this domain the effects of the low LET radiation exposure depend on the dose rate only insofar as this determines the total accumulated dose.

3.3 Relevant RBE values at the cell and individual level

RBE values that have been determined experimentally can be considered for the four umbrella endpoints in the FASSET framework. These four categories of effect are not, however, mutually exclusive, and a number of specific effects may contribute to each umbrella effect. In total, FRED identifies 78 papers that relates to RBEs (see brief overview at Appendix A). Of these, 65 papers (including 1736 observations) are judged to be directly relevant for FASSET. Studies performed with neutrons, although informative in respect to the LET dependence of RBE, are not regarded as being directly relevant in an environmental perspective.

Some endpoints have received increased attention in relation to environmental radiation protection; these include: mutation frequency, chromosomal aberrations, physiological changes, lethality and related changes at the individual level; and, reproductive impairment, productivity reduction, and altered life-span at the population level. As already pointed out, the RBE values for the survival of individuals (a deterministic effect) are considerably smaller than the values for various types of stochastic effects. Some studies also indicate very high RBE values for effects related to fertility and fecundity. An overview of studies that might be of importance in proposing relevant w_R values for dosimetric application in ecological risk assessments is given below.

Tritium β-particles (average energy ~6 keV) have been shown to be more effective in producing clusters of ionisation as compared with photon-generated electrons with energies above 100 keV. A high radiosensitivity has also been reported for reproductive effects such as an LD_{50} as low as 54 mGy for immature oocytes in mice with after exposure to external γ-radiation [Dobson and Kwan 1977]. Highly sensitive germ-cell stages also seem to exist in some primate species. Straume and Carsten [1993] reviewed a wide range of literature concerning RBE values for tritium. The arithmetic mean of the RBE for deterministic effects arising from tritium β-particle exposures was about 2, but many of the RBE values were


obtained using irradiation at higher doses and dose rates than would normally be found in the environment.

Extensive experimental investigations have been conducted to determine the RBE values for α-particle radiation as compared with low LET radiation. The preponderance of data concerning the RBE of α-particles, both *in vivo* and *in vitro*, have been obtained, however, using external beams of radiation. There are only a limited number of *in vivo* studies with internal α-particle emitters*, which* provide clear RBE information in terms of the dose specifically received by the target cells due to complex dosimetry involved. High RBE values have been reported for reproductive systems such as spermatogenesis [Kondratenko and Ganzenko, 1975]. Rao *et al*. [1991] reported RBE values around 7 for spermatogonial cell killing after exposures to the low energy Auger electrons emitted by radionuclides incorporated into DNA or 5.3 MeV α-particles emitted by Po-210 in the cells. Auger electrons are known to be highly radiotoxic when localised close to DNA. The RBE values reported for sperm head abnormalities at very low doses (less than 30 mGy) are about 8 times higher than for cell killing for Auger electrons and more than 30 times higher for Po-210. The absolute RBE value for sperm head abnormalities was found to be about 250 for Po-210 as compared with external x-irradiation. Recently, studies performed on the Medaka fish have shown that early-differentiating spermatogonial cells, which may be the immediate descendants of the spermatogonial cells, are very sensitive to radiation-induced cell-death [Kuwahara *et al*., 2002]. They are far more sensitive to cell death than other spermatogonial cells, and this may be due to the active DNA synthesis that exclusively occurs in these cells as evidenced from the incorporation of bromodeoxyuridine. This may explain the difference in the RBE values between the Auger electrons and Po-210 for induction of sperm head abnormalities, but it does not explain the high absolute RBE value obtained for Po-210. Studies have been performed of spermatogonial cell killing in the mouse testis after exposure to ^{212}Pb in equilibrium with daughters (6 and 8.8 MeV), and the RBE for the mixed radiation field was found to be 4.7 as compared with X-rays [Howell *et al*., 1994].

An RBE-value of 150 has been reported from a study of immature oocytes in mice after exposure to polonium-210 [Samuels, 1966]. The LD_{50} of immature oocytes was found to be between 1 and 2 mGy; a result that implies that less than 1 % of all oocytes had been hit by an α-particle. This extremely high RBE value is difficult to explain simply from the energy deposition pattern. However, a large amount of data produced during the last decade seem to indicate higher damage yields than expected, at low doses, due to the so-called “bystander effect”. A consequence of this effect might be that the relevant target for radiation-induced harm at low doses is larger than an individual cell.

High RBE values have also been reported for the developing haemopoietic system in mice after α-particle irradiation. Pregnant mice were either injected with ^{239}Pu or irradiated with γ-rays from day 13 of gestation. The spatial distribution of haemopoetic stem cells in 8-week-old offspring was then determined and compared for the different irradiation situations. The results indicated an RBE between 130 and 360 depending on the delivery of the γ-ray dose. The higher value refers to a continuous irradiation from day 13 of gestation to birth while the lower value refers to a single acute dose [Jiang *et al*., 1994]. Repetition of this study yielded an RBE of 150 [Lord and Mason, 1996]. However, the assumption was made in these reports of a homogenous distribution of α-radiation, and this may have implications for the interpretation of the results.

The probability of tumour induction by α-emitting radionuclides has been investigated. For example the induction of liver tumours in Chinese hamsters has been evaluated after administration of ^{239}Pu-citrate [Brooks *et al*., 1983]. Indirect comparison with the β-emitting


radionuclide ^{144}Ce yielded RBE values around 10. The relative effectiveness of chromosomal aberration induction by the same radionuclides was found to be higher at 15-20. This difference is expected since only viable cells will form liver tumours and the scoring of aberrations at first metaphase after the exposure included cells with complex exchanges that would have been unable to proliferate. Data for bone carcinoma induction in mice and beagle dogs indicated RBE values for ^{226}Ra compared to the β-emitting ^{90}Sr greater than 20 for the lowest dose ranges [Raabe *et al*., 1983]. However, the authors concluded that differences between the radionuclides, in the dose and dose rate to the sensitive cells in the skeleton affected the estimation of the RBE values. The incidence of lung tumours in rats exposed to aerosols of $^{239}PuO_2$ has been studied [Lundgren *et al*., 1995]. The RBE value of the α-particle dose to the lung from inhaled ^{239}Pu relative to the β-particle dose from inhaled ^{144}Ce was 21.

In a recent study, the RBE for ^{210}Po α-particles versus X-rays on lethality in bovine endothelial cells was reported to be 14 [Thomas *et al*., 2003]. It is known that up to 50% of the ingested body burden of ^{210}Po is initially found in the blood. Therefore the bovine endothelial cells may be one of the targets for the α-particles.

3.4 Radiation weighting factors

It is known that the exposure of the wild flora and fauna, whether from the natural background or from contaminant radionuclides, arises from radiations with a wide range of qualities (LET values) and, hence, likely RBE values. It must be accepted that, in the environmental context, there is no practical alternative to the use of the quantity absorbed dose, together with its SI unit (1 J kg^{-1} equivalent to 1 Gray (Gy)) for the measure of the transfer of energy from the radiation field to biological tissue. This has been the basis (the independent variable) for effectively all of the empirical relationships that have been developed between radiation exposure and the consequent biological effects in non-human organisms. The objective must be, therefore, to "translate" this physical quantity to a biologically relevant quantity for non-human organisms, analogous to the "equivalent dose" employed in human radiation protection practice. Any fundamental differences in the primary processes of radiation interaction and energy absorption in human and non-human tissues are not to be expected. The application of weighting factors in human radiation protection is already an established system and hence it is unlikely that there is any viable alternative to the use of (a) radiation weighting factor(s) to take account of the influence of radiation quality on the biological effects of radiation in non-human organisms. The challenge is to provide relevant values for the radiation regimes - radiation types, dose rates and accumulated doses - in contaminated environments, and the biological endpoints of concern.

As already stated, the choice of appropriate weighting factors for biota should involve the range of RBE values appropriate for the class of organism, relevant endpoints and range of dose rates and doses under consideration. An overview of the information on RBE values for the different wildlife groups that can be obtained from the database is given in Appendix A.

The lack of directly relevant data, as well as insufficiently-detailed knowledge concerning the basic mechanisms connecting the initial damage to the significant endpoints for the protection of non-human organisms render it difficult to suggest any radiation weighting factors for biota. In order to demonstrate the likely influence of the relative biological effectiveness of exposure to internal α-emitters, however, weighting factors ($w_R(\alpha)$) of 5, 10 and 50 have been applied for the calculation of the nuclide specific absorbed dose conversion factors for α-emitters in the dose calculations. Although these values encompass the greater part of the range of values discussed above, it must be emphasised that they have been selected for


illustration purposes only and no definitive conclusions have so far been drawn within the FASSET consortium concerning the appropriate numerical values of radiation weighting factors for non-human organisms.

Table 3-1 gives the values of w_R used in human radiation protection practice [ICRP, 1991]. It must be emphasised that, although these values are applied to situations of human exposure, most of these values are developed from the empirical RBE values obtained from experiments with animals. In addition, it must be remembered that these values have been explicitly defined for application to the situation in human radiation protection where the stochastic effects of cancer and mutation induction are of primary concern; they do not apply to deterministic effects. They have been included here simply as an example of how the available empirical knowledge can be applied to develop a consistent system of radiation dosimetry beyond the assessment of the physical absorbed dose towards a more biologically relevant predictor of effect. It is to be expected that the values (or ranges) of the radiation weighting factor that might be applicable to the exposure regimes experienced by, and the relevant biological endpoints for, non-human organisms in contaminated environments would differ from those used for humans.

Table 3-1 Radiation weighting factors.

Radiation type and energy range	**Radiation weighting factor, w_r**
Photons of all energies	1
Electrons and muons of all energies	1
Neutrons, energy < 10keV 10 keV to 100 keV > 100 keV to 2 MeV > 2 MeV to 20 MeV > 20 MeV	5 10 20 10 5
Protons, other than recoil protons, energy > 2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

Natural background represents a significant source of radiation exposure to non-human species. Hence, the selected weighting factor(s) for α-radiation may have a great impact on the risk assessments. One of the proposals has been to retain the same factor for biota as for humans as being adequately protective of all species [IAEA, 1992]. NCRP proposed a value of one based on the degree of conservatism built into the dose assessment models for biota [1991]. UNSCEAR [1996] proposed a value of 5 based on deterministic effects, and Kocher and Trabalka [2000] suggested a value in the range between 5 and 10 for α-radiation. Trivedi and Gentner [2000] have proposed an ecodosimetry factor to fill the role equivalent to the w_R in human radiation protection. A value of 10 was suggested for weighting doses from α-emitters at the population level with a span of 5 to 20 to consider either more realistic impact or more substantive assurance as to the long-term viability of ecosystems. An alternative strategy was put forward by Pentreath [1999] in which the weighting factor (W_f) could be derived as the quotient of the accepted maximum and minimum values of the linear energy transfer in water for α-particles, with energies up to 10 MeV, and the maximum and the minimum LET values for electrons with energies in the range of 0.01 to 2 MeV. Recognising the relative lack of numerical data, this approach assumes that the W_f is independent of the endpoints of interest. The value of W_f will, by this procedure, be in the range 100 to 250, substantially greater than the values proposed earlier. In its Priority Substances List - 2


Environment Canada proposed a weighting factor of 40 for α-radiation and 3 for tritium, in respect of deterministic endpoints [Environment Canada, 2001].

In recent years it has become increasingly apparent that different types of radiation can act differentially via a variety of untargeted mechanisms. Examples are radiation-induced genomic instability, germline minisatellite mutations and instability in unirradiated bystander cells. Little is known about the mechanisms underlying these responses, and the paucity of data makes it difficult to predict what influence, if any, they might have concerning the value of relative biological effectiveness. Although a recently reported study using biophysical modelling [Nikjoo and Kvostunov, 2003] has indicated that the RBE for oncogenic transformations at both low and high doses might be underestimated, if the contribution from the bystander signal is neglected, a second study has provided evidence in support of the *status quo* [Little and Wakeford, 2002]. While the possible importance of such mechanisms of radiation response is incontestable, it would be premature, at the present time, to attempt to accommodate the existing data within the FASSET system for the protection of the environment; the most that can be done is to adopt a precautionary approach.

3.5 Conclusions

Native wild organisms may be exposed to radiations from the natural background or from contaminant radionuclides with a wide range of values for the relative biological effectiveness. The use of radiation weighting factors, to take account of this influence of radiation quality on the biological effects of radiation, should be as applicable for non-human organisms as it is in the case of human radiological protection dosimetry. Concurrently, any recommendations on radiation weighting factors for non-human organism must be based on empirical information about RBE for the different radiation types. Consequently, the physical and biological parameters involved in RBE, such as dose and dose rate, radiation quality and biological system, will also influence the weighting factors. Thus, the selected w_R-values must reflect the endpoint of concern in the risk assessment and whether it can be induced by a single low LET track or whether it requires a larger amount of more generalised damage to the cell, in which many tracks may be required. Due to the general deficiency of relevant knowledge regarding the RBE phenomenon for wild biota (*e.g.* for the relevant endpoints at low dose rates), the derivation of w_R values for general application in the context of environmental exposures is not possible at present. In order to demonstrate the influence that radiation quality might have on the estimation of the biologically-effective dose rate, radiation weighting factors of 5, 10 and 50 for α-radiation from internal sources may be applied in the calculations of the nuclide-specific dose conversion factors for α-emitters. Because it is known that α-particles can contribute a significant fraction of the total absorbed dose rate from the natural background, and that deterministic effects (dependent on the total accumulated biologically effective dose) are important endpoints in the context of environmental protection, these values have been selected to illustrate how the natural background radiation may have an impact on ecological risk assessments. Of course, the absorbed dose rate from α-particle emitters may be of similar significance for contaminant radionuclides, depending on the particular situation under study.

4. Extrapolation issues

4.1 Introduction

A critical issue in the assessment of the possible impacts on biota from exposure to ionising radiation in a contaminated environment relates to the extrapolation of the relatively limited quantitative data that is available, and has been assembled into the database, to the practical conditions of exposure in the environment. Due to the relative paucity of the relevant information, the main extrapolations are:

- from high acute doses and dose rates (~ several Gy at ~ 10 - 100 Gy h^{-1}) of low LET γ- and X-rays to lower doses (< 1 Gy) accumulated at lower dose rates (~ 1 - 100 μGy h^{-1}) (the particular problem of comparisons between effects from low LET γ- and X-rays (< 1 keV μm^{-1}) to other radiation types such as high LET α-particles (~10^2 keV μm^{-1}) from internal sources - the RBE phenomenon - has been discussed in detail in section 3.);
- from one organism to another; and,
- from effects in the individual organism to possible impacts at the population and community levels of the biological hierarchy.

An understanding of the molecular and cellular mechanisms that underlie the observed responses at the tissue and organism level is a useful basis to guide the judgements that need to be made in such cases.

4.1.1 Molecular and cellular mechanisms

DNA is the principal, primary target for the induction of biological effects of radiation including mutation, cell killing, and cell transformation. The major types of DNA damage are single- and double-strand breaks, base damage, and strand cross-links. DNA damage response mechanisms include the processes of DNA repair, cell cycle checkpoint arrest and apoptosis. The latter two processes serve to prevent the proliferation of damaged cells that have failed to undergo successful repair.

Complex damage in DNA occurs as a result of clusters of ionisation events; these include not only prompt double strand breaks (DSB), but also clusters of non-DSB damage such as multiple single strand breaks of varying complexity, or multiple base lesions. The accurate repair of such complex types of break represents a difficult problem for the cell, and these lesions have been postulated to be largely responsible for the relative biological effectiveness of different types of ionising radiation. It has been demonstrated that the clustering of damage can arise from the passage of a single ionising particle and, therefore, may occur at any dose with no possibility for a dose-threshold effect.

The processes of DNA repair are under tight genetic control and mutations in the genes involved will result in a higher degree of radiosensitivity in the cell or its descendants. A regulatory function in the cell cycle is called a checkpoint and mutations in check points genes also contribute to an increase in cellular radiosensitivity.

Many different types of chromosomal aberrations are produced after irradiation; some are lethal to the cells and others are not. Dicentrics represent an asymmetrical exchange between two separate, broken chromosomes. The resulting chromosome contains two centromeres.

One or two acentric chromosome fragments remain after the formation of the dicentric, and these may develop into micronuclei. Cells having dicentric chromosomes and micronuclei are non-viable and will die at a subsequent mitosis due to the presence of unbalanced gene complements in the two daughter cells. The scoring of dicentrics or micronuclei represent the most commonly used methods for biological radiation dosimetry.

Deletions and translocations are examples of symmetrical exchanges found after irradiation. The formation of translocations involves breaks in two different chromosomes and the two fragments generated by the breaks are exchanged between the two chromosomes. Translocated chromosomes retain a single centromere and cells carrying translocations will survive and potentially transfer the aberrations to subsequent cell generations. In the case of deletions, radiations produce two breaks in the same arm of a chromosome. When the ends of the chromosome rejoin, the intervening fragment between the two breaks may be omitted from the repair, and then lost in a subsequent mitosis. Cells having symmetrical translocations and deletions may persist for many years after the original exposure and can be used to score radiation-induced cytotoxic damage (*biomarkers*).

Mutations comprise a mixture of rearrangements from point mutations, *e.g.* base changes, to large deletions or insertions. This may result in either the alteration or loss of information but most chromosomes and genes are present in two copies, except in the case of the non-homologous sex chromosomes, *e.g.* the X and Y chromosomes in male mammals. Radiations may induce small point mutations, *e.g.* single base changes, but it seems that the majority of radiation-induced mutations entail rather large genetic changes. The tolerance of genetic change may vary between different regions of the genome, and consequent cell lethality will limit both the frequency and the apparent size of induced mutations. Mutation induction is dependent on the dose rate. For example, the induction per unit absorbed dose of low LET radiation is reduced when the dose rate is decreased below ~ 6 10^3 μGy h^{-1} [UNSCEAR, 1993b], a situation applying to all environments contaminated by authorised discharges of radionuclides [UNSCEAR, 1996].

In terms of their possible consequences, somatic mutations have to be distinguished from those induced in germ cells. Somatic mutations may contribute to cancer induction and, hence, influence the survival of individuals in the present generation. Mutations in germ cells may be transmitted to the offspring and thereby enter the gene pool of the species concerned (*genetic load*); these inherited mutations may affect the fitness (survival potential) of individual descendants. For non-human organisms there is usually a strong natural selection pressure against individuals deviating from the phenotypic norm (*less fit or well adapted*); this, coupled with a reproductive surplus (often large), results in the rapid disappearance of detrimental mutations. Only when mutations confer a selective advantage with respect to a particular environmental state will they spread in the population. They may speed up adaptation and microevolution in such situations or facilitate the development of resistance to certain genotoxic agents.

A large fraction of the genome consists of non-coding DNA sequences that are, to a large extent, of a repetitive nature. Some of these multi-copy sequences are found in tandem repeat arrays such as mini- or micro-satellite loci. Minisatellites show a high germline mutation rate and various studies have indicated that mini-(micro-)satellites may serve as hypersensitive biomarkers for germ-line mutations after irradiation.

Two recognisable modes of cell mortality are apoptosis (programmed cell death) and mitotic death. Apoptosis has been recognised as an important element in the regulation of organ development and tissue maintenance, and to restrict growth in many normal cells (*e.g.*

erythroblasts) and tissues. It is believed that the balance between cell proliferation and apoptosis is crucial to the correct development of organisms. The apoptotic process is genetically controlled and the resulting death of the cell follows a characteristic sequence of morphologic events. Radiation-induced apoptosis appears to be different from the normal apoptosis through the involvement of different signalling pathways and differs between different types of cells. There are findings to indicate that apoptosis is independent of both dose rate and LET.

Mitotic death means that cells die at cell division due to chromosome damage (see above). This mode of death is most common after irradiation and there seems to be a close quantitative relationship between mitotic death and the induction of dicentrics.

It has become increasingly apparent that radiation, besides causing aberrations, mutations or inactivation of cells as direct targeted effects, can also induce less targeted effects such as genomic instability and bystander effects. A type of genomic change that may be detected a long time after exposure is chromosomal instability, which appears in the progeny of cells (cell clones) that had previously appeared to have survived the radiation dose unharmed. Many cell studies, mostly of cell cultures (*i.e. in vitro*), have demonstrated the effect but the underlying mechanisms are not fully understood. The dose responses commonly appear to consist of a rapid rise at low doses followed by an extended plateau, and high LET radiation seems to be more effective than low LET radiation. Nevertheless, not enough is known about the effects *in vivo* that might lead to implications for radiation protection.

A bystander effect refers to the detection of responses in cells that have not been directly hit by radiation. Numerous *in vitro* cell culture studies have demonstrated the effect for a variety of biological endpoints such as cell survival, mutation, cell transformation, apoptosis, gene expression and induced genomic instability. The effect has been observed after very low, acute doses and there are reasons to believe that the effects after high and low LET radiations may result from different mechanisms. Experiments using medium transfer from irradiated to unirradiated cells have indicated that cell-cell contact is not required to produce the effects after γ-ray and microbeam α-particle irradiation. In contrast, other studies using α-particle radiation have indicated that the gap junction-mediated transfer of biochemical signals between cells is a prerequisite for generating the effect. The confirmed existence of radiation-induced bystander responses and genomic instability *in vivo* would be likely to have profound implications for extrapolation issues. Although they cannot alter the primary observations on biological effects at high doses as summarised in the database, the interpretation of these data for the low-levels of irradiation arising in contaminated environments may be substantially different. There is a need for appropriately targeted research before these questions can be adequately addressed.

Pre-exposure of cells with a low radiation dose has been shown to modify the response to a subsequent larger (*challenge*) dose. This mechanism, called the adaptive response, has been observed in numerous experiments (see database) on different cell types using low LET radiations. It has been suggested that a low incidence of DNA breaks will act as a trigger for a response mechanism leading to accelerated repair of damage. The response is not universal, however, and some cells do not show an adaptive response. There appears to be a minimum dose rate for its induction at low doses of low LET radiation, and high LET radiations do not seem to stimulate any adaptive response in cells. Irradiation of whole animals (mice) has produced convincing evidence for the existence of an adaptive response after low LET irradiation *in vivo*. For example, exposure of mice *in utero* at low dose rates of low LET radiation resulted in a significantly lower yield of chromosome aberrations in males after


birth. Other studies have shown increased radioresistance in germ cells in mice following irradiation but the response did not have any influence on the offspring.

From the foregoing, it may reasonably be concluded that the initial damage to organisms from ionising radiations is independent of species, *i.e.* a large part of the initial damage is to the DNA as organised into genes and chromosomes. The consequence of this initial damage is, however, modified by the extra-chromosomal, but genetically determined, complexity of the biochemical machinery of the cells (including the number and efficiency of DNA repair mechanisms, and the efficiency of the mechanisms for eliminating (*e.g.* apoptosis), and/or replacing, damaged cells); all of these factors are likely to vary between species, and between life-cycle stages within species, leading to the variations in radiosensitivity indicated in Table 4-1.

4.2 Extrapolations from acute to chronic exposures

In the radiobiological and radioecological literature, the qualifiers “low-level”, “chronic”, “higher”, “acute”, etc., are generally used without any definition, and it is pertinent to consider just what they might reasonably be taken to mean in an environmental context. A simple example may be used to illustrate the nature of the problem: a radiation exposure lasting several days may be effectively “chronic” for a short-lived organism such as an aphid (*i.e.* the exposure period might be of the same order as the development time of the parthenogenetic embryo), but effectively “acute” for a long-lived organism such as the host oak tree. In practice, an exposure is usually termed “acute” if it is delivered in a time period that is shorter than that in which a very serious deterministic effect (*i.e.* one in which the severity of the effect, usually, but not necessarily, mortality, increases with dose) could appear and the dose rate is sufficiently high that a total dose likely to induce that deterministic effect could be accumulated in that time. Because deterministic effects show a sigmoid response curve with an effective threshold that may be as much as 0.2 - 1 Gy (see Figures 4-1 and 4-2 for two examples relating to humans, and to humans, rats and dogs, respectively [EA, 1998]), depending on the specific biological endpoint and the organism, this may be used to provide operational definitions of high doses and, if delivered within, for example, 24 hours, high dose rates (*i.e.* $>(8 - 40)\ 10^3$ μGy h^{-1}).

Two additional points may be made. First, even at “low” dose rates (*i.e.* $<(8 - 40)\ 10^3$ μGy h^{-1}), a long-lived organism could accumulate a “high” dose if it were exposed continuously (*i.e.* “chronically”) throughout its life. Second, in situations where “high” doses may be accumulated over extended life stages, the incidence of stochastic effects may plateau due to the induction of cell killing. Experimental studies show, however, that due to the intervention of repair processes, the onset of the deterministic effects is displaced to higher accumulated doses (see Figures 4-1 and 4-2). This factor, which will almost certainly depend on the specific biological endpoint and the organism, will make it difficult to extrapolate information concerning the appearance of deterministic effects from the “acute” to the “chronic” exposure domain. It is interesting to note, however, that the data presented in Figures 4-1 and 4-2 show that, as the exposure is protracted (*i.e.* dose rate is lowered), the accumulated dose for a given degree of effect increases by 1 - 2 orders of magnitude. There are very few data in the database that relate directly to the chronic, low-level irradiation conditions of relevance for wild organisms, *i.e.* exposures at dose rates of 10 - 100 μGy h^{-1} over the life span of the organisms, and the response endpoints most commonly assessed after acute, high dose irradiation. This makes it difficult, therefore, to develop a robust basis for extrapolation between the two irradiation conditions.

Table 4-1 Approximate ranges of acutely lethal radiation dose, LD_{50}, Gy [EA, 1998].

Group of organisms	Adults	Other developmental stages	
Vertebrates			
Mammals	2 - 15	1.0	Mouse embryo
Birds	5 - 20	7.0	Chicken embryo
Amphibians	7 - 50	-	
Fishes	7 - 60	0.2 - 1	Salmon, trout and plaice embryos
Reptiles	10 - 40	-	
Invertebrates			
Crustaceans	15 - 600	6.0	Production of young amphipods reduced to 50%
Molluscs	100 - 1000	-	
Echinoderms	390	-	
Insects	20 - 3000	1.0 - 2	Weevil, fruit fly and wasp embryos
Higher plants			
Trees, shrubs and herbs	7 - 800	4.0 - 100	Tree seedlings
		0.7 - <100	Seed production cut to 50%
Primitive plants			
Mosses, lichens and algae	30 - 10000	-	
Aquatic blue-green algae	<400 - >12000 *	-	
Other aquatic algae	3 - 120 *	-	
Bacteria	50 - 10000	-	
Viruses	200 - 10000	-	

* LD_{90} in these cases.

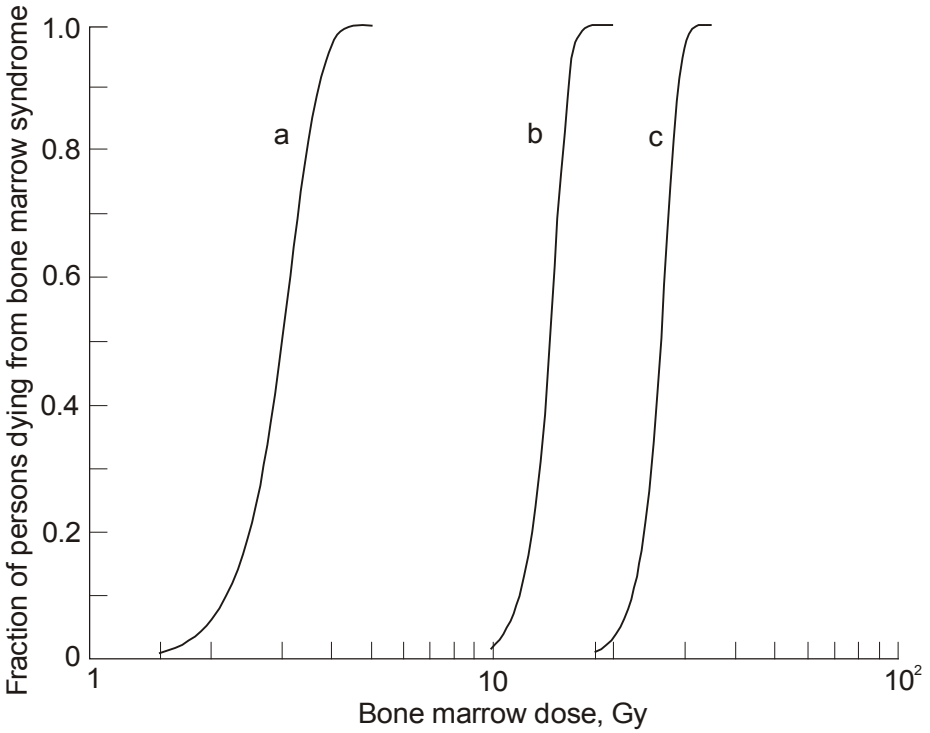


Figure 4-1 Predicted dose-response curves for human mortality due to bone marrow failure when the total dose is given continuously in (a) 1 day or less; (b) 3 months; or (c) 1 year. Reproduced from NRPB [1996] with permission..

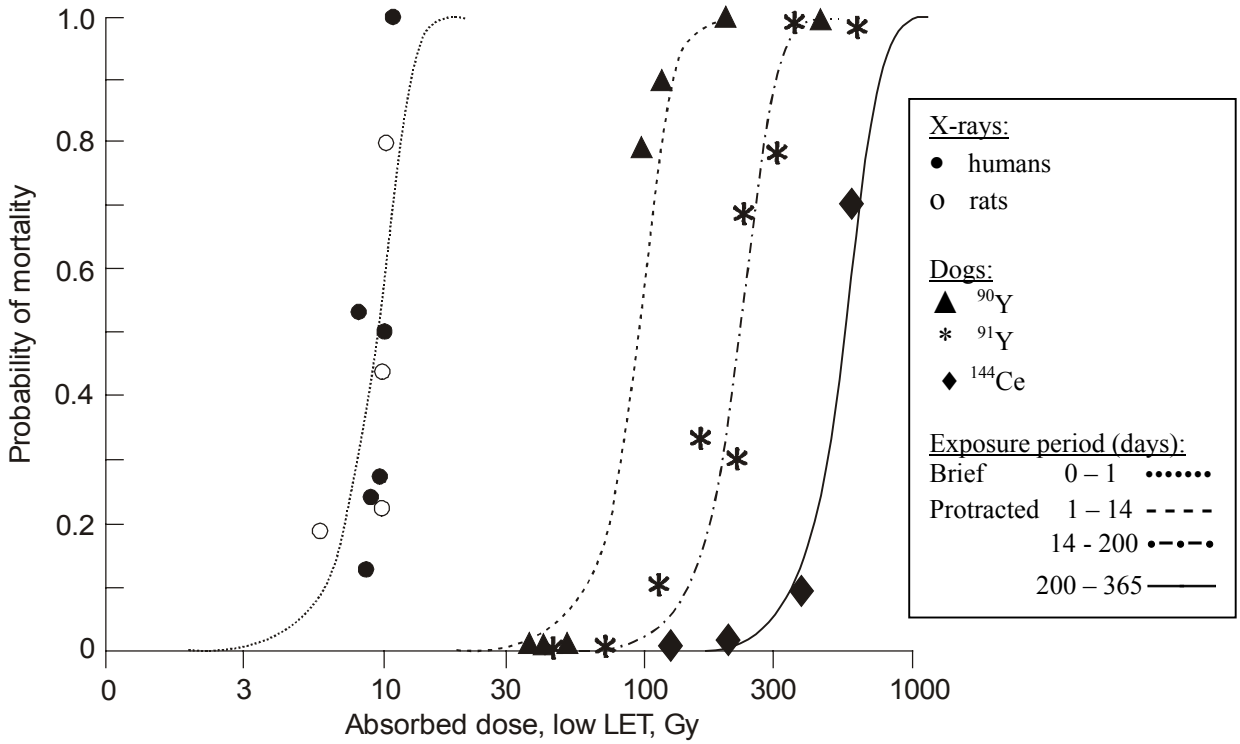


Figure 4-2 Relationship between protraction of lung dose and mortality. Reproduced from Scott and Hahn [1985], with permission.

In the context of the possible effects of radiation on non-human organisms, Rose [1992] has concluded the following.

This important point (*i.e. about the reduced effectiveness of low dose rate exposure as compared with acute, high dose rate exposure*) cannot be quantified for all organisms, but the following five references provide some indication of the degree of caution involved in assuming that an acute dose limit for radiosensitivity also applies to chronic irradiation:

- chronic exposures of fish in water containing radioactivity are approximately an order of magnitude less effective than acute exposures during the earliest and most radiosensitive embryonic stages of development [Kulikov *et al*., 1966];
- a single dose of 57 Gy to granary weevils reduces their survival from 97 to 5 days, but survival is totally unaffected when the same cumulative dose is given in 5 daily fractions [Jefferies *et al*., 1958];
- the ratios of acute to chronic daily dose for exposure causing a slight slowing of plant growth are about 10 for herbaceous and 60 for arboreal plants [Sparrow, 1966];
- somatic organs in mammals can tolerate chronic whole body exposures totalling 10 times the acute lethal doses that result in 50% mortality [Lorenz, 1954]; and,
- there is competition between injury and repair at low dose rates. A dose rate should exist (at least for somatic effects) at which repair processes keep pace with tissue injuries and chronic exposure produces no obvious ill-effects [Ophel *et al*., 1976]. (This comment does not apply to carcinogenesis where the effects are due to misrepair rather than failure to repair.)

Table 4-1 and Figure 4-3 indicate the approximate ranges of acutely lethal radiation dose for a number of types of organism, including many of those that have been selected as reference organisms for the FASSET system [EA, 1998]. Figure 4-4 gives a summary of some more detailed data indicating the relative radiosensitivities to acute irradiation of different endpoint in plants [UNSCEAR 1996]. Two points may be made: first, the data indicate that the vertebrate animals are amongst the most radiosensitive organisms; and, second, reproductive capacity is likely to be a more sensitive endpoint than adult mortality. There is a well-defined response to acute exposures in mammals. At doses below a threshold of about 1 Gy there is no apparent effect at the organism level, and certainly no acute lethality. This is because the natural defence and repair mechanisms can deal with the radiation damage occurring at the cellular level. As the dose increases, the probability of death rises slowly at first before accelerating rapidly and reaching unity at about 10 Gy. The main cause of death is the failure of the haematopoietic system due to deterministic damage to the blood-forming stem cells in the bone marrow and the response relationship is sigmoid in form (see Figure 4-1 illustrating the predicted human mortality from bone marrow failure following both acute and protracted exposures [NRPB, 1996]). The effects of extended exposure on the bone marrow response have been studied in a number of species including mice, guinea pigs, sheep, and pigs.

These data have been used to develop an approximate formula to predict the human response to chronic radiation exposure as a consequence of bone marrow damage by estimating the equivalent acute dose from the following formula [UNSCEAR, 1988]:

$$\text{Equivalent acute dose} = [\text{Dose rate to bone marrow (Gy d}^{-1}) \times \text{exposure period (days)}] - 1.5\ \text{Gy} - [0.1\ (\text{Gy d}^{-1}) \times \text{exposure period (days)}].$$

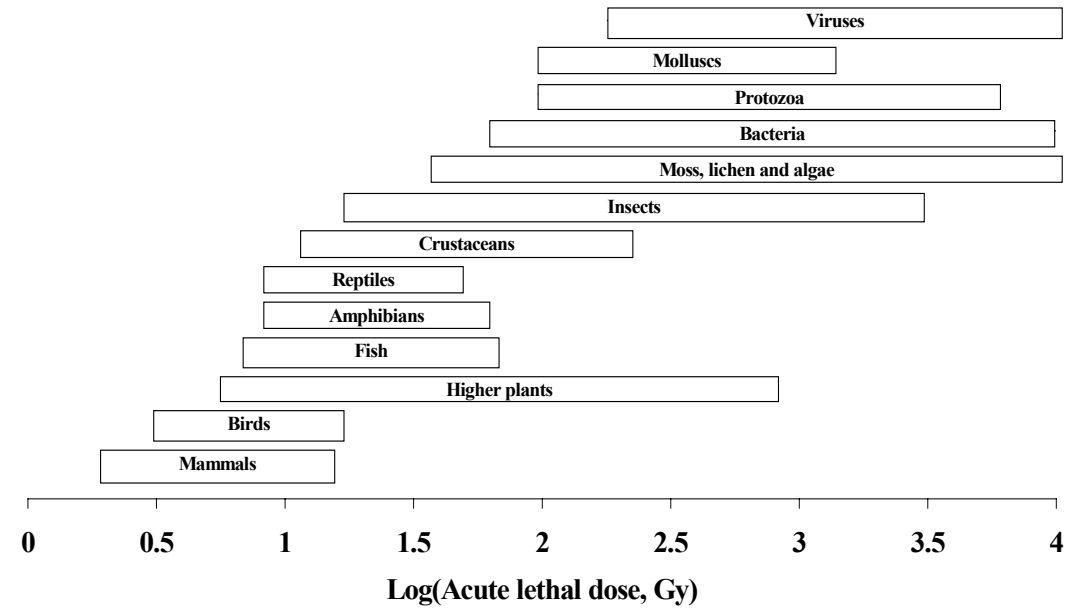


Figure 4-3 Approximate acute lethal doses for various taxonomic groups.

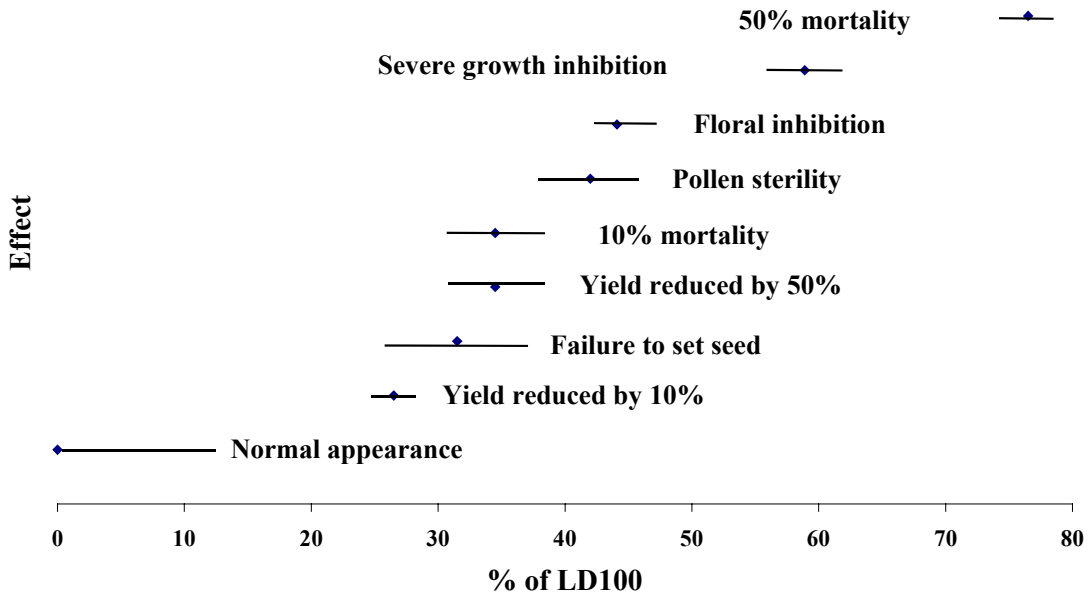


Figure 4-4 General summary of radiation response in herbaceous plants.

In this formula, negative doses have no meaning; the 1.5 Gy term indicates that there is effective recovery from this dose in the first day after an acute exposure; and the processes of repair and repopulation in the bone marrow can accommodate the effects of a dose rate of 0.1 Gy per day. A lethal dose of 5 Gy would, therefore, be accumulated in about 65 days at a dose rate of 0.2 Gy per day (8.3×10^3 μGy h^{-1}). The important point, however, is that this formula,

intended for application to humans but derived from non-human mammalian data, indicates that it is unlikely that there would be any mortality from deterministic effects in the bone marrow (or in any of the less sensitive cell systems) at dose rates less than about $4x10^3$ μGy h^{-1}. It may be conservatively assumed, therefore, that this would also not only apply to other mammals (see [UNSCEAR, 1988; Myers, 1989] for additional discussion), but also to the deterministic responses in other, less radiosensitive, organisms.

For stochastic effects, *i.e.* those for which the severity of the effect - cancer induction or heritable genetic damage - is independent of the dose but the probability of the outcome increases proportionately with the dose, it has been accepted practice to employ the linear, no threshold (LNT) hypothesis over the 0 - 1 Gy dose range. In human radiation protection, because the main evidence for the risk of cancer induction has been obtained from epidemiological studies the outcomes of the acute radiation exposures to the victims of the atomic bombing of Hiroshima and Nagasaki, it has been necessary to consider how these data might apply to low dose and dose rate situations. It has been concluded that the risk factors obtained from these epidemiological studies for low LET radiations must be adjusted downwards for lower doses and dose rates (the dose and dose rate effectiveness factor (DDREF)) [ICRP, 1991]. The Commission noted that the range of DDREF values obtained from animal studies was 2 - 10, but that a number of other factors indicated that the relevant value, for application in situations of human exposure to low doses and low dose rates, would be 2.

In a few cases for plants, there is sufficient information to indicate the sparing effects of lowering the dose rate on a number of relevant endpoints. Figure 4-5, adapted from the data given in [IAEA, 1992] shows how the accumulated dose required to induce 50% mortality in pine trees increases with decreasing dose rate and increasing duration of exposure.

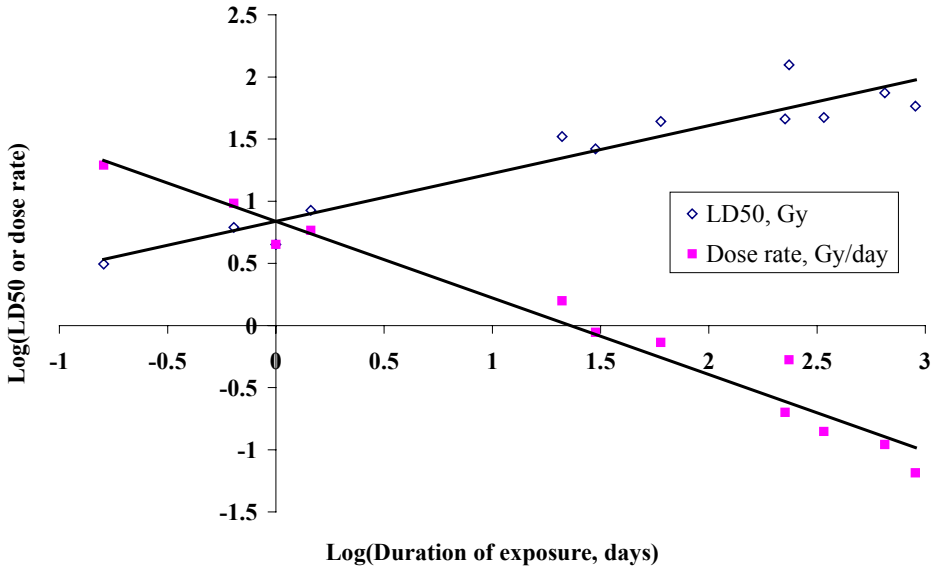


Figure 4-5 Relationship between duration of exposure, dose rate and total dose causing 50% mortality in pines.

Similarly, but at a higher level in the biological hierarchy, Figure 4-6 (a) and (b) show how the threshold total dose and dose rate for a significant change in the coefficient of community (a measure of the qualitative changes in species composition, *i.e.* the presence or absence of species) depend on the duration of exposure, at least for herbaceous plant communities (the data presented in Figure 4-6 were derived from Table 1 in [IAEA, 1992]).

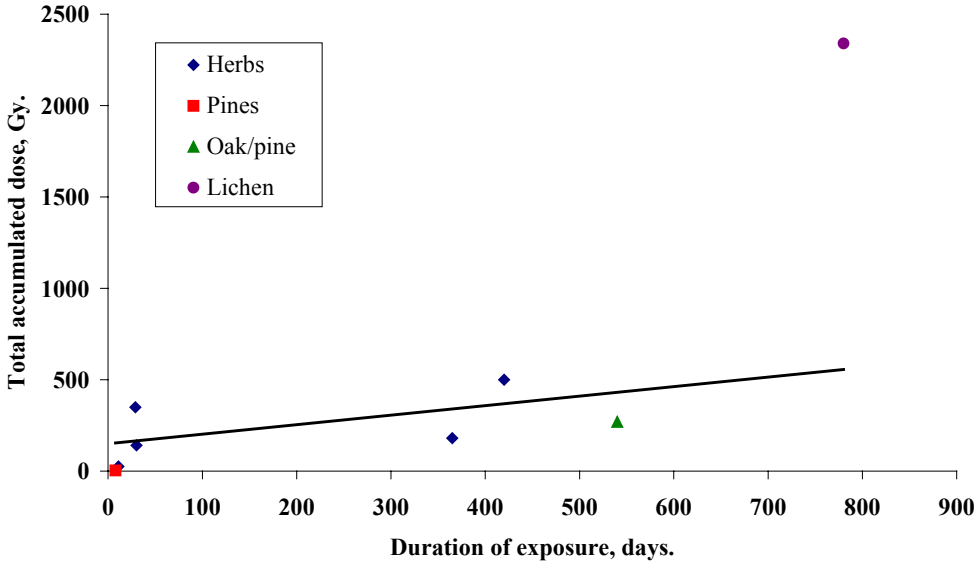


Figure 4-6(a) Estimated threshold total accumulated dose for an effect of chronic irradiation on the coefficient of community (CC).

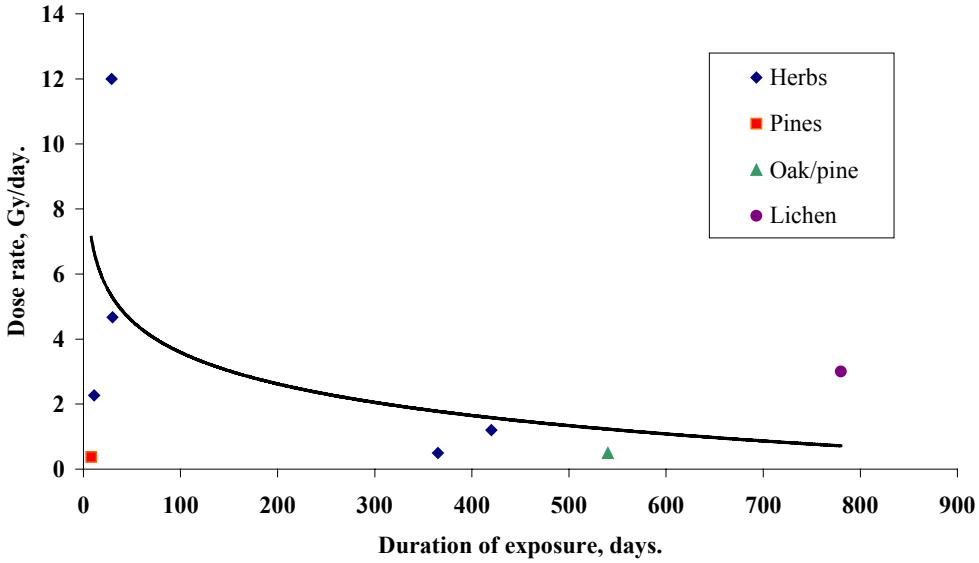


Figure 4-6(b) Estimated threshold dose rate for an effect of chronic irradiation on the coefficient of community (CC).

Notwithstanding the five references quoted by Rose [1992] and the additional evidence presented here concerning the reduced effectiveness of low dose rate, as compared with acute high dose rate, exposure, it remains the case that it is not possible to provide a simple or generalised procedure for extrapolating between the two exposure situations; each case would have to be carefully considered on its merits.

4.3 Extrapolations from the level of the individual to the population

Although the ultimate aim of environmental protection may be to protect natural populations and ecosystems (with due consideration of those that, for a variety of reasons, are given legislative protection as individuals, *e.g.* endangered species), there is a dilemma in that, as the ecological relevance of an experimental system increases, so does the complexity of the system, and, correspondingly, the difficulty in assessing or measuring the response(s) to a stressor. This is why toxicological investigations most often focus on simpler systems, or on lower levels of the biological hierarchy, such as endpoints at the cellular, tissue or individual level; these are, by far, the most common toxicity data currently available. An attempt must then be made to extrapolate these effects data from individuals to populations and the higher levels of organisation.

Many studies have documented the effects of radiation at the cellular, tissue and individual levels, and the likely consequences have been found to be increases in morbidity and mortality, decreases in fertility and fecundity, and increase in mutation rate [Woodhead, 2003]. These are the four FASSET umbrella endpoints that are presumed to aggregate all of the radiation effects observed at the individual and lower levels, and for which a great deal of information can be found in FRED. Ionising radiation does not appear to have any direct effects at the population or higher levels in the biological hierarchy, *i.e.* all such effects are mediated by effects at the individual, or lower, levels. It is difficult, therefore, to see how criteria to protect the population or ecosystem, related directly to population or ecosystem level attributes, could be developed from the available information. If, however, protective controls were to be applied at the level of the individual, for which information is available, the question immediately arises - are these sufficient to provide an acceptable degree of protection for the population, species, etc.? Can these data relating to individuals be extrapolated to higher levels of organisation?

Extrapolation of the effects of toxicants from a limited number of test species to whole ecosystems is an essential part of environmental risk assessment. One of two approaches is generally taken for non-radioactive contaminants, depending on the data available.

The safety factor method. This method is widely used when there are limited data and toxicity test results are available for very few species. The lowest concentration value from toxicity tests, frequently a no-observed-effect concentration (NOEC) for mortality, is derived and divided by an application factor (or safety factor) that varies from 10 to 1000 depending on the endpoint. This safety factor is meant to take into account the shortcomings of the data. In ecotoxicological risk assessments, the safety factor is used for extrapolations from acute to chronic exposure, from lethal to sub-lethal effects, and from one or two genera to a larger number of genera at different trophic levels. If more than one literature value is available for a species, the lowest one is usually taken [Forbes *et al*., 2001; Larsson *et al.*, 2002].

Distribution based method. When NOEC values are available for a larger number of species, representing a wide spectrum of genera, distribution based extrapolation models may be used. The NOECs are then used to estimate the parameters of the distribution; this, in turn, is used to estimate the toxicant concentration at which the NOECs for a specified percentage of the species (usually 95%) is not exceeded. This concentration is considered to be protective with respect to the ecosystem [Forbes *et al*., 2001; *Larsson et al.*, 2002].

Extrapolations are associated with a large number of assumptions and uncertainties, and there are several issues that need to be carefully considered, for example:

- different stages in the life cycle of an organism can be differentially sensitive;
- the radiation sensitivity and sensitivity of a specific life history trait for population growth can differ;
- differences in life cycles between species can affect extrapolations to the population level. For example, a 5% reduction in juvenile survival of species x can have the same effect on population growth as 80% reduction in juvenile survival in species y (see example below);
- density dependent factors; and,
- assessing risks of effects on the structure and function of the ecosystem.

4.3.1 Different life stages of organisms

As demonstrated by the data in Table 4-1 and Figure 4-3, the various life stages of organisms are differentially sensitive to ionising radiations, and it is often assumed that the population will be protected if the most sensitive stage of the life history is protected. This assumption seems to be true in most cases [Forbes and Calow, 2002; Larsson *et al.*, 2002]. However, the most sensitive life stage is often difficult to identify *a priori*. Consequently, if effects data only exist for one or two life stages, it is hard to know if these data represent information on the most sensitive life-stage (even though the greater part of the available information indicates that gametogenesis and embryonic development are among the most radiosensitive stages of the lifecycle). In any situation where the most sensitive life stage has not been positively identified, or there is a lack of data (this would be the case for organisms that are not represented in FRED), there seems to be a need to introduce a margin of safety (*i.e.* the use of safety factors) when using the available dose-effect information on the umbrella endpoints to develop measures to protect field populations.

Furthermore, the most radiosensitive life stage of a species might not necessarily be the most important stage for maintaining population viability. For example, in species that produce a large number of offspring, *e.g.* most bivalve molluscs, contaminant effects on later stages of the life cycle will actually be more significant for the maintenance of the population. For populations of such species, a 10% reduction in survival of juveniles due to radiation may have little effect on the population, whereas a 10% increase in mortality in the adult stages may have a great impact (but, in general, not more than 10%). If effect assessments are performed for this type of species, estimates of population effects based on effects on embryos and larvae (usually assumed, together with gametogenesis, to be the most sensitive life stages) may lead to measures providing a reduced level of protection; the actual outcome of this assessment is, however, very dependent on the degree of exposure experienced by each life stage and the consequent effect. Since the relationship between effects on individual life

history traits and population effects are, in general, proportional or less than proportional (see below), there does not seem to be any major risk that this discrepancy between the radiation sensitivity of various life stages and population sensitivity will introduce a reduced protection level for the population. Rather, the major problem seems to be to identify the most sensitive life stage, or, by use of safety factors, ensure that the most sensitive life stage is protected (as discussed above). An alternative, and probably the most robust, way of assessing population level impacts seems to be the approach of integrating the effects on various life history traits via population growth rate analysis. In most cases, however, this will not be possible in practice due to the lack of relevant information.

4.3.2 Effects of different life cycles on extrapolating individual effects to populations

Different species have different reproductive strategies and life cycles, and may, therefore respond differently to the same degree of radiation effect on reproductive capacity and survival. Forbes *et al*. [2001] considered the life cycles of the test species most widely used in ecotoxicological studies, and estimated the proportional decline in population growth rate resulting from a decline in juvenile survival using a simple two-stage demographic model. Figure 4-7 illustrates effects of the different life cycles of the typical species of green algae, fish, daphnids and benthic invertebrates, on population growth rate (λ). A reduction in juvenile survival had very different effects on the population growth rate, dependent on the life cycle parameters. A 10% reduction in juvenile survival was found to result in reductions of 10%, 5%, 2% and 0.6% in λ for, respectively, a benthic invertebrate, a green algae, a fish, and a daphnid. A 5% reduction in juvenile survival for the benthic invertebrate life cycle would have the same effect on population growth rate as an 80% reduction in juvenile survival for the daphnid life cycle [Forbes *et al*., 2001; Forbes and Calow, 2002].

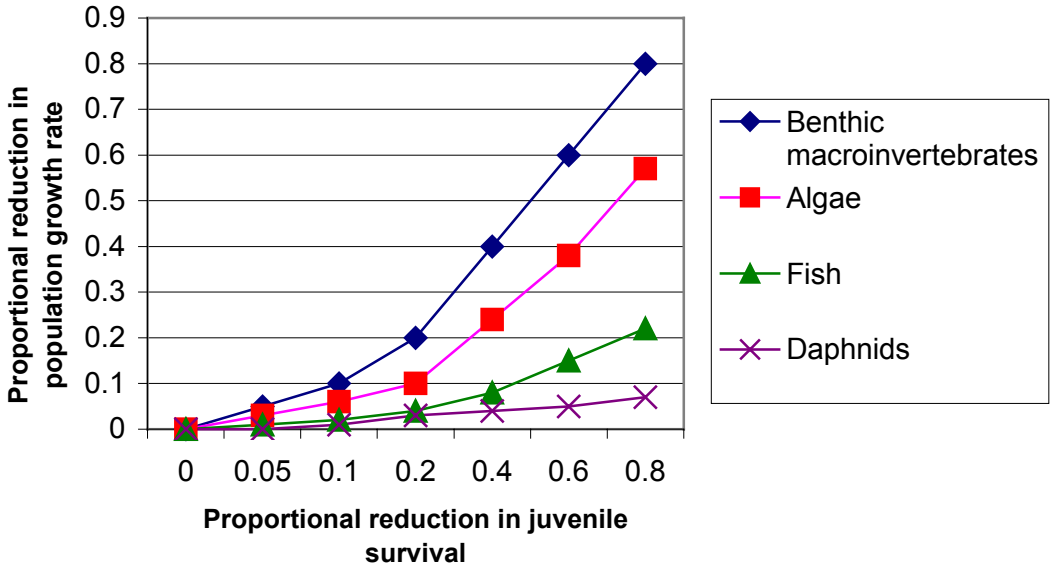


*Figure 4-7 Proportional reduction in population growth rate (λ) resulting from a given proportional reduction in juvenile survival for different life cycle types (*from Forbes *et al.*, 2001*).*


The degree to which the responses of the individual demographic traits overestimated the impacts on population growth rate varied widely among life cycle types, and shows the importance of taking the life cycles of the particular species into account when extrapolating effects from individuals to populations.

4.3.3 Density dependent factors

Most ecotoxicological tests and, presumably, most studies of the effects of ionising radiation are performed under non-limiting growth conditions (*i.e.* sufficient food and space are available). In contrast, wild organisms are often regulated by varying degrees of density dependence through various types of competition at the different stages of their life cycle. Therefore, there is concern that conclusions drawn from toxicity tests can have low relevance for field populations. In most cases, the density dependent factors (*e.g.* decreased juvenile survival at higher population densities) seem to imply that toxicity tests performed at low densities tend to overestimate toxic effects at higher densities. But theoretical and empirical studies have also indicated that the opposite can be true (*i.e.* more severe effects at the population level) [Forbes *et al*., 2001]. Based on current knowledge, therefore, it is hard to draw general conclusions on how density dependent factors may influence the extrapolation of effects data from individuals to populations. The lack of a general understanding of this issue must be borne in mind when using FRED.

4.3.4 The Leslie matrix population model approach

Woodhead [2003] has developed a Leslie matrix population model approach to investigate how the effects of radiation on individuals may propagate to produce (or not) a response at the population level. It has been applied to two fish species with somewhat contrasting life cycles and reproductive strategies - the plaice (*Pleuronectes platessa*) and the thornback ray (*Raja clavata*). The results from the models appear to confirm the relative sensitivities of the two populations, as might have been predicted on the basis of their life cycles and reproductive strategies, to possible effects of radiation on individual fertility, fecundity and mortality. The female plaice can produce thousands of eggs, while the thornback ray produces fewer (but more protected) eggs and more highly developed neonates. Although the model, as currently implemented, probably lacks full biological realism, it has generated some interesting and useful information. It appears that rather small radiation-induced reductions in egg production and embryonic survival, and increases in age-dependent mortality could aggregate to produce significant effects at the population level.

An advantage of the Leslie matrix model for investigating the effects of radiation is that the major parameters required to run it relate precisely to those attributes of the individuals in the population that are affected by irradiation, *i.e.* their fertility, fecundity, morbidity, and mortality. Also, once the model has been set up, it is very easy to use it in an experimental mode, *i.e.* to change the individual model parameters and see immediately how the population responds.

4.3.5 Effects of DNA damage on the population level

At low doses, one of the main concerns about ionising radiation is, perhaps, that it may, by inducing damage to the DNA, cause heritable genetic effects (genetic effects are assumed to be included in the umbrella endpoints of morbidity and mortality). Mutations occur at the


molecular level, but it is important to keep in mind that there are emergent effects at the level of the population. Heritable mutations in germ cells are capable of affecting the genetic diversity of populations, and can lead to increased or decreased genetic diversity, as well as changes in phenotype that can affect Darwinian fitness. Increases in mutation rate can increase genetic diversity of the population by producing new alleles or genotypes, but they can also result in decreased genetic diversity, since the mutations could reduce the viability or fertility of the individuals [Theodorakis, 2001]. Consequently, increases in mutation rate can affect the population genetic structure, and thereby have ecologically relevant effects. It is, however, no simple matter to extrapolate individual mutations to effects on the genetic structure of populations and further to the viability of the population.

4.3.6 Assessing risks of effects on the structure and function of the ecosystem

The task of extrapolating the possible effects of toxicants from the available information for a limited number of test species to ecosystems is an essential part of ecotoxicological risk assessments (*e.g.* using species sensitivity distributions). The models used to perform this type of extrapolation suffer, however, from a number of weaknesses. Apart from the recurring problem that the species chosen for toxicity testing are often neither representative, nor even members, of the ecosystem of interest, there is much evidence that toxicity tests are biased towards the tolerant end of the species-sensitivity distribution of the ecosystem. This bias is to a large extent caused by the choice of relatively tolerant or robust species for toxicity testing under laboratory conditions, but selection towards genetic and phenotypic similarity among individuals in the organisms maintained within laboratories might also be a significant problem. Furthermore, these extrapolations usually consider only the direct toxic effects and not indirect effects mediated by trophic interactions via the food-web. Even though these indirect effects are probably less important than direct toxic effects, they may still be significant for some pollutant-community interactions. In theory, it should be possible to use the effects data from FRED to perform this type of extrapolation. In practice, it is likely that the incorporation of additional margins of safety through safety factors would be the means of counteracting both lack of knowledge on the representativity of the available effects data, as well as lack of knowledge on indirect effects.

Effects on the functioning of essential processes (*e.g.* nutrient cycling) of an ecosystem are generally thought to be brought about by changes in its structure (*e.g.* species composition). Consequently, protection of species will protect functions. The presence of key species, or low species diversity within functional groups (*i.e.* low functional redundancy), may result in severe functional effects if such especially important species are affected. If key species have been described in a specific ecosystem, this knowledge should be used to increase the reliability of the assessment, especially in site-specific assessments. In most cases, however, the identity of such keystone species will not be known. The vital objective, therefore, should be protection of species in general so that the key species are not lost.

4.4 Possible implications for the FASSET framework

Although there is abundant evidence that the low dose and dose rate, chronic radiation exposures expected to prevail in environments contaminated by authorised releases of radionuclides will be generally less damaging than the high dose and dose rate conditions often employed in laboratory studies, there is not a well-based, and generally applicable, method for extrapolating the available data between these contrasting conditions. The more


limited experimental data pertaining to chronic, low dose rate exposures in FRED must form the primary basis for assessments.

There is abundant evidence that there are substantial variations in the radiosensitivities of organisms both within, and between taxonomic groups; this differential sensitivity also extends to different stages of the life cycle for any given organism. A general, but probably not universal, conclusion might be that the highest radiosensitivity might be exhibited by the umbrella attribute of reproductive capacity, including fertility (gametogenesis) and fecundity (embryonic and larval development) in the class *Mammalia*, or perhaps more generally in the order *Vertebrata*. The caveat on the universality of this conclusion arises from the fact that many types of organism, *e.g.* the corals, are not represented in the radiation effects database. Nevertheless, the development of measures to protect populations of organisms based upon the information available for reproduction in the mammals (or more generally, the vertebrates) should, taking due account of estimates of the actual radiation exposures experienced by a representative variety of organisms (including the different life stages, taxa and habitats), be conservative.

The available information and understanding concerning the effects of radiation in individual organisms, and its integration into assessments of effects at the population, and higher, levels of the biological hierarchy, appears to indicate that measures intended to limit radiation damage in individuals to an acceptable degree will also provide a sufficient degree of protection for populations, communities and ecosystems.

5. Effects of other environmental stressors

5.1 Background

All wild plants and animals are adapted to their environment, *i.e.* their genotype has been moulded by natural selection so that the resulting phenotype can operate efficiently, *i.e.* pass on its genes to subsequent generations, in the ambient range of varying environmental conditions that is normally encountered. This is not to say that there is a single, environmentally appropriate genotype or phenotype - some degree of heterozygosity and phenotypic variation is the norm. For each species, however, there will be a relatively small range of any given environmental variable that is optimal, *e.g.* temperature, insolation, soil type and nutrient status, and rainfall for terrestrial plants, and temperature, water chemistry and salinity for aquatic organisms. It has been shown that the acute radiation sensitivity is likely to be increased when plants, small mammals, or fish are additionally stressed by the occurrence of environmental conditions outside the optimal range [211][147]. While it may be presumed that similar interactions will arise between low-level, chronic irradiation and environmental factors, this has not yet been convincingly demonstrated.

It is well known that the biological effects induced by ionising radiation may become apparent at all levels in the biological hierarchy from the DNA to the whole organism. Genotoxic, cytotoxic and higher level damage is not specific, however, to ionising radiation but may also be initiated by other environmental variables, including toxic contaminants [Sugg *et al*., 1996]; there is not, at present, an unambiguous biochemical or biological indicator of radiation exposure. Available information indicates that the radiation exposures of a variety of organisms in environments contaminated by authorised releases of radionuclides is generally less than 100 μGy h^{-1} and very occasionally up to 10^3 μGy h^{-1} [211]. According to the generalised classification of the biological responses to all magnitudes of radiation dose rate proposed by Polikarpov [238], these chronic irradiation conditions largely correspond to the so-called “physiological masking zone” or the “ecological masking zone” (*i.e.* between 0.4 - 4 μGy h^{-1}, and 4 - 460 μGy h^{-1} respectively). In the lower range of dose rates, any response to the incremental irradiation from the contaminant radionuclides is likely to be masked by the natural variability in physiological status of individual organisms. In the upper range of dose rates, there are likely to be some effects of radiation in sensitive individual organisms, but these will be masked at the population level by the natural variability induced by the random fluctuations in environmental conditions and seasonal changes. All these factors make it difficult, if not impossible, to detect radiation impacts with any degree of certainty in environments contaminated by managed releases of radioactive wastes.

In addition to the natural environmental factors, it is also necessary to consider the possible influence of the various kinds of non-radioactive contaminant, or other insults of human origin (*e.g.* increases of temperature from waste heat releases), that may qualitatively or quantitatively modify the biological effects induced by ionising radiation from radionuclides released to, or present within, the biosphere. Such stable contaminants include the heavy metals and organic micropollutants, and their interactions with radionuclides, and with the concomitant radiation exposure, have not been extensively investigated for non-human biota. In this context, two separate, but connected, influences may be distinguished:

- The effect of co-exposure to the non-radioactive contaminants or other insults on the bio-accumulation kinetics and internal tissue distributions of a radionuclide. This may

influence the bio-kinetic parameters used within a radioecological assessment model for a radionuclide [see Larsson *et al*., 2002] and the estimates of the consequent radiation exposure of the non-human organisms; and,

- The possible modifying influence of co-contaminants or other insults on the biological effects induced by the exposure to ionising radiation.

5.2 Experimental and field evidence for modifying factors of the radiosensitivity of living organisms

5.2.1 Natural environmental factors

The interactions between some environmental factors and acute ionising radiation have been demonstrated in the 1960s - 70s. Several authors reported modifications of the survival and metabolism of test organisms showing results as a function of the type and doses of radiation, the tested environmental factors, the tested species, the duration of the experiment, etc. Angelovic *et al*. [147] reported from a bibliographical survey that an increase in temperature at the time of irradiation or after irradiation produces a greater sensitivity in different types of organisms: *Artemia*, *Tetrahymena pyriformis*, *Fundulus heteroclitus*, and *Carassius carassius*. Low temperature protects against radiation damage by slowing metabolism. Radiation damage appears in a shorter time at higher temperatures due to increased metabolic activity. Carrying out experiments with postlarval pinfish (*Lagodon rhomboides*), White and Angelovic [35] reported that a particular combination of radiation dose and temperature (0.83 rad/h (8.3 mGy h^{-1}) x 15°C), produced a heavier and deeper bodied fish and suggested that stimulation of growth could be a possible explanation. Similar effects have been reported for salmon [265] and blue crab [314]. Angelovic *et al*. [147] assessed the interactions of salinity, temperature, and ionising radiation (acute gamma irradiation) as environmental factors affecting the mortality, LD_{50}, and ^{22}Na efflux of the euryhaline fish, *F. heteroclitus.* All factors had a significant effect on mortality of the fish. At the upper end of their temperature range, the fish tolerated more radiation at low salinity. At the lower end of their temperature range this tolerance was reversed. Irradiated fish generally lost ^{22}Na more rapidly than unirradiated fish, suggesting the lethal effects of radiation may stem from damage to osmoregulatory capabilities. They concluded that interactions might be caused by radiation-induced changes in oxygen uptake, and Na uptake and excretion. Irradiated rainbow trout appeared to have a less efficient uptake of Na, implying damage of the Na active transport system [Neuhold and Sharma, 1967]. Engel *et al*. [1974] reported that the degree of radiation damage to ionic regulation in the blue crab (*Callinectes sapidus*) exposed to acute irradiation (10000 rads (100 Gy)) was influenced by the environment of the organism, both before and after the irradiation. They reported that radiation interacted with these two variables to cause alterations in ionic regulation such as an increase in Na, K and Cl in the hemolymph even at low salinity. Radiation might induce damage to the active transport system into the hemolymph. Salinity and temperature also affect the survival of irradiated brine shrimp [Angelovic and Engel, 1970].

For phytoplankton (*Chlamydomonas)*, thermal shock associated with acute ionising irradiation (50 to 400 krads (500 to 4000 Gy)) decreased ^{14}C uptake at a rate greater than that expected from thermal shock only [Grayum, 1971]. For tree species, it has been proved that radiosensitivity was not constant and varied with water content. This latter increases seed


radiosensitivity indirectly by affecting the rate of physiological activity in these species [Heaslip, 1961].

5.2.2 Non-radioactive contaminants

The majority of biochemical techniques for detecting DNA damage at the molecular or cellular level lack specificity for radiation induced DNA damage [Tice and Strauss, 1995]. However, Tsytsugina [1998], and Tsytsugina and Polikarpov [2003] proposed an analysis of the distribution of chromosome aberrations in cells, and of the frequency of the different types of aberrations, to discriminate between the contribution of radioactive and chemical factors to the total damage to natural populations of aquatic organisms. Using these indicators of radiation effects, these authors showed that the chromosome damage observed in aquatic worm populations exposed to 10 $\mu Gy.h^{-1}$ or more in lakes located in the vicinity of the Chernobyl Nuclear Power Plant was mainly caused by radioactive pollution.

Field studies have been carried out in various locations in the vicinity of the Chernobyl site [Sugg *et al*., 1996] and the Savannah River site [Sugg *et al*., 1995; Lingenfelser *et al*., 1997] to investigate possible causal relationships between genetic effects and exposure to particular pollutants. These studies have been devoted to populations of aquatic organisms inhabiting various contaminated sites with a range of concentrations of both radionuclides and stable chemicals (*e.g.* PCBs, heavy metals – As, Hg, Pb, etc.). These few studies have showed that genetic damage was associated with chemical and/or radiation exposure although interactive relationship could not be identified. Comparing fish populations from several chemically and/or radioactively contaminated ponds at the Savannah River Site, Sugg *et al*. [1995] reported that largemouth bass (*Micropterus salmoides*) inhabiting the contaminated ponds had more DNA strand breaks than fish from reference sites. Lingenfelser *et al*. [1997] carried out field studies on over 3000 specimens of the same fish species collected from various locations in Georgia and South Carolina to evaluate the potential genetic impacts but could not determine the relative contributions from stable and radioactive toxicants. They reported that DNA content tends to be more variable in fish populations residing in contaminated areas as compared with fish from control zones (*i.e.* relatively uncontaminated aquatic systems). For catfish from the Chernobyl cooling pond, Sugg *et al*. [1996] reported that fish exhibited an amount of DNA damage that increased with the concentration of radiocaesium in individuals. More recently, Dallas *et al*. [1998] collected four species of fish, channel catfish (*Ictalurus punctatus*), crucian carp (*Carassius carassius*), common carp (*Cyprinus carpio*) and tench (*Tinca tinca*) from waters within a 10 km radius of the Chernobyl Nuclear Power Plant, and compared their DNA with that from reference populations from two uncontaminated locations far removed from the plant. Abnormal DNA distributions were observed in several of the fish from Chernobyl relative to the reference populations. In addition, Matson *et al*. [2000] and Baker *et al*. [2001] investigated the possible genetic and population effects resulting from the chronic radiation exposure of bank voles, *Clethrionomys glareolus*, inhabiting contaminated sites near Chernobyl. In both cases, it was reported that genetic diversity was elevated at the contaminated sites when compared with relatively uncontaminated sites, but, based on these data, it has not been possible to identify any significant detrimental effects in the bank vole populations inhabiting the contaminated Chernobyl environment. Even though this finding seems paradoxical (among mammals, bank voles from the contaminated areas are characterised by the highest radiocaesium body burdens and external dose rates), Baker *et al*. [2001] concluded that several additional factors, including other contaminants, may be affecting the population genetic dynamics both spatially and temporally.


Finally, it may be suggested that the application of biodosimetric (cytogenetic-structural chromosomal aberrations) techniques, as proposed by Ulsh *et al*. [2000, 2003], could be a useful tool for the assessment and quantification of genetically relevant damage in a variety of non-human species, and may also provide a means to investigate and understand the possible interactions between stable contaminants and ionising radiation.

5.3 Potential interactions between radioactive and non-radioactive contaminants

The cellular damage generated by irradiation is mainly associated with oxidative damage due to the formation of several types of oxygen free radicals by radiolysis of water in cells. This oxidative stress may also be caused by other stressors, such as chemical pollutants, and cellular defence mechanisms that may be induced against ROS (reactive oxygen species) are not stressor-specific [Sato and Bremner, 1993]. Interactions between heavy metals and radiation, with a consequent modification of radiosensitivity, may occur, depending on the capability of the antioxidant defence systems in the organism. Recently, some studies from human radiobiology, reviewed by Cai *et al*. [1999], have focused on the protective role of metallothioneins (MT) against DNA damage caused by chemical stressors, such as cadmium for example, and radiation. The MT that exist in various animal tissues are low molecular weight (about 6-7 kDa), cysteine-rich (30%) intracellular proteins having a high affinity for both essential (Zn and Cu) and non-essential (Cd and Hg) metals. In addition to their role in the sequestration of potentially toxic heavy metals, and in regulation of the homeostasis of essential trace metals, MT can also act as antioxidants and a free radical scavengers [Sato and Bremner, 1993; Viarengo *et al*., 2000]. The presence of MT may, therefore, provide protection from radiation-induced genotoxicity and/or cytotoxicity. In their bibliographical review, Cai *et al*. [1999] emphasised that experimental work had provided evidence for both induced synthesis of MT, and a protective role for MT against free radicals during radiation exposure. However, all the studies have been carried out on rodent experimental models or cells in culture, with high doses of ionising radiation. These experimental conditions make it difficult to extrapolate these results to low level or repeated exposures to radiation in non-human biota. In addition, the induction of MT has been suggested as one of the mechanisms for the adaptive response to low dose ionising radiation exposure where it may act as a free radical scavenger [Cai and Cherian, 1996]. It is unclear, however, whether radiation itself can induce MT synthesis directly, or whether these effects are secondary due to the formation of free radicals or release of cytokines. Cai *et al*. [1999] concluded that more work would be needed to understand the potential role of MT in the adaptive response. More recent results from Cai *et al*. [2003] have suggested that MT, particularly when bound to zinc, is a high-capacity antioxidant that protects against radiation-induced DNA damage.

6. Conclusions and recommendations

6.1 Introduction

The major objectives of this work package have been to provide the tools for an analysis of the possible radiation effects within a system for assessing the impacts of radiation on the organisms in an environment that is, or may become, contaminated with radionuclides through human activities. Specifically, the effects analysis must:

- be relevant for the protective aim - usually to maintain population viability, but may also include protection of endangered species at the level of the individual, so that any incremental radiation exposure does not provoke changes, over and above those occurring naturally, in ecosystem structure and function;
- be manageable, *i.e.* the available information must be organised so that it can be applied for the purpose of an impact assessment and, just as importantly, identify where there are major deficiencies in relevant data;
- identify the relevant biological effects for assessing the impact (the relationship between exposure and effect); and,
- identify the severity of the effects at differing levels of exposure (the relationship between the extent of exposure and the degree of response).

6.2 The protective aim

In terms of protecting the environment, an early decision was made to concentrate on the effects of increased radiation exposure on the plants and animals. This was based on the prevailing understanding that, although an ecosystem is an integrated, but varying, totality of the abiotic and living components, the effects of ionising radiation on the former are only apparent at dose rates far above those that are relevant for protection purposes. In addition, if the presence of contaminant radionuclides were to be considered an environmental effect *per se*, any limits on their concentrations (above zero, that is) would have to consider the possible impacts of the resulting radiation emissions on the living components of the ecosystems.

While the primary aim in the protection of the living components of an ecosystem might be the maintenance of viable populations, with due note being taken of individuals of endangered or otherwise valuable species, a number of factors nevertheless forced the primary focus to be placed on the possible effects in individual plants or animals.

First, it was not possible to identify any effect at the population level that was not mediated by the effects of radiation in the constituent individuals (it was accepted that indirect effects might occur in a population of a less radiosensitive species if they were dependent, *e.g.* in a predator-prey relationship, on another, more radiosensitive, species). Such an outcome is not particularly surprising in view of the fact that the initial consequence of radiation interaction with an organism is the ionisation of a small number of its constituent atoms.

Second, virtually the whole of the radiobiological literature relates to effects in individual organisms, or in lower levels of the biological hierarchy, *e.g.* DNA, the cell, etc. Although some of these latter effects, *e.g.* chromosome aberrations, are often sensitive indicators of radiation exposure (amongst others), there is rather little information concerning the


implications of such damage for the host individual. That is, experiments rarely attempt to correlate a response in a sensitive endpoint with the response of the individual, or, more realistically, determine what effect occurs at the chromosomal level in an individual that is showing some higher level radiation response. Similarly, there have been very few attempts to examine the effects of radiation on populations in terms of strictly population properties, *e.g.* age distribution, age-dependent birth rate, age-dependent death rate, etc., and, just as importantly, correlate these responses with the effects that are happening at the level of the individuals.

It became clear that the effects of radiation are better understood in the individual and also that, in principle, they could be more easily controlled at this level in the biological hierarchy. It was also difficult to see how, in the absence of direct information on radiation effects at the population level, criteria could be developed for their protection.

6.3 Organisation of effects data

An initial search of the radiobiological literature indicated that there was a very substantial amount of radiation effects data related to very many different species, endpoints, and radiation regimes, and that it would be impossible to review it all. Some of these data had, however, previously been reviewed in the context of effects in contaminated environments, and this provided a starting point for the collation of relevant information.

Given the factors outlined in Section 6.2, it was concluded that the information on radiation effects in individuals should be summarised in such a way that it was directly relevant to possible responses at the population level. To this end, four "umbrella" categories of radiation effects were identified, *i.e.* morbidity, mortality, reproductive capacity and mutation. It was recognised, however, that these categories were not mutually exclusive in their implications, particularly in the natural environment, *e.g.* a morbid individual might die earlier than otherwise, and this early mortality could affect its lifetime reproductive capacity, and mutations can affect reproductive capacity and the fitness of descendents. Nevertheless, these categories were accepted as a useful means for summarising the available data.

Equally, it was not considered helpful to attempt a summary of the data at the level of the species, although this might be possible for certain types, *e.g.* the mouse or rat. Rather, it was concluded that the data should be aggregated by wildlife groups that related to the types of organisms for which an assessment might be regarded as necessary in the European context, *i.e,* the reference organisms defined by Strand, *et al*. [2001]. This approach led to the general categories as set out in Table 2-2 together with their relationship to the reference organisms. Within each grouping, however, the information concerning the species studied was retained.

Finally, it was recognised, as already noted, that the studies had employed a wide variety of irradiation regimes. Some, employing high doses at high dose rates (usually termed acute), appeared to have a rather tenuous connection with the usual situation in an environment contaminated with radionuclides released under regulatory control, *i.e.* continuing low dose rate exposure over all, or a large fraction, of the lifespan of the organisms (see Chapter 3). It was concluded, therefore, that the information should be categorised by the irradiation conditions - acute, chronic or transitory - whilst retaining the available information relating to dose rate, total dose, radiation type, and the nature of the source - internal or external.

These considerations led to the conclusion that the best approach to the collation of the data would be to develop a database that could be interrogated to generate summaries according to


wildlife group, umbrella endpoint, and in user-defined ranges of total dose or dose rate. The details are set out in Chapter 2 and a copy of the database, together with the operating instructions, is included with this report.

6.4 Dose effect relationships

The results of interrogating the database are also given in Chapter 2, together with some brief discussions of the information in the context of environmental impact assessment. It is immediately apparent from the summary Tables 2-4 to 2-13 that there are many areas where the available information is deficient, *i.e.* there are no, or very few, data. This is particularly the case for information concerning the effects of low dose rate, *i.e.* $< 10^3$ μGy h^{-1}, chronic exposure that would be directly relevant to an assessment of a waste management situation [see UNSCEAR, 1996].

The fragmentary nature of the available, and relevant, information has made it very difficult to develop the desired dose rate - response relationships in any detail. Some very broad and general conclusions may, however, be drawn:

- although minor effects may be seen at lower dose rates in sensitive species and systems, *e.g.* haematological cell counts in mammals, immune response in fish, growth in pines, and chromosome aberrations in many organisms, the threshold for statistically significant effects in most studies is about 10^2 μGy h^{-1}; the responses then increase progressively with increasing dose rate and usually become very clear at dose rates $>10^3$ μGy h^{-1} over a large fraction of the life-span;

- there are, however, some data that do not fit too comfortably within this broad generalistion, *e.g.* the effects of tritium β-radiation on the developing immune response in fish embryos, on the developing goose barnacle embryo, and also, perhaps, on the developing oocytes in embryonic and neonatal mice; and,

- the significance for the individual, or for the population more generally, of the minor responses, particularly in terms of morbidity and cytogenetic effects, seen at dose rates less than 10^2 μGy h^{-1} has yet to be determined.

6.5 Radiation quality

A longstanding and vexatious problem relates to the treatment of radiation exposures from radiations of differing quality, *i.e.* differing energy deposition rates along the particle track or linear energy transfer (LET). It is known that radiations having a high LET are more effective in generating damage, per unit of absorbed energy, than radiations of low LET - the relative biological effectiveness (RBE). In the context of an environmental assessment, this mainly relates to exposures from internal contamination with emitters of α-particles, *e.g.* ^{239}Pu and ^{241}Am, or β-particles with energy less than 10 keV, *e.g.* tritium (it should be noted that this concern also applies to the exposures from the natural background). The database permits the selection of papers that have been tagged as giving information that may be of use in estimating RBE values. Altogether, there are 78 papers in FRED that have been identified, of which 65 have been useful for the FASSET framework. As a consequence, there are too few data to make a recommendation for appropriate radiation weighting factors for the umbrella endpoints, wildlife groups and dose rates of interest for FASSET. Nevertheless, there are reasonable grounds for concluding that the RBE for α-particles is unlikely to be greater than


~200, and < ~5 for low energy β-particles. As an interim measure, the FASSET consortium have recommended that, in order to demonstrate the influence that radiation quality might have on the estimation of the biologically effective dose rate, radiation weighting factors of 5, 10 and 50 should be applied in the calculation of nuclide-specific dose conversion factors for internal sources of α-particles.

6.6 Extrapolation issues

In view of the relative paucity of relevant radiation effects data, the question arises as to whether it is possible to make extrapolations to fill some of the data gaps. The radiation effects data included in the database are heavily weighted (2:1) towards acute high dose exposures. Although there is considerable evidence that low dose and dose rate, chronic irradiation exposures are generally less damaging than high dose and dose rate, acute exposures, there does not appear to be a robust, and generally applicable, basis for extrapolation between these two contrasting exposure conditions. For the present, therefore, the FASSET assessment system must depend on the more limited information in the database relating to low dose and dose rate exposures.

From the summaries of data from the database (Chapter 2), it was concluded that the relatively large differences in radiosensitivity between the taxonomic groups that are seen in the responses to acute irradiation, particularly in terms of the LD_{50} values (see, for example, Figure 4-3), become less pronounced for continuous, low dose rate radiation exposure, and particularly for endpoints other than mortality. Nevertheless, there remain substantial differences in radiosensitivity between taxonomic groups, and between the different life stages of a given species, and there is no generally valid basis for making extrapolations.

A very few attempts have been made to integrate the available information concerning the effects of radiation in individuals into an assessment of possible responses at the population level. These appear to indicate that measures intended to limit the radiation effects on mortality and reproductive capacity in individuals will also provide a sufficient degree of protection for populations. In addition, the few experimental studies with water fleas (*Daphnia pulex*) indicate that the levels of chronic radiation exposure (< ~100 $\mu Gy\ h^{-1}$) expected from regulated waste management activities will not affect population parameters.

6.7 Other environmental stressors

There is abundant evidence that other environmental variables, within their natural range of values, interact with radiation exposure to influence the response, and that radiosensitivity is likely to be increased if the environmental conditions move from the optimum. In respect of radiation interactions with other contaminants, there are too few data to draw any general conclusions.

6.8 Recommendations for the future

The work undertaken within this part of the FASSET project has highlighted the fact that there is a number of deficiencies in the information required to support the assessment system that has been developed. Primarily, these relate to:

- the availability of information concerning the effects of low dose rate, continuous irradiation (< 10^3 μGy h^{-1}) on the morbidity, mortality, reproductive capacity and mutation rate in the reference organisms as represented by the wildlife groups - some groups, *e.g.* the mammals and fish, are well, or reasonably well, covered, but for others there is a complete lack of data;

- despite the inevitability that the wildlife will be exposed to other contaminants in addition to incremental irradiation from the radionuclides, there is a lack of information concerning possible interactions, in terms of both the bioaccumulation of the radionuclides (relevant to dosimetry) and the radiation damage; and,

- the correlation between effects seen at different levels in the biological hierarchy - this is particularly the case for first, the bio-indicators of radiation damage, *e.g.* chromosome aberrations in cells, and the response of the individual, and second, between the responses in the individual and that at the population level.

It would be helpful if these particular aspects could be specifically addressed in any future programme.

7. References

[number] – refers to the reference ID number in the FASSET Radiation Database (FRED), which can be found in the accompanying CD.

Anderson R.M., Stevens D.L., and Goodhead D.T. (2002) M-FISH analysis shows that complex chromosome aberrations induced by α-particle tracks are cumulative products of localized rearrangements Proceedings of the National Academy of Sciences, USA, 99 12167-12172.

Angelovic, J.W., Engel, D.W. (1970) Effects of radiation on estuarine organisms. *Marine Pollution Bulletin* 1: 103-105.

Baker, R. J., Bickham, A. M., Bondarkov, M., Gaschak, S. P., Matson, C. W., Rodgers, B. E., Wickliffe, J. K., Chesser, R. K. (2001) Consequences of polluted environments on population structure: The bank vole (*Clethrionomys glareolus*) at Chornobyl. *Ecotoxicology* 10(4): 211-216.

Barendsen G.W. (1979) Influence of radiation quality on the effectiveness of small doses for induction of reproductive detah and chromosome aberrations in mammalian cells International Journal of Radiation Biology 36: 49-63.

Blakely E.A., and Kronenberg A. (1998) Heavy-ion radiobiology: new approaches to delineate mechanisms underlying enhanced biological effectiveness Radiation Research 150, 126-145.

Blaylock, B.G. and Trabalka, J.R. (1978) Evaluating the effects of ionizing radiation on aquatic organisms. In Lett, J.T. and Adler, H. (Eds.): *Advances in Radiation Biology*, Vol. 7. Academic Press, New York.

Blaylock, B.G., and Griffiths, N.A. (1971) Effects of acute beta and gamma radiation on developing embryos of carp (*Cyprinus carpio*). *Radiation Research* 46: 1 99-104.

Bond V.P., Feinendegen L.E. and Booz J. (1988) What is a "low dose" of radiation? International Journal of Radiation Biology 53: 1-12.

Brooks A.L., Benjmin S.A., Hahn F.F., Brownstein D.G., Griffith W.C., and McClellan R.O. (1983) The induction of liver tumors by ^{239}Pu citrate or $^{239}PuO_2$ particles in the Chinese hamster Radiation Research 96: 135-151.

Cai, L., Cherian, M. G. (1996) Adaptive response to ionizing radiation-induced chromosome aberrations in rabbit lymphocytes: Effect of pre-exposure to zinc, and copper salts. *Mutation Research* 369(3,4): 233-241.

Cai, L., Cherian, M. G. (2003) Zinc-metallothionein protects from DNA damage induced by radiation better than glutathione and copper- or cadmium-metallothioneins. *Toxicology Letters* 136(3): 193-198.

Cai, L., Satoh, M., Tohyama, C., Cherian, M. G. (1999) Metallothionein in radiation exposure: its induction and protective role. *Toxicology* 132(2,3): 85-98.

Dallas, C. E., Lingenfelser, S. F., Lingenfelser, J. T., Holloman, K., Jagoe, C. H., Kind, J. A., Chesser, R. K., Smith, M. H. (1998) Flow cytometric analysis of erythrocyte and leukocyte DNA in fish from Chernobyl-contaminated ponds in the Ukraine. *Ecotoxicology* 7(4): 211-219.

Dobson R.L. and Kwan T.C. (1977) The tritium RBE at low-level exposure-variation with dose, dose-rate and exposure duration Current Topics Radiation Research. Quarterly 12: 44-62.

EA (1998) The Impact of Radioactive Discharges on Native British Wild-life and the Implications for Environmental Protection. Environemtn Agency (EA) R&D Technical Report P135, Bristol, UK, 80 pp.

EC (1979) Directive on the Conservation of Wild Birds (79/409/EC).

EC (1992) Directive on the Conservation of Natural Habitats and of Wild Fauna and Flora (92/43/EC).

EC (1996) Directive on Integrated Pollution Prevention and Control (96/61/EC).

EC (2000) Directive Establishing a Framework for Community action in the field of Water Policy (2000/60/EC).

Ehrenberg L., and Eriksson G. (1966) The dose dependence of mutation rates in the rad range, in the light of experiments with higher plants Acta Radiologica Supplement 254 73-81.

Engel, D. W.; Davis, E. M.; Smith, D. E.; Angelovic, J. W. (1974) Effect of salinity and temperature on the ion levels in the hemolymph of the blue crab, *Callinectes sapidus*. *Comparative Biochemistry and Physiology, Part A: Molecular & Integrative Physiology* 49(2): 259-66.

Environment Canada (2001) PSL-2000 Priority Substances List Assessment Report – Releases of radionuclides from nuclear facilities (Impact on non-human biota), Environment Canada and Health Canada.

FASSET (2000) FASSET Annex I - description of work. EC proposal FIS5-1999-00329 Framework for Assessment of Environmental Impact (FASSET), 37 pp.

Forbes, V.E. and Calow, P. (2002) Extrapolation in Ecological Risk Assessment: Balancing Pragmatism and Precaution in Chemical Controls Legislation. *BioScience* 52(3): 249-257

Forbes, VE., Calow, P. and Sibly, RM. (2001) Are current species extrapolation models a good basis for ecological risk assessment? *Environ. Toxicol. Chem.* 20(2): 442-447.

Goodhead D., Thacker J. and Cox R. (1993) Effects of radiations of different qualities on cells: molecular mechanisms of damage and repair International Journal of Radiation Biology 63: 543-556.

Goodhead D.T. (1994) Initial events in the cellular effects of ionising radiations:clustered damage in DNA International Journal of Radiation Biology 65: 7-17.

Goodhead, D.T. (1992) Tack structure considerations in low dose and low dose rate effects of ionizing radiation. *Adv. Radiat. Biol.* 16: 7-44.

Grayum, M. G. (1971) Effects of thermal shock and ionizing radiation on primary productivity. In: Radionuclides in ecosystems. Proc. 3rd national Symposium on Radioecology, Oak Ridge, May 10-12, 1971, Nelson, D.J. (ed).

Heaslip, M.B. (1961) Factors affecting tree seed and seedling radiosensitivity. In: Radioecology. Proc. 1st national Symposium on Radioecology, Fort Collins, September 10-15, 1961, Schultz, V. and Klements, A.W. (eds).

Howell R.W. Azure M.T., Narra V.R. and Rao D.V. (1994) Relative biological effectiveness of alpha-particle emitters in vivo at low doses Radiation Research 137: 352-360.

IAEA (1976) Effects of Ionizing Radiation on Aquatic Organisms and Ecosystems. International Atomic Energy Agency Technical Report Series No 172, Vienna, 1-131.

IAEA (1988) Assessing the Impact of Deep Sea Disposal of Low Level Radioactive Waste on Living Marine Resources. International Atomic Energy Agency Technical Reports Series No. 288. IAEA symposia, Vienna 1-127.

IAEA (1992) Effects of Ionizing Radiation on Plants and Animals at Levels Implied by Current Radiation Protection Standards. International Atomic Energy Agency Technical Report Series No 332, Vienna, 1-74.

ICRP (1991) Recommendations of the International Commission on Radiological Protection. International Commission on Radiological Protection (ICRP) Publication 60, Ann. ICRP 21, Pergamon Press, Oxford.

Jefferies, D.J., *et al*. (1958) Lethal and sterilising effects of single and fractionated doses of gamma radiation on *Calandra granaria* L. *Nature (London)* 182: 402.

Jiang T-N., Lord B.I., and Hendry J.H. (1994) Alpha particles are extremely damaging to developing hemopoiesis compared to gamma irradiation Radiation Research 137: 380-384.

Kocher, D.C. and Trabalka, J.R. (2000) On the application of a radiation factor for alpha particles in the protection of non-human biota. *Health Physics* 79: 407-411.

Kondratenko V.G. and Ganzenko L.F. (1975) Effects of small doses of radiation of spermatogenesis UDC 577391:591.463.1.

Kulikov, N.V., *et al*. (1966) Influence of ionizing radiations on the early stages of development of *Limnea stagnalis*. *Radiobiologiya* 6: 908.

Kuwahara Y., Shimada A., Mitani H., and Shima A. (2002) A critical stage in spermatogenesis for radiation-induced cell-death in the Medaka fish, Oryzias latipes Radiation Research 157: 386-392.

Larsson, C.-M., Brewitz, E, Jones, C. (2002) Deliverable 2: *Part 1 - Formulating the Fasset assessment context*. FASSET Contract FIGE-CT-2000-00102, www.fasset.org, 77 pp.

Lingenfelser, S. F.; Dallas, C. E.; Jagoe, C. H.; Smith, M. H.; Brisbin, I. L., Chesser, R. K. (1997) Variation in DNA content of blood cells of largemouth bass from contaminated and uncontaminated waters. *Environmental Toxicology and Chemistry* 16(10): 2136-2143.

Little M.P., and Wakeford R. (2002) The bystander effect in experimental systems and compatibility with radon-induced lung cancer in humans Journal of Radiological. Protection 22**,** A27 - A31.

Lord B.I., and Mason T.M., (1996) On the relative biological effectiveness of alpha-particle irradiation with respect to hemopoietic tissue Radiation Research 145: 510-518.

Lorenz, E. (1954) Effects of long-continued total-body gamma irradiation on mice, guinea pigs and rabbits. In: *Biological effects of external X and gamma radiation*. Ed. R Zirkle, pp 226-242.

Lundgren D.L., Haley P.J., Hahn F.F:, Diel J.H., Griffith W.C. and Scott B.R. (1995) Pulmonary carcinogenicity of repeated inhalation exposure of rats to aerosols of ^{239}PuO2 Radiation Research 142: 39-53.

Matson, C.W., Rodgers, B.E., Chesser, R.K., and Baker, R.J. (2000) Genetic diversity of Clethrionomys glareolous populations from highly contaminated sites in the Chernobyl region, Ukraine. *Environmental Toxicology and Chemistry* 19(8): 2130-2135

Myers, S. (1989) *The General Principles and Consequences of Environmental Radiation Exposure in Relation to Canada's Nuclear Fuel Management Concept*. AECL Rep. No. AECL-9917, Chalk River Nuclear Laboratories, Chalk River. 96 pp.

NCRP (1990) The relative biological effectiveness radiations of different quality. National Council on Radiation Protection and Measurements (NCRP) Report # 104, Washington, DC, USA.

NCRP, 1991 NCRP (1991) Effects of Ionising Radiation on Aquatic Organisms: Recommendations of the National Council on Radiation Protection and Measurements Bulletin of the Japanese Society of Scientific Fisheries, 1-115.

Neuhold, J.M., Sharma, R.K. (1967) Interacting effects of gamma radiation and sodium halide concentrations on rainbow trout. In: Radioecology. Proc. 2nd national Symposium on Radioecology, Ann Arbor, May 15-17, 1967, Nelson, D.J. & Evans, F.C. (eds).

Nikjoo H., and Khvostunov I.K. (2003) Biophysical model of the radiation induced bystander effect International Journal of Radiation Biology 79: 43-52.

Nikjoo H., O´Neill P., Wilson W.E.and Goodhead D.T. (2001) Computational approach for determining the spectrum of DNA damage induced by ionizing radiation Radiation Research 156 577-583.

NRPB (1996) *Risk from Deterministic Effects of Ionizing Radiation*. Documents of the Naional Radiation Protection Board (NRPB), Volume 7, N^{o} 3, Chilton, UK. 31 pp.

Ophel, I.L., *et al*. (1976) Effects of ionizing radiation on aquatic organisms and ecosystems. *IAEA Tech. Rep Series 172* pp 57-88.

Pentreath, R. J. (2003) Evaluating the effects of ionising radiation upon the environment. In: *Protection of the Environment from Ionising Radiation - The Development and Application of a System of Radiation protection for the Environment*, Proc. 3rd International Symposium, Darwin, Australia, July 2002, Conference & Symposium Papers 17/P, IAEA, Vienna.

Pentreath, R.J. (1999) A system for radiological protection of the environment: some initial thoughts and ideas. *J. Radiol. Prot.* 19: 117-128.

Raabe O.G., Book S.A. and Parks N.J. (1983) Lifetime bone cancer dose-response relationships in beagles and people from skeletal burdens of ^{226}Ra and ^{90}Sr Health physics 44 33-48.

Rao, D.V., Narra, V.R., Howell, R.W., Lanka, V.K. and Sastry, K.S.R. (1991) Induction of sperm head abnormalities by incorporated radionuclides: Dependence on subcellular distribution, type of radiation, dose rate, and presence of radioprotectors. *Radiation Research* 125: 89-97.

Rose, K.S.B. (1992) Lower limits of radiosensitivity in organisms, excluding man. *Journal of Environmental Radioactivity* 15: 113-133.

Samuels, L.D. (1966) Effects of polonium-210 on mouse ovaries *Int J. Radiat. Biol.* 11(2): 117-129.

Sato, M., Bremner, I. (1993) Oxygen free radicals and metallothionein. *Free Radical Biology & Medicine* 14(3): 325-37.

Scott, B.R. and Hahn, F.F. (1985) Early occurring and continuing effects. In Evans, J.S., Moeller, J.W. and Cooper, D.W. (Eds): *Health effects models for nuclear power plant accident consequence analysis*. NUREG/CR-4214 (SAND85-7185), Nuclear Regulatory Commission, Washington, DC.

Sparrow, A.H. (1966) Research uses of the gamma field at BNL. *Radiation Botany* 6, 377-405.

Strand, P., Beresford, N., Avila, R., Jones, S.r., Larsson, C.-M. (2001) FASSET Deliverable 1: *Identification of candidate reference organisms from a radiation exposure pathways perspective*, FASSET Contract FIGE-CT-2000-00102, www.fasset.org, 48 pp + appendices.

Straume, T., Carsten, A.L. (1993) Tritium radiobiology and relative biological effectiveness. Health Phys. 65: 657-672.

Sugg, D., Chesser, R., Brooks, J., Grasman, B. (1995) The association of DNA damage to concentrations of mercury and radiocesium in largemouth bass. *Environmental Toxicology and Chemistry* 14: 661-668.

Sugg, W., Bickham, J., Brooks, J., Lomakin, M., Jagoe, C., Dallas, C., Smith, M., Baker, R., Chesser, R. (1996) DNA damage and radiocesium in channel catfish from Chernobyl. *Environmental Toxicology and Chemistry* 15: 1057-1063.

Tarkhanov, I. (1896) Experiments upon the action of Roentgen's X-rays on organisms. *Izv. S-Peterb. biol. Lab.,* 1, 47-52.

Theodorakis, CW. (2001) Integration of genotoxic and population genetic endpoints in biomonitoring and risk assessment. *Ecotoxicology* 10: 245-256.

Thomas P.A. Tracy B.L. Ping T., Wickstrom M., Sidhu N., andd Hiebert L. (2003) Relative biological effectiveness (RBE) of ^{210}Po alpha particles versus X-rays on lethality in bovine endothelial cells International Journal of Radiation Biology 79: 107-118.

Thompson, P. and Chamney, L. (2001) Environmental protection program to be implemented to fulfil the mandate of the new Canadian Nuclear Safety Commission. In: 2nd Int. Symp. on Ionizing Radiation, Atomic Energy Board of Canada, pp 131-135.

Tice, R.R., Strauss, G.H.S. (1995) The single cell gel electrophoresis/comet assay: apotential tool for detecting radiation-induced DNA damage in humans. *Stem Cells* 13(suppl 1): 207-214.

Trivedi, A., Gentner, N.E. (2000) Ecodosimetry Weighting Factor (e_R) for Non-Human Biota, Health, Chemistry & Environment Division, AECL, T-1-5, P-2a-114, Chalk River, Ontario, Canada.

Tsytsugina, V. G. (1998) An indicator of radiation effects in natural populations of aquatic organisms. *Radiation Protection Dosimetry* 75(1-4): 171-173.

Tsytsugina, V. G., Polikarpov, G. G. (2003) Radiological effects on populations of Oligochaeta in *the Chernobyl contaminated zone. Journal of Environmental Radioactivity, in* press.

UK Parliament (1990) The Environmental Protection Act.

Ulsh, B. A., Muhlmann-Diaz, M. C., Whicker, F. W., Hinton, T. G., Congdon, J. D., Bedford, J. S. (2000) Chromosome translocations in turtles: a biomarker in a sentinel animal for ecological dosimetry. *Radiation Research* 153(6): 752-759.

Ulsh, B., Hinton, T. G., Congdon, J. D., Dugan, L. C., Whicker, F. W., Bedford, J.S. (2003) Environmental biodosimetry: a biologically relevant tool for ecological risk assessment and biomonitoring. *Journal of Environmental Radioactivity*, In Press.

UNSCEAR (1988) Early effects in man of high doses of radiation. Annex G in: *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 Report to the General Assembly, with Annexes, pp 545-612. United Nations, New York.

UNSCEAR (1993a) Hereditary effects of radiation. Annex G in: *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation, 1993 Report to the General Assembly, with Scientific Annexes, pp 729-804. United Nations, New York.

UNSCEAR (1993b) Influence of dose and dose rate on stochastic effects of radiation. Annex F in: *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation, 1993 Report to the General Assembly, with Scientific Annexes, pp 619-728. United Nations, New York.

UNSCEAR (1996) Effects of radiation on the environment. Annex in: *Sources and Effects of Ionizing Radiation*. United Nations Scientific Committee on the Effects of Atomic Radiation, 1996 Report to the General Assembly, with Annexes, pp 1-86. United Nation, New York.

Viarengo, A., Burlando, B., Ceratto, N., Panfoli, I. (2000) Antioxidant role of metallothioneins: a comparative review. *Cellular and molecular Biology* 46(2): 407-417.

Woodhead, D.S. (1984). Contamination due to radioactive materials. In Kinne, O. (Ed.) *Marine Ecology,* vol. 5: *Ocean Management*: Part 3: 1111-1287. John Wiley and Sons, Chichester.

Woodhead, D.S. 2003. A possible approach for the assessment of radiation effects on populations of wild organisms in radionuclide-contaminated environments*? J. Environ. Rad.* 66: 181-213.

Appendix A: A brief summary overview of data in FRED, concerned with RBEs

	Relevant	Possibly relevant
Number of papers	65	13 (all mammals)
Number of observations	1736	143

Brief overview of the 1736 observations (*i.e.* from the 65 papers) that are relevant to RBEs.

Ecosystem type		
	Terrestrial	86 %
	Aquatic	6 %
	Marine	8 %
	Undefined	< 1 %
Type of experiment		
	Controlled field	2 %
	Laboratory	97 %
	Undefined	< 1 %
Endpoints		
	Morbidity	28 %
	Mortality	34 %
	Reproduction	18 %
	Mutation	20 %
Dose rate type		
	Acute	77 %
	Chronic	17 %
	Transitory	6 %
Exposure type		
	External	78 %
	Internal	10 %
	Mixed	12 %
Radiation type		
	Alpha	7 %
	Beta	6 %
	Gamma	30 %
	Mixed	7 %
	Neutrons	28 %
	X-rays	21 %
	Undefined	< 1%
Wildlife groups		
	Aquatic plants	1%
	Crustaceans	5%
	Fish	5%
	Mammals	51% mouse 11% rest
	Molluscs	2
	Plants	18
	Soil fauna	7

Appendix B: Conversions in FRED to standardised units

The following details the values inserted into the code of the database in order to convert the dose or dose rate values entered into standardised dose or dose rate values (as Gy or μGy h^{-1}).

Dose units:

```
Select Case strdose
    Case "Gy"
    rsUpdate("StandardisedDoseUnit") = numdose * 1
    Case "μGy"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.000001
    Case "mGy"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.001
    Case "cGy"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.01
    Case "μrad"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.00000001
    Case "mrad"
    If Asc(Left(strdose, 1)) = 109 Then
       rsUpdate("StandardisedDoseUnit") = numdose * 0.00001
    Else
       rsUpdate("StandardisedDoseUnit") = numdose * 10000
    End If
    Case "rad"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.01
    Case "krad"
    rsUpdate("StandardisedDoseUnit") = numdose * 10
    Case "R(oentgen)"
    rsUpdate("StandardisedDoseUnit") = numdose * 0.01
    Case "kR(oentgen)"
    rsUpdate("StandardisedDoseUnit") = numdose * 10
    End Select
```

Dose rate units:

```
    strrate = rsUpdate("Unitsd2")
    numrate = rsUpdate("DoseRate")
    Select Case strrate
    Case "μGy/s"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 3600
    Case "μGy/min"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 60
    Case "μGy/h"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 1
    Case "μGy/d"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 0.041666667
    Case "mGy/s"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 3600000
    Case "mGy/min"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 60000
    Case "mGy/h"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 1000
    Case "mGy/d"
    rsUpdate("StandardisedDoseRateUnit") = numrate * 41.66666667
```

```
Case "cGy/s"
rsUpdate("StandardisedDoseRateUnit") = numrate * 36000000
Case "cGy/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600000
Case "cGy/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 10000
Case "cGy/d"
rsUpdate("StandardisedDoseRateUnit") = numrate * 417
Case "Gy/s"
rsUpdate("StandardisedDoseRateUnit") = numrate * 3600000000#
Case "Gy/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 60000000
Case "Gy/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 1000000
Case "Gy/d"
rsUpdate("StandardisedDoseRateUnit") = numrate * 41666.66667
Case "mrad/s"
rsUpdate("StandardisedDoseRateUnit") = numrate * 36000
Case "rad/s"
rsUpdate("StandardisedDoseRateUnit") = numrate * 36000000
Case "µrad/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 0.6
Case "mrad/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600
Case "rad/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600000
Case "µrad/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600000
Case "mrad/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 10
Case "rad/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 10000
Case "R/s"
rsUpdate("StandardisedDoseRateUnit") = numrate * 36000000
Case "R/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600000
Case "R/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 10000
Case "µGy/y"
rsUpdate("StandardisedDoseRateUnit") = numrate * 0.0000019
Case "R/d"
rsUpdate("StandardisedDoseRateUnit") = numrate * 416.67
Case "kR(oentgen)/min"
rsUpdate("StandardisedDoseRateUnit") = numrate * 600000000
Case "kR(oentgen)/h"
rsUpdate("StandardisedDoseRateUnit") = numrate * 10000000
Case "kR(oentgen)/d"
rsUpdate("StandardisedDoseRateUnit") = numrate * 417000
End Select
```