176. Reproductive effects are a more sensitive indicator of radiation response in aquatic organisms. Chronic dose rates in the range 3,200-17,000 μGy h^{-1} have been shown to reduce reproductive capacity in the fresh-water snail *Physa heterostropha* and in the marine polychaete worms *Ophriotrocha diadema* and *Neanthes arenaceodentata*. A dose rate of 7,300 μGy h^{-1} rendered male fresh-water fish (*Ameca splendens*) effectively sterile after 50 days exposure, and a dose rate of 1,700 μGy h^{-1} over the life-span of pairs of guppies (the fresh-water fish *Poecilia reticulata*) significantly reduced the lifetime production of offspring [W27]. It has been concluded that significant effects in fish gonads from chronic radiation exposure would be unlikely at dose rates less than 1,000 μGy h^{-1} [I3, W9]. Overall consideration of the data available for the effects of chronic irradiation on aquatic organisms has led to the conclusion that dose rates up to 400 μGy h^{-1} to a small proportion of the individuals in aquatic populations (and, therefore, lower average dose rates to the whole population) would not have any detrimental effects at the population level [I4, N1].

D. CLASSIFICATION OF RADIOSENSITIVITIES

177. Because radiation effects on organisms trace their origin to interactions and initial damage and its non-repair at the molecular or cellular level, there have been a number of attempts to classify organisms according to their molecular or cellular characteristics. A review of these studies can be found in Sparrow et al. [S1]. More recent studies have included phylogenetic factors in correlations of radiosensitivity with molecular and cellular characteristics [S45].

178. In 8 of 10 viruses, Epstein [E2] found equivalence (within a factor of 2) between the estimated volumes of nucleic acid in individual virus particles and the estimated target volumes obtained from radiation inactivation studies assuming a single-target, single-hit model. The exceptions were two large viruses that were known to have complex internal structures and for which the simple model might have been inappropriate. These data supported the proposition that the radiosensitive component of the virus is the nucleic acid and not the nucleoprotein. Terzi [T2, T3] extended Epstein's general approach to include bacteriophage, bacteria, yeast and cultured mammalian cells in addition to viruses. In this study, a correlation was made between D_{37} (the dose increment reducing survival to 37% on the exponential segment of the survival curve, i.e. the linear segment on a semi-logarithmic plot) and the nucleic acid content, using the lethal efficiency (the reciprocal of the number of ion pairs produced in the nucleic acid content of an individual organism or cell at D_{37}). It was found that the organisms could be segregated into four more or less distinct groups on the basis of the calculated lethal (inactivation) efficiency, which appeared to decrease in value as the structural complexity of the genetic material increased from single-stranded RNA and DNA to a haploid chromosome complement. A further increase in radiosensitivity above that of haploid organisms was considered as being due not necessarily to the increased complexity of the genetic material but more likely to a change in the phenogenetic patterns of lethality. Kaplan and Moses [K1] critically re-evaluated the data set analysed by Terzi [T2, T3], rejecting some but also making additions. The outcome was very similar in that essentially the same four groupings were identified: (in order of increasing radiosensitivity) RNA and single-stranded DNA viruses, double-stranded DNA viruses (including bacteriophage), haploid bacteria and yeast, and finally, diploid yeast mammalian cells and avian cells (in culture).

179. Sparrow et al. [S1] showed, for 79 organisms ranging from viruses to mammalian cells, that there is a higher degree of correlation between D_{37} and the interphase chromosome volume (interphase nucleus volume divided by somatic chromosome number) than between D_{37} and the nuclear volume. The D_{37} values of the 79 organisms plotted against their respective chromosome volumes resulted in a series of eight regression lines (corresponding to eight radiotaxa), the slopes of which did not differ significantly from −1 (Figure VI). Thus, the mean chromosome volume appears to be a highly significant index of cellular radiosensitivity. However, when all eight radiotaxa are taken into consideration, it appears that for a given value of D_{37}, there can be a 10^5-fold range in chromosome volume; conversely, for a constant chromosome volume, D_{37} can vary by a large factor. The organisms included in those eight radiotaxa did not show any consistent relation with respect to classical taxonomy, genetic complexity or level of ploidy. Organisms without true chromosomes in a morphological sense (prokaryotes) occurred in seven radiotaxa, although viruses were restricted to the first four groups. Organisms with true nuclei or chromosomes (eukaryotes) were restricted to the last four radiotaxa (see Figure VI). Sparrow et al. [S1] concluded that the survival response is partly a function of chromosome size but that other parameters are involved that need to be identified. The results of Sparrow et al. [S1] have been presented schematically by Whicker and Schultz [W5] and are shown in Figure VII. This hierarchy indicates that mammals, including man, are the most sensitive organisms with regard to acute lethal effects. Most resistant to radiation effects are the microorganisms, bacteria, protozoa and viruses.

180. A cautionary note has, however, been sounded concerning the use of chromosome or cell nucleus characteristics as an absolute basis for predicting

radiosensitivity. The observed effects of chronic gamma irradiation on six species of woody plants in their natural environment were compared with predictions based on chromosome number and cell nucleus volume [W24]. In terms of a 50% reduction in shoot growth relative to controls, the prediction consistently underestimated the radiosensitivity of the plants, often by a large margin. On the basis of the dose rate required to produce greater than 90% mortality, the prediction overestimated the radiosensitivity of three species, although not by a significant margin, and underestimated the sensitivity of the remainder, in two cases by a factor of at least 5. Two factors were put forward as having significantly contributed to the observed general increase in radiosensitivity: (a) the stresses associated with the natural environment and (b) the fact that the prediction was developed from a (broad-based) general correlation based on data for both woody and herbaceous plants, even though it was recognized that, other things being equal, the former are generally more sensitive than the latter [W24].

181. The correlation of radiosensitivity with molecular or cellular characteristics has been extended to mutations, and it has been suggested on the basis of empirical evidence that the forward mutation rate per locus per unit dose of acute radiation might be linearly dependent (within a factor of 3) on the DNA content of the haploid genome [A8]. The conceptual basis of this relationship has, however, been severely criticized [S42] on the grounds that the studies underlying the apparent correlation employed differing genetic end-points that were not directly equivalent to specific locus mutations and detection systems of varying sensitivity. In addition, it was pointed out that intra-locus mutation rates are not found to be correlated with the apparent DNA content in specific salivary gland chromosome bands (identified with loci or complementation groups) of *Drosophila melanogaster*, leading to the conclusion that not all the DNA in a band represents a target for radiation-induced mutations of the type detected experimentally. It was concluded that these factors weakened the validity of the hypothesis developed by Abrahamson et al. [A8].

182. In summary, it may be stated that although there is suggestive evidence for correlations between specific characteristics of the nucleus and nuclear components and a variety of indicators of radiation-induced damage, none of these correlations has been developed to the point where it could reliably be used to predict, from the relatively small experimental database, potential radiation effects in the wide variety of organisms likely to be present in a contaminated area.

III. EFFECTS OF RADIATION ON POPULATIONS OF PLANTS AND ANIMALS

A. STUDY LIMITATIONS

183. Literature on radiation effects in an ecological context began to appear in the early 1960s. Although some of these research programmes were terminated by the early to mid-1970s because of changes in funding priorities, investigations continued into the 1980s in a few countries, such as Canada, France and the former Soviet Union [D1, F1, G3, K2, M3, S4].

184. The general approaches to studying radiation effects on populations and communities (assemblages of populations) have included large field irradiation facilities, observations at nuclear test sites and in areas of high natural background radiation or contamination, the release of irradiated individuals to the environment, the experimental application of radioactive particles, and the irradiation or contamination of laboratory systems or microcosms. Each of the above approaches has its advantages, but most suffer from a lack of ecological realism or from dose levels insufficient to produce unequivocal results.

185. The expense and difficulty of doing a meaningful study of radiation effects on plant and animal populations and communities in their natural environment makes it impossible to provide information on a large number of species and community types. For example, studies have been completed on coniferous and deciduous forests, certain shrublands and grasslands, a tropical rain forest, herbaceous old fields and moss-lichen communities [W3]. However, little work appears to have been done on aquatic plant communities or on Arctic or alpine tundra, taiga, savannah or desert communities. Also, very little work has been done on the interaction of radiation with other stresses or agents. This may be a serious omission in light of the multiple forms of pollution that threaten many contemporary populations and ecosystems.

186. Other areas that have received very little attention include the possible long-term effects of chronic, low-level radiation and the patterns of repair and recovery following radiation damage. It may take considerable time for damage from low-level chronic irradiation to be expressed at the ecosystem level, and most studies are short term. Several studies have looked at repair and recovery for a few years, but many systems require a decade or even much longer to complete their recovery from severe damage.

187. Despite these and other shortcomings in the general database, sufficient information is available to predict, within broad limits, the effects of ionizing radiation on at least a reasonable sample of the populations and communities in terrestrial and aquatic environments. However, this prediction must rely on adequate dosimetry, which is often difficult to achieve. For example, the calculation of doses to the critical tissues of higher plants following atmospheric deposition of radionuclides is a complex, difficult task and subject to considerable variability and uncertainty.

188. Ecosystems can be large and complex with many species of organisms, or they can be relatively simple with only a few species of organisms constituting a simple food-chain. The number of organisms in a population may be altered by changes in environmental conditions, or species may be completely replaced.

189. General characteristics of diminished ecosystem functioning under environmental stress have been identified [R4] that may also apply to radiation stress: (a) loose cycling of nutrients, (b) changes in primary production, (c) reduction of species diversity, (d) retrogression, as opposed to natural succession, (e) reduction in the average size of organisms and (f) other distress, such as increases in disease incidence. The stages in ecosystem response to stress are initial effects on sensitive parts, coping mechanisms to counteracting the stress and ecosystem rebalance or breakdown. It is not easy to predict specific effects in diverse ecosystems, which are usually under multiple stress, and further observations in contaminated environments are needed to increase knowledge and experience.

190. In the specific case of continuing exposure to low-level irradiation, Woodwell and Houghton [W25] concluded that the response of a temperate oak-pine forest (and other plant communities) is (a) systematic and predictable, (b) common in nature, (c) cumulative and progressive over an indefinite period measured in decades, (d) measurable in stages and (e) best characterized by the concept of "impoverishment". By "impoverishment" is meant the loss of large, long-lived, slowly reproducing species with replacement by smaller, opportunistic, short-lived species with high reproductive rates. These are readily recognizable as the weeds and pests of common currency and are typical of all disturbed habitats. In ecological terms, impoverishment is the reverse of succession, and it frequently appears to be a more rapid process [W25].

191. One of the problems in evaluating the effects of radiation on populations and ecosystems is to determine which parameters to measure and how radiation influences them. Typically measured attributes at the population level include numbers of individuals, mortality rate, reproduction rate and mean growth rate. In general, measurable changes in populations and communities require rather severe effects at the cellular and individual organism levels. For example, alteration in the structure of a biotic community requires a change in the component populations, which in turn requires widespread mortality and/or reduced reproduction of individuals [W3]. In the same way, genetic or somatic mutations that can be produced by lower levels of exposure may have little or no impact on population or community performance because of natural selection [B3, M4, N2, P2, T6] and the convergence of genetic information among adjacent populations [R1]. For example, in organisms whose reproductive rates are very high and on which selective pressures are strong, the value of one or even many thousands of individuals to the population may be rather insignificant [I2, T6]. In such populations, normally a small fraction of the individuals will mature and perpetuate the gene pool, even in the absence of radiation or other stresses. In most species, genetic information that is altered by radiation is extremely unlikely to be perpetuated in the population, even though it may not be immediately lethal at the individual level.

192. Radiation effects at the population and community levels are manifest as some combination of direct changes due to radiation damage and indirect responses to the direct changes. This seriously complicates the interpretation of radiation effects on organisms exposed in the natural environment. The wide range of radiosensitivities of the organisms that make up most natural communities creates a situation in which, if doses are such that the sensitive species but not the more resistant ones are affected, the latter may gain a significant competitive advantage and perhaps increase in abundance or vigour [W12]. This could erroneously be interpreted as a hormetic response. Such a response might not be produced if the resistant species alone were irradiated. This is but one of many examples of indirect response to the direct effects of radiation.

193. Individual populations of organisms, and the community as a whole, may be altered by radiation exposure only as a consequence of dependence on a much more radiosensitive species for food or shelter. For example, many plant species in a pine forest would be largely unaffected by an acute dose of 10 Gy, but the pine component would probably experience severe mortality [W11]. This would cause both positive and negative perturbations in the populations of other species not directly damaged by the radiation exposure. Because of such indirect responses, in any situation where all the species in a community have been exposed concurrently, great care will be necessary to identify the species most directly affected by the irradiation.

194. Changes in the composition and structure of vegetation lead to changes in the animal population [C2,

H2, W13]. Such changes could also involve interrelated populations of animals (predator-prey or host-parasite relationships), but these are more difficult to demonstrate. Numerous and extensive changes in the chemical and biological properties of the soil can occur as an indirect effect of radiation damage to vegetation. Recent work in France has demonstrated these kinds of changes clearly [C4, S2, T4, T20] (see also paragraph 215).

195. Relevant information concerning the effects of increased chronic radiation exposure of populations of wild organisms is beginning to become available from two additional sources, the two large-scale accidents that occurred in the former Soviet Union: the one in 1957 at a nuclear waste storage site near Kyshtym in the southeastern Urals and the other in 1986 at the Chernobyl nuclear reactor in Ukraine. Apart from the immediate, effectively acute radiation response observed in plants and animals near the release points for each of these accidents, there have been continuing studies of the effects of the longer-term chronic radiation exposures. The results of these studies are summarized in Section III.D.

B. EFFECTS ON PLANT POPULATIONS AND COMMUNITIES

196. Studies of radiation effects in natural plant communities have been more or less limited to terrestrial systems. The characteristics that have been measured in relation to the stress of ionizing radiation include physiognomy (growth-form), species composition, species diversity and vegetation cover and production [W3]. At the population level, parameters such as density or frequency of occurrence, growth and vigour, mortality, reproduction, phenology and morphology are often measured [G2, O2]. Effects on individuals or components of populations can give some insight into potential changes at the population and ecosystem level.

197. Some specific measures of change in plant communities that have been used to investigate the potential effects of radiation include the coefficient of community, similarity, diversity and biomass. The coefficient of community is a parameter calculated from a list of species present in an irradiated area and a control area, or in one area before and after the irradiation. This parameter is designed to detect changes in species composition resulting from the elimination and possibly replacement of populations. Similarity is like the coefficient of community, except that the relative abundance of individuals within each species is considered as well. Diversity is a measure of the number of species within a community and the evenness of apportionment of individuals among the species. Both the loss of individuals and the loss of species would change the diversity. Biomass is a measure of the mass of biological tissue per unit area. It may be estimated for individual populations or for entire communities, and owing to sublethal alterations in growth, it can change without a loss of individuals or species. These parameters are defined more precisely in various publications [G2, W3, W6], and more complex indices and means for analysing change are available [G7].

198. An example of radiation effects in plant communities has been seen in a study in a granite-outcrop ecosystem common to the southeastern United States [M6]. The composition of this ecosystem is relatively simple, and there are well-defined boundaries. One such system was treated with simulated fallout particles (^{90}Y), and effects of the beta irradiation were observed over a 60-day period [M6]. Accumulated doses were measured with thermoluminiscent dosimeters at the ground surface and at 40 cm height, the average height of terminal buds of the summer dominant plant, *Viguiera porteri*. The mean doses in two experimental systems were 40 Gy and 70 Gy, with 20% higher doses at the ground surface and 20% lower doses at the 40 cm height.

199. In these irradiated systems, there were no obvious changes in appearance of the experimental plots; rather close observation and measurement were required to detect effects of the radiation exposures. Only one change in the 40 plant species constituting this ecosystem was noted that could be related to the radiation exposure. A sedge, *Bulbostylis capillaries*, decreased by 17% in the 70 Gy community but increased by 12% in the control and 40 Gy communities [M6]. Other studies had shown this plant to be relatively radioresistant, but because its growing apices are close to the ground, it may have retained high densities of fallout particles in close proximity to sensitive meristems. Thus, the geometry of the radiation field is an important consideration when interpreting the observations.

200. In the main species, *Viguiera porteri*, in the 70 Gy community, 46% of all terminal buds died, resulting in a 37% height reduction; however, there was compensatory lateral branch development. In this plot, community biomass was reduced by 16% owing to decreased production of flower and stem biomass, but leaf biomass was similar to control levels [M6]. An additional observation was that beta radiation was twice as effective as gamma radiation over comparable periods and equivalent total doses [M6].

201. The effects of chronic irradiation on the micro-algal population in soil have been examined [F9]. The micro-algae appear to be relatively radioresistant, even though some part of the observed change might have been attributable to the gross effects (mortality, much reduced litter fall etc.) of radiation on the higher plants

in the zone examined, i.e. the change was partly an indirect response. The total number of taxa that could be isolated from the soil samples did not appear to change markedly with dose rate up to the maximum delivered (approximately 1.7 Gy h^{-1}). Above a threshold of approximately 0.3 Gy h^{-1}, however, eukaryotes were replaced by prokaryotes. Estimates of the coefficient of community and percentage similarity (relative to unirradiated controls) were consistent in showing a threshold for decline at approximately 0.4 Gy h^{-1}, 50% reductions at about 0.9 Gy h^{-1} and extrapolation to zero at 2.5-3.0 Gy h^{-1} [F9].

202. Chronic irradiation also had a substantial effect on the populations of microfungi at the base of the humus layer in an oak-pine forest. Where higher plants persisted, i.e. in the intact oak-pine forest, and where the dose rate at the sampling depth increased from less than 400 μGy h^{-1} to about 8,000 μGy h^{-1}, there appeared to be little direct effect of radiation on the microfungi. The fungal species isolated were typical of podzolic soils in mixed conifer-hardwood forests and were dominated by eight morphologically complex taxa (71% of isolates but only 5% of the species). There was also a consistently high concentration of about 10^5 viable spores per gram of dry soil. At the edge of the sedge zone, where the dose rate was about 30.000 μGy h^{-1}, the concentration of viable spores fell to 1.6 10^4 g^{-1} dry soil, but the species diversity increased in this transitional band between the endemic forest populations and opportunistic pioneer species, and there were few dominant forms at low densities. Closer to the radiation source, where there were no higher plants, the distribution of the microfungi was related to the radiation gradient. The viable spore density, the coefficient of community and the incidence of morphologically complex taxa all declined. At the highest dose rate, about 0.75 Gy h^{-1}, the viable spore density was reduced to 500 g^{-1} dry soil and the population was dominated by sterile, slow-growing forms of morphologically simple yeasts [G8].

203. Based on the results of several investigators, Whicker and Schultz [W5] summarized the effects of radiation on major plant communities of North America. The results given in Table 9 are the dose levels that give minor, intermediate and severe effects following short-term (8-30 day) exposures. Minor effects are considered to include changes in productivity and reproduction, from which rapid recovery would be expected after the radiation stress has been removed. Intermediate effects include changes in species composition and diversity through selective mortality of more radiosensitive species. Recovery could take place through processes of plant succession requiring one to several generations. Severe effects are those that drastically change the species composition by causing mortality of all or nearly all the higher plants. Recovery may be slow, requiring decades or even centuries if there has also been extensive leaching of soil nutrients and erosion. To estimate the chronic exposures that would be expected to result in comparable effects, the dose ranges in the Table should be divided by 25-100 to give daily dose ranges.

204. The plant communities included in Table 9 are listed in approximate order of sensitivity, from coniferous forests to moss-lichen communities. The greater radiosensitivity of the coniferous forest is correlated with the large chromosome volumes of pine trees. The other communities listed in Table 9 are much more resistant because they are dominated by more resistant species having generally smaller chromosomes. Lichen-dominated communities are exceptionally resistant [G1]. This resistance may be explained by diffuse centromeres and asexual reproduction as well as by small chromosomes [W3].

205. The general capacity of plant communities to withstand environmental stress (low rainfall, high temperatures) also enables them to withstand low to moderate radiation stress. There may be alterations in community structure (species abundance changes) and morphological changes in individual plants (lateral branch development), depending on the total radiation stress, but the compensations are generally such as to maintain a normal energy balance. While it is possible for radiation stress to induce systemic defence mechanisms in individual plants that could increase their potential to respond to secondary stresses such as parasitic fungi, it should also be pointed out that apparent similarities in plant regrowth and recovery, after either radiation exposure or some other form of stress, may be superficial and conceal the existence of stress-specific responses.

C. EFFECTS ON ANIMAL POPULATIONS AND COMMUNITIES

206. The impact of radiation exposure on an animal population is likely to be a complex combination of effects within individual animals (direct effects) and the positive or negative effects of the responses of the other biological components of the environment with which the population normally interacts (indirect effects). Where there is a close coupling between two species, e.g. plant-herbivore, predator-prey or host-parasite, it is very likely that their responses to chronic low-level radiation (whether similar or different at the individual level) will be modified at the population level by interspecies interaction. The direct effects of irradiation measured in animal populations have included changes in the birth rate, the death rate and, in combination, the intrinsic rate of natural increase [F2]. Because a reduction in reproductive capacity has been considered

to be a more limiting end-point than mortality, in terms of the maintenance and survival of the population, changes in fertility and fecundity have been measured and the response at the population level estimated using an appropriate model of population dynamics. The published studies have rarely, however, taken account of the influence of either intra- or interspecies interactions or factors other than radiation.

1. Terrestrial environment

207. Because animals are mobile, it is difficult to conduct field studies of radiation effects. The use of enclosures to retain animals in exposed areas may unduly restrict their movement, feeding and behaviour, causing effects in addition to those under study. Investigations in areas of high background or in more widely contaminated areas may be less affected by spatial limitations.

208. Notable effects in animal communities can result from changes in vegetative cover, particularly for insects. As vegetation dies in highly irradiated areas, herbivorous insects and their predators disappear and are replaced by species subsisting on dead and decaying material. Aphid increases were noted in irradiated oak-pine forest on Long Island, New York, the insects perhaps having been attracted by the altered quality or appearance of the oak leaves [W13]. Bark beetles invaded an irradiated tropical forest in Puerto Rico when natural defence processes in the trees were weakened [S5]. The presence of moribund pine trees in the high-dose-rate zone of a chronically irradiated oak-pine forest provided an ideal substrate for colonization by bark beetles and other xylophagous insects. Moribund trees were heavily attacked by two species of bark beetle irrespective of the ambient radiation dose rate, but the ensuing degree of developmental success was inversely correlated with dose rate. At above 200,000 μGy h^{-1} the adults attacked the trees and began excavating galleries but were killed before they could complete the task of preparing cavities for eggs or laying eggs. Between 40,000 and 200,000 μGy h^{-1}, the egg cavities were completed but there was no egg hatch, owing either to infertility or damage to the developing embryos. In the range 30,000-40,000 μGy h^{-1}, where eggs hatched, there was total larval mortality; at 20,000-30,000 μGy h^{-1}, there was low larval mortality but all the pupae died. Between 10,000 and 20,000 μGy h^{-1} there was some pupal mortality and some adult emergence, and below 10,000 μGy h^{-1} adult emergence was as high as, or higher than, normal. Within this overall picture there were also interesting observations on the influence of interspecies competition with other xylophagous insects: those species with more protracted life cycles tended, at any given dose rate, to be at a competitive disadvantage. The importance of shielding, in this case between distal and proximal segments of the trunks, was also noted. Lastly, it was concluded that if pines were debilitated by a short-term but spatially variable radiation exposure, then the less-radiosensitive bark beetles could, owing to the availability of many suitable feeding and breeding sites, reach epizootic proportions and further damage and kill trees that would otherwise have survived [B25]. These findings show how important it is to appreciate the overall context of radiosensitivities and interactions between species when assessing potential environmental damage from chronic, low-level irradiation.

209. Density-dependent responses play an important role in modifying the impact of radiation. Such compensation and adaptation in populations is not apparent in laboratory experiments on individual organisms. Studies of lizards irradiated in a nine-hectare desert enclosure in Nevada in the United States showed impaired fertility and altered population levels [T8, T9]. Species response depended on life-spans, time of sexual maturity and population age distributions. One shorter-lived species of lizard, *Uta stansburiana*, was able to maintain population numbers in spite of appreciable proportions of sterile older females, apparently because the young animals survived better [T9].

210. Radiation effects in exposed animal populations have not been readily apparent. For example, studies of mammals on the dry bed of the retention pond at White Oak Lake, near Oak Ridge, Tennessee, United States could not ascribe any effects to radiation exposures [D3]. Lifetime doses to the wild rodents were probably 2-3 Gy [T9]. The study of lizards in the irradiated enclosure in Nevada revealed no differences in body weight and no form of tissue pathology, although some changes occurred in ovaries and oviducts of continuously irradiated lizards at annual gamma doses of 2-5 Gy [T9]. In all species of lizard in which female sterility was observed, the amount of body fat was increased.

211. In a region of high natural background radiation in the former Soviet Union, abnormalities, decreased body fat and reduced fertility were observed in mammals living in close contact with soil (*Microtus oeconomus*, *Talpa europaea*, *Arvicola terrestris*, *Lutra lutra* and *Sorex araneus*) [M1]. The dose rates were about 80 μGy h^{-1}, or 700 mGy a^{-1}. Since results at such low dose rates have not been obtained in laboratory or other field studies, the validity of the dose calculations has been questioned [T9].

212. In France, definite effects on reproduction in female mice maintained in captivity at a site where the external background was about 80 μGy h^{-1} were suggested by Leonard et al. [L1, L2, L3]. In the same study, rabbit lymphocytes showed an increased number of unstable chromosome aberrations. It is possible,

however, that internal doses. which were not calculated, contributed substantially to the total dose.

213. Radiation effects in populations of soil invertebrates were reported by Krivolutsky [K2]. Various radionuclides, including ^{90}Sr, ^{137}Cs, ^{106}Ru, ^{95}Zr, ^{239}Pu and ^{226}Ra, were added to the soil in small plots. At various intervals thereafter, the numbers per square metre of several types of soil invertebrates were determined in small ecosystem plots. Dose rates that apparently produced reductions in animal numbers were generally quite high (420-42,000 μGy h^{-1}); however, some effects were reportedly observed at dose rates of around 100 μGy h^{-1}. The most sensitive organism observed was the common earthworm.

214. An apparent response by ants to chronic irradiation has been observed in an oak-pine forest at a dose rate of 80,000 μGy h^{-1}. A thriving nest was identified prior to the commencement of radiation exposure. Over three years of irradiation, the number of ants in the colony declined (in part by emigration to a secondary colony further from the source in the first year), fewer individuals (and eventually, none) were seen on the burned pine stump forming the centre of the nest mound, and less plant debris was collected to maintain the nest mound. At the end of the period the colony appeared to increase in number, and a 1.25 m subsoil surface pathway covered with litter had been formed leading at an angle away from the radiation source: the runway was lost at 29 m from the source (dose rate of around 28,000 μGy h^{-1}), and no secondary colony was found. The ants used this pathway exclusively for travel to and from the nest. Because the vegetation canopy and its dependent populations of insects (ant food) were reduced as early as the first year, at least some of the responses (emigration and foraging further from the source) could be attributed to a decline in the food supply, but the decline in the habit of collecting plant debris to maintain the nest could most easily, albeit speculatively, be attributed to radiation avoidance [B26]. Over an 18-year period of chronic irradiation of a Mediterranean oak forest, the number of ant colonies was reduced in areas where dose rates were greater than 5,000 μGy h^{-1}. Although the number of species was little changed, the species composition was altered. Three species (of which two were not present at the beginning of the irradiation period) were found near the source at dose rates greater than 100,000 μGy h^{-1}. The changes in the ant fauna were mainly attributed to the loss of vegetation canopy, but direct effects of radiation could not be discounted [P10].

215. Two to three years after chronic irradiation of a Mediterranean oak forest there were changes in the populations of insects that could be attributed to both the direct and indirect effects of the exposure. Small insects of the order *Psocoptera* (booklice) were substantially increased in numbers in the dose rate range 14,000-38,000 μGy h^{-1}, and even at approximately 100,000 μGy h^{-1} the increase, although less, was still greater than in the control area. It was suggested that this increase was due to an increase in food supply (unicellular algae) in response to higher light levels following radiation-induced leaf loss in the canopy. In contrast, the populations of springtails (order *Collembola*) declined with increasing radiation exposure and accumulated dose [B27, P11]. In addition, later studies showed decreased overall activity in the soil system following a reduction in the microbial population [T19]. Near the source, where all the trees and shrubs had died and been replaced by small, more radioresistant annual plants, the litter input to the soil was negligible. Unlike in a temperate oak-pine forest [W24] the rate of loss of existing litter declined with increasing dose rate, but in both environments the total organic matter content of the soil decreased with increasing dose rate [P12, T19, T20]. Although the normalized oxygen consumption rate of the highly irradiated soil was also lower than in the control, the specific respiration (CO_2 production normalized to unit soil biomass) was slightly higher than in the control: the NO_3^- content of the irradiated soil was generally higher, owing to a reduced microbial requirement [P12, T19]. While the cumulative consequences of the chronic irradiation, both direct and indirect, are clearly complex, it is nevertheless true that all the observed responses stemmed from the initial damage to the most radiosensitive components of the system, the trees and shrubs; at lower dose rates, where the higher plants were much less affected, there were no consequential indirect responses [P12].

2. Aquatic environment

216. A number of aquatic field studies were conducted at sites of enhanced environmental radiation from anthropogenic sources [W5]. Examples of such sites include the Irish Sea in the vicinity of the Sellafield facilities; the Animas River near Durango, Colorado, United States, where uranium milling waste once entered the river; and a radioactive waste retention pond at the Oak Ridge National Laboratory in the United States. An extensive review of research on the ecological effects of nuclear testing was made by Templeton et al. [T6] for test sites in the Pacific. Several investigations were completed for marine organisms around the atolls [B5, H1, W1, W2]. The effects of the testing programme could not, in general, be ascribed solely to radiation because of concomitant effects of environmental disturbance. The recovery processes following the testing programme were relatively rapid, and deleterious effects on marine and terrestrial populations were not persistent, presumably because of the rapid declines in the intensity of radiation and other impacts and the recolonization of damaged areas by healthy individuals from distant locales.

217. Ponds, ditches and streams on the Hanford reservation in the United States in the past received a variety of radioactive wastes, resulting in radiation dose rates at the sediment-water boundary of up to 44.000 $\mu Gy\ h^{-1}$ (measured with LiF thermoluminiscent dosimeters). Although diversity was occasionally reduced, there were no consistent differences between the contaminated ponds and streams on the Hanford site and off-site reference locations. Across the sites examined, it was not possible to demonstrate any correlation between the variation in radiation dose rates and the biological parameters investigated, i.e. rates of periphyton and invertebrate colonization (colonization pressure) and a range of diversity indices: individuals per unit area, species richness, community diversity and species evenness [E13].

218. At the Savannah River site in the United States a number of catchment basins have received low-level waste from fuel reprocessing activities, leading to relatively high cumulative inputs of ^{3}H, $^{89/90}Sr$ and $^{134/137}Cs$. Natural populations of slider turtles (*Pseudemys scripta*) inhabit the ponds and, because they are known to be long-lived, could have accumulated relatively high total doses. The technique of flow cytometry has been used to investigate the potential genetic effects of accumulated radiation exposure by measuring the coefficient of variation of the distribution of DNA content (at the G_1 phase in the cell cycle) of nuclei isolated from red blood cells. The mean coefficient of variation estimated from measurements of 16 exposed animals was significantly greater (and hence indicative of a gain and loss of chromosomal DNA) than that estimated from measurements of 6 control animals. For 4 other exposed animals there was clear evidence of aneuploidy mosaicism in the form of G_1 DNA peaks with either a distinct shoulder or an adjacent peak; the finding that 4 of 20 exposed turtles exhibited aneuploidy mosaicism, compared with 0 of 6 controls, although suggestive of an effect, did not reach statistical significance ($p > 0.05$) owing to the small sample size. Insufficient data were provided to permit dose rates to the animals to be estimated (in a separate study, however, the dose rate to turtles in this environment from internal sources was estimated to be not greater than 240 $\mu Gy\ h^{-1}$ [N1]); however, the exposed males ($n = 10$) revealed a significant ($p < 0.10$) positive correlation between the coefficient of variation in G_1 DNA content and plastron length (size). This might be indicative of increasing coefficient of variation with age (and therefore possibly with accumulated dose). A similar analysis for exposed females ($n = 6$) was non-significant, as was that for control males; there were too few control females to complete the analysis. Again, the presence of other, potentially mutagenic contaminants (chromium and mercury) clouds the picture, and these data represent no more than qualitative circumstantial evidence for a radiation response in a contaminated environment [B28, B29].

219. The sensitivity of developing fish embryos was extensively studied following the experiments of Polikarpov [P4], which had indicated that developing fish eggs were sensitive to minute quantities of radionuclides in water. In their review of the subject, Blaylock and Trabalka [B4] concluded that none of the experiments support Polikarpov's contention, and Woodhead [W9] attributed the conflicting results to the dosimetric problems encountered in this type of experiment.

3. Summary

220. Radiation effects on populations of organisms have been examined in large field irradiation studies, in experimental enclosures and in observations in areas with high natural background, contamination from waste disposal or accidental release of radionuclides. There are inherent limitations in obtaining information on the large number of species and community types making up the biosphere, on the interactions of the many different environmental factors of both natural and anthropogenic origin and on the long-term nature of successional and generational effects. In addition, there are difficulties in providing adequate dosimetric information for complex distributions of sources and movements of organisms within the environments.

221. The exposure to radiation of a natural community, which comprises organisms with a wide range of radiosensitivities, may result in direct damage only to the more sensitive species. Other species may be indirectly affected, for example by loss of habitat or gain of competitive advantage. For any stress to an ecosystem, such as radiation exposure, there may be a complex and long-term sequence of disruption, adjustment and rebalancing.

222. Coniferous trees of the genus *Pinus* have been found to be the most sensitive of the plant species studied following either acute or chronic irradiation, and plant communities including these species are the most radiosensitive of the plant communities for which data are available. In general terms, a forest in which pines are the dominant (or codominant) species would probably suffer minor effects at total short-term doses of 1-5 Gy or at long-term chronic dose rates of 400-4,000 $\mu Gy\ h^{-1}$. In this context, minor effects are small changes in productivity and reproduction, from which rapid recovery would be expected following removal of the radiation source. Severe effects in the coniferous forest could occur at acute doses of more than 20 Gy or at long-term chronic dose rates in excess of 40,000 $\mu Gy\ h^{-1}$. Severe effects would include mortality of almost all higher plants, and the ecosystem would recover, if at all, only over time periods of decades or centuries. Other types of plant community can withstand doses or dose rates at least one order of

magnitude greater before demonstrating corresponding effects (Table 9).

223. The radiosensitivity of individual organisms is but one factor in determining population effects from radiation exposure, and observations in the laboratory may not apply exactly to the environment, where there are additional stresses from competition, predation and the like. Some compensation for radiation-induced reductions in either survival or reproductive rates may be possible, but there are numerous indirect effects that could be of overriding importance.

224. Changes in vegetative cover can affect animal communities. When plant species die in highly irradiated areas, the food supply of herbivorous animals and insects and their predators is reduced. The animals may disappear and be replaced by species subsisting on dead and decaying material. Aphids were attracted to an irradiated oak-pine forest, and bark beetles invaded trees in a tropical forest when the natural defence processes were weakened. The insects may further damage and kill trees that might have otherwise survived.

225. Because of the compensation and adjustment that are possible in animal species, it is considered unlikely that radiation exposures causing only minor effects in the most exposed individual would have significant effects on the population. Reproductive changes are a more sensitive indicator of radiation effects than mortality, and mammals are the most sensitive animal organisms. On this basis, chronic dose rates of less than 100 $\mu Gy\ h^{-1}$ to the most highly exposed individuals would be unlikely to have significant effects on most terrestrial animal communities (see paragraphs 121 and 133). It has also been concluded that maximum dose rates of 400 $\mu Gy\ h^{-1}$ to a small proportion of the individuals in aquatic populations of organisms would not have any detrimental effect at the population level (paragraph 176). These conclusions refer to the effects of low-LET radiation. Where a significant part of the incremental radiation exposure comes from high-LET radiation (alpha particles), it is necessary to apply an appropriate radiation weighting factor to this component of the absorbed dose rate and to use the total weighted absorbed dose rate for the assessment of potential radiation effects.

D. EFFECTS OF ACCIDENTS

226. Two major accidents in the former Soviet Union have provided opportunities to observe radiation-related changes in plant and animal communities. Any accident is likely to be unique in terms of the quantity and composition of the radioactive material released, the time course of the release, the dispersal and deposition patterns governed by local and regional meteorological or hydrographic conditions and the biogeochemical character of the areas subject to contamination. Where long-lived radionuclides are released, biogeochemical processes will determine the long-term behaviour and redistribution of the radionuclides in the environment. Given the multiplicity of factors, it is to be expected that any accident will yield new radioecological information. It is also true, however, that the primary concern following an accidental release of radionuclides will be to ensure that the radiation risks to human populations are controlled and minimized. An inevitable corollary is that the only environmental information likely to be collected is information immediately necessary to meet this concern, which will therefore be more or less deficient for the purpose of developing a complete radioecological description of the situation. The larger the incident and the greater its potential human impact, the more limited will be the resources available to collect radioecological information in the early phases of assessment and damage limitation.

227. It is particularly the case that the data required to develop estimates of the radiation exposure of wild organisms, that is, the space- and time-dependent variation of the radionuclide concentrations (especially for the short-lived isotopes), both within the organisms and in their external environment immediately following an accident, will not be known. These variations will result in substantial intra- and interspecies inhomogeneities in exposure and will pose considerable difficulties for establishing a clear and reliable relationship between cause (the accumulated radiation dose) and any observed effect. In practice, it is likely that estimates of the dose rates in the early period following the release would be made retrospectively by extrapolation and calculation from the observed distribution of contamination densities of the longer-lived radionuclides, a knowledge of the relative quantities of the radionuclides released and models of radionuclide behaviour in the environment. Such dose-rate estimates are inevitably imprecise and could be subject to significant systematic error.

228. Aside from the radioactive half-lives, other radionuclide-dependent factors significantly affect the potential radiation exposures received by wild organisms. These include the chemical identity of the radionuclide, which influences its environmental behaviour and its radiation characteristics (alpha, beta or gamma emissions), which profoundly affect the spatial dose field from any given source distribution. Additional complicating factors are the highly variable habits and target geometries of the wild organisms. These range, for example, from soil bacteria to single-celled algae and protozoa and include a wide variety of terrestrial and aquatic invertebrates, mammals (shrews to deer) and large deciduous or evergreen trees. If a radioactive aerosol is released, plants provide a very

high surface area to mass ratio (compared with animals) for deposition/adsorption. Because the leaves, flowers and terminal buds of plants are responsible for both energy absorption and growth and reproduction, a coincidence arises between radionuclide accumulation (and hence radiation dose) and potential radiosensitivity. Other examples of coincidence are the surface litter layer and its populations of invertebrate decomposers, and the surface sediments and benthic organisms in aquatic systems.

229. Depending on the quantities of specific radionuclides released in an accident, the radiation exposures might range from low (a few multiples of the natural background) to high (absorbed doses greater than about 1 Gy). More importantly, for the higher total doses, different phases of biological response may be distinguished. Initially, and particularly if short-lived radionuclides make up a significant proportion of the release, there might be an acute phase in which total doses sufficient to produce immediate or relatively early detectable biological responses are accumulated. In the intermediate phase, dose rates become lower owing to decay of the short-lived radionuclides and possibly, but not necessarily, owing to the redistribution of the longer-lived radionuclides by natural processes. In this phase the slower accumulation of radiation dose may still result in total integrated doses sufficient to prevent recovery of organisms damaged in the initial phase or to lead to the appearance of medium-term damage. In the final, long-term phase, post-irradiation recovery (and adaptation) becomes apparent, provided that the initial and medium-term damage have not been large enough to radically alter the population or community structure. It is important to be aware, however, that such descriptions can be no more than qualitative.

1. The accident in the southeastern Urals

230. The accident at the Mayak nuclear materials production complex east of the town of Kyshtym in the southeastern Urals occurred on 29 September 1957. A fault in the cooling system of a concrete tank containing mixed, highly active nitrate-acetate wastes led to a large chemical explosion. Approximately 74 PBq of fission products were released as an aerosol that moved northeast. Approximately 95% of the activity was associated with radionuclides having half-lives of one year or less (^{144}Ce, ^{95}Zr-^{95}Nb and ^{106}Ru), while the remainder consisted almost entirely of ^{90}Sr. More than 15,000 km^2 of territory were contaminated with ^{90}Sr at a density of greater than 3.7 kBq m^{-2} (twice that from global fallout), and this included 1,000 km^2 at over 70 kBq m^{-2} and 120 km^2 at over 3.7 MBq m^{-2} [N6].

231. The greater part of the total dose to wild organisms was delivered within the first year of the accident, during which time the contamination density (total Bq m^{-2}) decreased through decay by approximately 66% (see Table 10) [T21]. At the time of deposition the decay energy from beta radiation was approximately three times greater than that from gamma radiation, which meant that the dose-rate distribution in space and time in the contaminated area (forest, meadow, swamp, lakes, rivers and agricultural land) closely followed the detailed deposition pattern and the subsequent redistribution of the radionuclides by environmental processes. Estimates of the dose rates to various components of a pine forest (normalized to a ^{90}Sr contamination density of 1 MBq m^{-2}) are given in Table 11 [T17]. Because an area of approximately 120 km^2 was contaminated with ^{90}Sr at a density greater than 3.7 MBq m^{-2}, it is very probable that a wide variety of wild organisms would have received total doses at which acute effects might be expected.

232. The main part of the radiation exposure (and, usually, the highest dose rates) was delivered by the short-lived ($t_{½}$ < 1 year) beta/gamma emitters ^{95}Zr-^{95}Nb, ^{106}Ru-^{106}Rh and ^{144}Ce-^{144}Pr and occurred in the autumn and winter immediately following the accident, when the metabolic activity of the wild plants and animals was generally much reduced. This apparently increased radioresistance, in that the exposure had relatively little immediately visible impact. As a corollary, however, repair processes, which are dependent on metabolic activity, were drastically inhibited, and the difference in effectiveness between acute and chronic exposure was largely eliminated. Thus when metabolic activity resumed in the spring of 1958, the effects of the chronic irradiation (effectively equivalent to an acute exposure) became apparent and were more closely related to the total accumulated dose than to the dose rate [T17]. Estimates of the dose rates (normalized) and total doses accumulated during the acute period (autumn 1957 and winter 1957-1958) to a variety of organisms in the contaminated area are presented in Table 12. By the late spring of 1958, the dose rates to the majority of organisms had been reduced by radioactive decay and radionuclide migration, although the latter factor meant that there were also some exceptions, e.g. populations of invertebrates in the leaf litter and at the soil surface and small rodents. From that time on, the radiation exposure was genuinely chronic, and repair processes were largely able to accommodate and mitigate the radiation damage [A14, S49].

233. The major damage to the environment following the southeastern Urals accident was seen in the local forests. This was due to the coincidence of a high capacity for intercepting the active aerosol, a relatively slow clearance of the deposit and a relatively high radiosensitivity, especially in the case of coniferous trees [A9, A10, S20, T22, T23]. Pine trees that had accumulated total absorbed doses estimated to be greater than 30-40 Gy during the autumn and winter of

1957-1958 showed radiation damage, a desiccation of the needles in the crown, the following spring [K23]. The damage appeared initially in the lower and middle parts of the canopy, because the active deposit had been cleared more rapidly from the upper canopy by wind and rain, but by the autumn of 1959 the pine trees had died completely (the absorbed dose to the bud apical meristem was estimated to have been greater than 15-20 Gy). At lower, sublethal doses (greater than 5 Gy), yellowing, desiccation and partial shedding of needles, defects in the development of new needles, inhibition of shoot development and trunk growth and reduced seed and pollen viability were observed in the two seasons following the release. Birch trees showed lower radiosensitivity, with lethality apparent at estimated absorbed doses greater than 200 Gy and sublethal responses, comparable to those described above for pine trees, being observed at lower total doses (greater than 50 Gy) received in four years following the accident. One characteristic sublethal effect in the trees was a clear shift in the timing of development: delayed sprouting of new leaves in the spring and earlier leaf fall in the autumn. In severely damaged trees (100-200 Gy) the delay in bud burst amounted to an increase in the integrated time-temperature product of 30 °C-days. In 1960, this corresponded to a delay of 7-9 days and in 1961, 4-5 days. Five years after the accident the developmental delay began to decrease, and after seven years the onset of bud-burst had returned to the normal time. The data on the responses of pine and birch trees to irradiation in the contaminated area of the southeastern Urals are summarized in Table 13.

234. Following the acute phase in the first year after the accident, the dose rates dropped to long-term, relatively low levels, and the forest began to recover through both vegetative processes and seed germination. The intensive production of side shoots even restored the crowns of severely damaged pine and birch trees, which had lost up to 95% of their needle or leaf cover and suffered a complete growth check. After 8-10 years, irradiated and unirradiated trees were indistinguishable in superficial appearance and trunk growth had been restored. In areas of ^{90}Sr contamination density above 1,000 MBq m^{-2}, where pine seeds had received radiation doses greater than 20 Gy, the germination potential was lost, but at an intermediate dose of 6 Gy (300 MBq m^{-2}) some pine seeds remained viable and developed. The growth rate of pine seedlings was, however, dependent on the ambient radiation field, and an absorbed dose of 20 Gy or more during the first season severely restricted development. In areas of ^{90}Sr contamination density below 100 MBq m^{-2}, full recovery through seed propagation was possible [T23].

235. Radiation damage was noted in the first year after the accident in all 20 herbaceous plant communities that were recognized in the contaminated southeastern Urals region. The damage was considerable where ^{90}Sr contamination densities were above 130 MBq m^{-2} but slight where they were 18-26 MBq m^{-2}. The most sensitive herbaceous species were those with dormant buds at or near the soil surface (hemicryptophytes and hameophytes). These species disappeared from plant communities where contamination densities were greater than 18-26 MBq m^{-2} and were replaced by species with dormant buds either below ground or high above the surface and by species with short life cycles [B30, S36].

236. The long-term effects of increased chronic irradiation on the soil alga *Chlorella vulgaris* were investigated in the contaminated zone. Samples of algae were collected in years 5, 6, and 11 after the accident from areas contaminated with ^{90}Sr at between 0.04 and 1,300 MBq m^{-2} (equivalent to absorbed dose rates in the range 4-5,400 μGy h^{-1}) and tested for changes in radiosensitivity in response to an additional acute dose of 300 Gy. At all ^{90}Sr contamination densities an increase in radioresistance was observed, by a factor of up to 1.5-2 at intermediate densities. At the highest environmental dose rates it was concluded that the induced genetic load of mutations had reduced population viability. Over the 11-year study period the changes in radiosensitivity apparently stabilized in the algal populations sampled [S37, S38].

237. Because they were subject to some of the highest long-term dose rates, as the deposited radionuclides accumulated more or less rapidly in this zone, the invertebrate populations inhabiting the litter and underlying surface soils in the birch forests of the contaminated area of the southeastern Urals have been studied in some detail [K15]. Eleven years after the accident, in an area where ^{90}Sr contamination was 165-340 MBq m^{-2}, the total mesofauna densities were less than half those in control plots. The most severely affected group was the saprophages (phytodetritivores: earthworms and millipedes). It was concluded that this response arose from the enhanced radiation exposure attributable to their relatively sedentary lifestyles rather than from any intrinsically greater radiosensitivity; the more mobile predatory species showed a lesser response (Table 14). Although enhanced radiation exposure was considered to be the probable cause of the observed changes, other ecological factors could not be excluded. A second survey was made 30 years after the accident to obtain comparative data. Overall, the total density of organisms and their biomass remained depressed, at about 30% of the control values. The earthworms showed some recovery between 1969 and 1988 (Table 15), but it was notable that juvenile individuals were underrepresented in the irradiated population. The numbers in the other major groups also remained depressed relative to the controls: the phytophages, at 16% of control values, had declined since 1969, while

the predatory beetles, at 61% of control values, showed little change overall, although there was a decline in one of the two taxa studied and a recovery in the other.

238. At the same density of radionuclide contamination (deposition on the ground), different species of insects and other invertebrates receive different radiation exposures depending on the specific variations in their behaviour and habitat at particular stages of their life cycle, and for a given radiation dose there will be a range of radiation responses as a consequence of interspecies and age-dependent differences in radiosensitivity. The invertebrate species most likely to be affected by a radionuclide deposit are those whose early (pre-adult) stages of life are spent in the forest litter and surface soil, although length of life cycle is also a significant determinant. It has been concluded that a significant reduction in invertebrate numbers and loss of species from the typical leaf litter communities on the forest floor can be expected at a ^{90}Sr contamination density of 3.7 MBq m^{-2} [G12].

239. Populations of small rodents (dark field mouse: *Microtus agrestis*; red bank vole: *Clethrionomus rutilis*; and wood mouse: *Apodemus sylvaticus*) also attracted attention in the contaminated zone. Populations were isolated in large open-air enclosures and studied for more than 40 generations. In an enclosure with an initial ^{90}Sr contamination density of 44 MBq m^{-2}, the estimated absorbed dose rate to the rodent skeleton decreased from 340 µGy h^{-1} in 1962 to 20 µGy h^{-1} in 1981. Control enclosures were established at the periphery of the contaminated zone. In the early part of the study, when the dose rates were highest, a number of changes were observed in rodent populations in the contaminated enclosures: the death rate increased and individual life-spans decreased owing to accelerated ageing of the older animals; the reproductive performance declined owing to increased embryo loss and a shift in the timing of, and a decrease in, the reproductive span; the incidence of ecto- and endo-parasitism increased; the susceptibility to predation increased; there were changes in behaviour, e.g. a decrease in the number of individual habitation sites used by the dark field mice; individual animals appeared to have greater tolerance of stress, e.g. wood mice proved to be more resistant to a physical load such as swimming; individual animals showed a lower rate of oxygen consumption (considered to be an adaptive response); and, very clearly, there was an overall increase in the variability of most population and individual morphophysiological attributes [I13, I14, I15]. In bank voles and wood mice living at sites with ^{90}Sr contamination densities of 19-63 MBq m^{-2}, the incidence of aberrations in bone marrow cells increased over the 25-30 generations after the accident, i.e. with increasing cumulative dose. Individuals from contaminated sites showed greater radioresistance to single injections of 75-185 kBq ^{90}Sr per gram body weight than did the controls [D17]. Despite all these changes, apparently attributable to the increased radiation exposure, the rodent populations in the contaminated enclosures have survived for many generations, and it has been concluded that there has been some homeostatic adjustment or adaptation to the increased irradiation.

240. At the time of the southeastern Urals accident some farm animals in the contaminated area were still grazing in the fields, although relocation to barns and stables had been in progress. At three sites close to the release point, where the total radionuclide contamination density 20 days after the accident was between 930 and 1,100 MBq m^{-2}, the external dose rate to farm animals was high (Table 16), as was the intake of radionuclides from contaminated grass and subsequent incorporation into tissue (Table 17). Estimates of the absorbed doses over 12 days to different segments of the gastro-intestinal tract (up to 50 Gy) and the skeleton (up to 2 Gy) of cows and sheep are given in Table 18. At these doses the symptoms of acute radiation sickness and the gastro-intestinal syndrome (mucosal bleeding, diarrhoea and leukopaenia) appeared, and the animals began to die 9-12 days after the accident. Where the total radionuclide contamination density was 170 MBq m^{-2}, resulting in an external dose rate from gamma radiation of up to 920 µGy h^{-1} (a total dose of 0.13 Gy in 12 days) and absorbed doses from internal contamination of 4.2 Gy to the rectum and 0.15 Gy to the skeleton, no animals died within six months of the accident. Over a period of 120 days the total radionuclide concentration in some of the tissues of the animals had decreased by up to 75%, but those in the liver and skeleton had increased (Table 17). Those animals from this area that were relocated outside the contaminated zone did not differ from the controls in terms of subsequent mortality or reproductive performance, and there was no firm evidence of an increase in teratogenic effects [A11, B30].

241. Rather less information has been provided concerning the effects of the contamination on aquatic systems. A study of fish populations (pike, perch, roach and golden and silver carp) was made in two lakes 14-15 years after the accident. Although no dose rate estimates are given, the concentration data for ^{90}Sr and ^{137}Cs in water and fish tissues, together with data from previous studies [N1], suggest that at that time the total absorbed dose rate might have been a few thousand microgray per hour, mainly from ^{137}Cs incorporated into the lake sediments, for which no data are given. No effects, compared with controls, were noted for reproductive performance or morphological characteristics [M17]. The general conclusion has been drawn that there are no observable genetic effects in fish at dose rates below 400-1,200 µGy h^{-1}, although under adverse environmental conditions, the threshold might

be lower by a factor of 10, particularly for developing fish eggs [S37].

2. The Chernobyl accident

242. The accident at the Chernobyl nuclear power plant occurred on 26 April 1986. A brief account of the events leading up to the accident, the time-course of the release of the radionuclides and the initial atmospheric dispersion was given in the UNSCEAR 1988 Report ([U3], Annex D); further details on the cause of the accident are given in [I11]. A wider range of radionuclides than in the southeastern Urals accident was released in this accident because the reactor core contained an operational inventory of fission and activation products at the time. The total release, exclusive of noble gases, was estimated to be 2 ± 1 EBq [I11]. The variable time-dependency of the release rates for the different radionuclides and the changing meteorological conditions over the 10-day release period resulted in very inhomogeneous deposition patterns. Not including the 30-km exclusion zone, an area of approximately 2.4 10^4 km^2 was contaminated with ^{137}Cs at a deposition density greater than 200 kBq m^{-2}, with 5,710 km^2 at greater than 600 kBq m^{-2} and 1,360 km^2 at greater than 1.5 Mbq m^{-2} [I12]. Within the exclusion zone the contamination density may have been more than two orders of magnitude greater in limited areas [K14].

243. From the point of view of potential effects on the environment, the main differences between the Chernobyl and southeastern Urals accidents were the time of occurrence and the quantity of activity released. The Chernobyl accident occurred in late April, just as wild plant and animal populations were entering the accelerated growth and reproductive phases of their life cycles. i.e. when they were at their most radiosensitive. Other differences, such as the extended (10-day) period of the release and the radionuclide composition were generally of less significance. As indicated in paragraph 230, three main phases of the radiation impact on the environment were discerned [K3]. In the first, 10-20 days following the accident, essentially acute exposures, in large part from vapour clouds, were delivered to organisms close to the power plant from the large quantities of short-lived radionuclides (^{133}Xe, ^{131}I and ^{99}Mo) released. The second phase extended through the summer and early autumn of 1986, when despite a decline in dose rates at the soil surface to 25%-20% (and sometimes to as low as 10%) of the initial values, damaging total doses were accumulated. In the third and on-going phase of chronic exposure, dose rates are less than 10% of the initial values and are derived mainly from ^{134}Cs and ^{137}Cs contamination. Approximately 80% of the accumulated exposure was delivered within three months of the accident, and over 95% of this was due to beta radiation [S39].

244. Within two weeks of the accident, lethal effects were visible in pine trees close to the damaged reactor. In this zone of 500-600 ha the trees were estimated to have received doses in excess of 80-100 Gy, i.e. doses greater than the acute LD_{50}, mostly from beta radiation. Although the trees were moribund, there was some evidence initially of root survival. The deciduous trees in this zone suffered partial damage. A second zone, of approximately 3,000 ha, received estimated doses above 8-10 Gy, and dieback of new vegetative shoots of pine trees was apparent, needles and buds were damaged and deciduous trees showed morphological changes. In a third zone of 12,000 ha there were moderate effects: coniferous trees received doses estimated to be 3.5-4 Gy and showed various morphological changes, including growth suppression and needle loss, reduced reproductive capacity and genetic damage during 1986 and 1987. There was some evidence of minor abnormalities in growth, morphology and reproduction throughout a large part of the 30-km exclusion zone [K24, K25, S41]. The data on radiation doses in the four zones are summarized in Table 19. It should also be noted, however, that the distribution of absorbed dose in the tissues of trees could be markedly non-uniform owing to the presence of hot particles in the fallout from the reactor. These particles, containing mainly ^{95}Zr-^{95}Nb, ^{106}Ru, ^{134}Cs, ^{137}Cs and ^{144}Ce, were of irregular shape (2-10 to 30-40 μm) and were found sticking to the waxy or resinous covering of pine needles. It has been estimated that the additional absorbed dose from them may have been an order of magnitude greater than the external gamma-ray dose [K25].

245. The radiosensitivity of spruce trees was observed to be higher than that of pine trees. At absorbed doses as low as 0.7-1 Gy, spruce trees showed disturbances in needle morphology, bud development and shoot growth in 1986. In 1987, the trees developed large apical shoots with needles 35-40 mm long and exhibiting a variety of straight, twisted and curved forms [K25].

246. The effects noted in the pine trees were mainly determined by the initial acute (over a period of days) exposures. During the summer of 1986, as dose rates declined, there was continuing inhibition of growth owing, mainly, to meristem damage and the reduced synthesis of growth hormones; new growth was also evident, dependent on the accumulated dose. By the spring of 1987 stems and leaves were actively growing, although some morphological changes were noted in trees that had received doses greater than 2-2.5 Gy. With an overall decline of dose rates to less than 10% of initial values and a relative stabilization of the exposure from internal sources, growth of trees continued and by 1988-1989 was apparent even in the second zone (Table 19) [K3].

247. The reproductive organs, female (seed) and male (pollen) cones, of the pine trees showed the greatest

radiosensitivity. In 1987, at doses of 0.7-1.1 Gy, the incidence of chromosome aberrations in microsporocytes (the premeiotic stage of pollen production) was more than three times the natural level, and the viability of the resultant pollen (tested by *in vitro* germination) decreased by 30%. The female gametophyte, a small, multicellular (approximately 2,000 cells) organ that arises from a single haploid cell (the megaspore) following meiosis and produces 2-6 ova, was also found to be very radiosensitive. In 1988, as can be seen from Table 20, there was some evidence for recovery [K25].

248. In the summer following the accident, disturbances were noted in the process of gametogenesis in crop plants, and grain yields were reduced by 50% [S40]. Dose estimates to the affected plants are not available. Within the 30-km zone around the power station, where the initial dose rates to herbaceous plants had ranged from 2 to 8,000 μGy h^{-1}, there was no correlation in 1988 between the contamination density and effects in seeds of different species, as measured by seed mass and aberrations in root cells from germinated seed. In contrast, seeds of *Plantago lanceolata* showed increased sensitivity to additional radiation exposure [T5].

249. In 1986-1987 a marked reduction was observed in the number of species in the litter microarthropod community of the forests of the 30-km zone; the impact was less pronounced for the soil microarthropods and the larger invertebrates. At an estimated total dose of 30 Gy, no changes were noted in adult animals, but the numbers of juvenile stages were seriously depleted. In the succeeding 2-2.5 years the populations recovered [K16]. Immigration of individuals from outside the zone contributed significantly to the recovery of the insects, and larval abundance reached near-normal levels [S41]. Within the 10-km zone changes in the numbers of wood lice (Crustacea, *Isopoda*) persisted until 1988-1989 [K17].

250. Within the 30-km zone it was estimated that the radiation doses to small rodents over the acute phase (up to mid-May) may have reached 880 Gy (20 Gy from gamma rays and 860 Gy from beta radiation), which would have been lethal [T7]. An increase in morphological variability was noted over 10 generations in populations of bank voles in the contaminated region of Mogilev, Belarus. In addition, individual animals showed lower oxygen consumption, increased tolerance to stress and an increase in radioresistance; it was concluded that all these changes were symptomatic of an adaptation to the increased radiation exposure [I7, K18, K19]. The responses here parallel those observed in rodents inhabiting the contaminated area of the southeastern Urals (see paragraph 240). Biochemical studies of rodents captured in the summer-autumn of 1987 in an area where they were receiving a dose rate of 1,500-2,000 μGy h^{-1} from external gamma radiation showed disturbances of membrane lipid oxidation when compared with animals exposed at 2-10 μGy h^{-1} [K26]. The range of radionuclides present in the deposit on pasture meant that the consequent exposure of farm animals was far from uniform; for example, cows grazing open fields for 240 days following the accident were estimated to have received doses to the thyroid, the gastro-intestinal tract mucosa and the whole body in the ratio 230:2.1:1, and it was suggested that the thyroid exposure might well have contributed to the observed morbidity and mortality [A12]. There was no evidence of teratogenic effects in domestic animals outside the 30-km exclusion zone.

251. In populations of brown frogs (*Rana arvalis* Nills) in contaminated areas close to the Chernobyl power plant, a decrease in male fertility (spermatogenesis) was identified as the only effect that could be unambiguously attributed to the increased radiation exposure (dose estimates are unavailable). In the spring of 1987 more than one third of the egg clusters deposited were wholly or partially infertile. In eggs that were fertile, so-called partial division was observed as a consequence of the anomalous behaviour of the male pronucleus and/or the anomalous replication of the chromosomes. In controls, the proportion of clusters with infertile eggs was less than 1.5%. In 1988 the proportion of partially or completely infertile egg clusters remained high (27%), but this declined to a stable incidence of 3% from 1989 onwards. No effects were detected in the processes of either ovogenesis or embryonic development [C21]. An increased incidence, compared with controls, of cells with chromosome aberrations was found in tissues sampled from frogs in the 30-km zone in 1987 [K27]. In frogs inhabiting areas in Belarus with contamination densities of 180-2,200 kBq m^{-2} of ^{137}Cs and 3.7-96 kBq m^{-2} of ^{90}Sr, the chromosome aberration rate in red bone marrow cells was found to be greater by a factor of 2-10 in the period 1986-1989. The estimated absorbed dose rate of 0.2-7.1 μGy h^{-1} from ^{90}Sr-^{90}Y was considered to be the primary cause [E14]. Chromosome aberrations were also observed in *Chironomid* larvae collected from the Chernobyl power station cooling pond and from small ponds near the village of Yanov, within 10 km of the power station [P19].

252. The cooling water reservoir of the Chernobyl nuclear power plant received a substantial input of radionuclides as a consequence of the accident. Estimated inventories for the end of May 1986 are given in Table 21 [K27]. Maximum dose rates to aquatic animals from external sources (water, particulate material trapped on aquatic plants and sediments) were estimated, using established methodologies, to be 4,200-8,400 μGy h^{-1} in 1986 (10^5 times greater than the

natural background dose rate) [I2, I9, K28]; the estimated dose rates from radionuclides accumulated in tissues were lower, in the range 80-120 μGy h^{-1} [K20]. In 1987 it was estimated that the external dose rate had fallen to 1,300 μGy h^{-1} [P15], and in 1989 radionuclides within the fish were a more significant source of exposure (20-1,300 μGy h^{-1}) than gamma radiation from external sources (0.4-83 μGy h^{-1}) [L10]. For bottom-living fish of the 1985-1986 year class, the accumulated dose from internal and external sources was estimated to have reached 10 Gy by 1991, with over 50% having been received in the three-year period 1986-1989 [K24, K29, K30]. Radiation-induced damage was observed in the gonads of fish surviving the accident and in subsequent generations (see Table 22) [B33, M22]. Over the period 1989-1992, 5 of the 70 silver carp (*Hypophthalmichthys molitrix*) examined were sterile, and 35% of females and 48% of males showed gonad abnormalities, including degeneration of the gametogenic cells. The high dose rates experienced by benthic animals from radionuclides accumulated in the reservoir sediments produced reproduction disturbances in bream (*Abramis brama*) and silver bream (*Blicca bjoernka*) and in colonies of molluscs [K24, S41].

3. Summary

253. The effects on ecosystems of radiation exposures caused by the accidents in the southeastern Urals and at Chernobyl in the former Soviet Union have been analysed. Each accident was unique, clearly so with respect to the radionuclides emitted, the time course and season of the release, but also with respect to the local and regional environmental conditions influencing dispersion and deposition. The highest doses resulted from the acute phase following the accident, until many short-lived radionuclides had decayed. The measurements were most limited in this important phase, and the dosimetry was most complex.

254. There are considerable problems in making accurate estimates, particularly retrospectively, of the total absorbed doses received by the wide variety of organisms inhabiting the areas contaminated by the two accidents. There were substantial variations in the dose rates over time, both between the two accidents and between the accidents and controlled experimental studies. Despite these admitted and considerable uncertainties, it must be concluded that the observed environmental consequences of the accidents are generally consistent with the results of experimental work either under controlled laboratory conditions or employing large, sealed gamma-ray sources in the natural environment.

255. General features of species radiosensitivities were noted in these accidents. Coniferous trees were most sensitive, deciduous trees less so. Herbaceous species with dormant buds at or near the contaminated soil surface were most affected and were replaced by species with buds either below or high above the soil surface and by species with short life cycles. Populations of soil invertebrates received high doses in highly contaminated areas, and their numbers were depressed even 30 years after the accident in the southeastern Urals. The observed effects on fecundity and fertility under continuing chronic irradiation conditions are to be expected and, for the particular cases of fish and molluscs in the cooling water reservoir of the Chernobyl power plant, could have been predicted from available information. There has been no report of a local (i.e. isolated) population of a single species having been eliminated as a consequence of the radiation exposure. Populations of small rodents have been isolated in large enclosures and studied for more than 40 generations. Radiation-related effects have been observed, along with some homeostatic adjustment or adaptation to the altered conditions. There is evidence of recovery, in many instances, from the initial acute-phase responses, and in all areas the populations continue to survive under long-term chronic irradiation.

CONCLUSIONS

256. All living organisms exist and survive in environments where they are subject, to a greater or lesser degree, to the natural radiation background and, more recently, to man-made contamination from global fallout following atmospheric nuclear weapons tests. At times, and generally in restricted areas, there are additional increments of radiation exposures either from authorized (controlled) discharges of radioactive wastes to the air, ground or aquatic systems or from accidental releases. In the majority of cases there have been no apparent effects in wild plants and animals from these additional exposures. Following severe accidents, however, damage has been observed in individual organisms and populations, and long-term effects could develop in communities and ecosystems from the continuing increased chronic irradiation.

257. The available data on the exposure of wild organisms to radiation from the natural background and from contaminant radionuclides are relatively limited. They relate to a very restricted variety of organisms, although for the marine environment they do provide a reasonably representative picture of the range of dose-rate regimes likely to be experienced. Because the

estimates are largely derived either from localized measurements of the concentrations of radionuclides within the organism and in its immediate external environment or from models that assume an equilibrium state, there is very little information on the temporal variation in dose rates to be expected from short-term fluctuations in discharge rates, differing stages in the life cycle, changes in behaviour and short-term environmental factors such as seasonality. It is thus very difficult to estimate from the available data the total doses that are likely to be accumulated over specific stages of the life cycle, e.g. during embryonic development or up to reproductive age.

258. For both terrestrial and aquatic environments, there appears to be a significant contribution to the natural background dose rate from alpha radiation. For the former the main source appears to be ^{222}Rn and its short-lived decay products, and for the latter the main source is ^{210}Po. Owing to the short range of alpha particles, the absorbed dose rates are tissue-specific, and the results underline the crucial need for more detailed information on the distribution of the radionuclides relative to the biological targets that might be considered important (e.g. the developing embryo or the gonads) if accurate estimates of background radiation exposure are to be made. The usual range for the background radiation exposure is up to a few microgray per hour, but in exceptional cases (e.g. the hepatopancreas of a small pelagic marine shrimp) the absorbed dose rate may be as high as 150 μGy h^{-1}.

259. It is accepted that the release of radioactive wastes to the environment is likely to increase the radiation exposure of wild organisms. For discharges to the atmosphere, to a landfill or to surface waters, the published assessments reviewed in this Annex indicate that the radiation exposures to some (but not all) individuals in endemic wild populations could reach about 100 μGy h^{-1} in general; in exceptional cases, depending on the quantities of specific radionuclides in the wastes, absorbed dose rates might reach several thousand microgray per hour. In a very limited number of instances the dose rates estimated from measured concentrations of radionuclides in the contaminated environment have been broadly confirmed by *in situ* measurements employing dosimeters attached to the animals.

260. The dose rates in the environment following an accidental release clearly depend on the quantities of specific radionuclides involved, the time-scale of the release, the initial dispersal and deposition patterns, and their subsequent redistribution by environmental processes over time. It is equally clear that these accidental releases have the potential to generate much higher dose rates and higher total doses in the environment than do normal operations. Such was the case following the accidents in the southeastern Urals and at Chernobyl, where numerous studies have indicated that trees (and, by reasonable extension, other organisms) close to the release points could have accumulated doses up to 2,000 Gy and 100 Gy at the two accident sites, respectively, over relatively short periods of time. At both sites, longer-term chronic exposures from the deposit of longer-lived radionuclides have continued to be significantly higher than exposures from controlled waste disposal.

261. From these data it may be concluded that it is the responses of plants and animals to chronic radiation exposures up to a maximum absorbed dose rate of 1,000 μGy h^{-1} that are of interest from the viewpoint of providing a basis for assessing the environmental impact of controlled radioactive waste releases; in practice, information at lower dose rates, up to 100 μGy h^{-1}, would probably be sufficient in the great majority of cases. For accident situations, where experience has clearly demonstrated that initial dose rates can be high enough to allow accumulating lethal doses in relatively short periods (days), data are needed to provide the basis for predicting the progress of environmental recovery at generally lower, long-term chronic dose rates, down to the upper end (1,000 μGy h^{-1}) of the range of interest for assessing waste disposal practices.

262. There is a wide range over which organisms are sensitive to the lethal effects of radiation. A general classification has been devised based on the interphase chromosome volume of sensitive cells. These and other results of experimental irradiations show mammals to be most sensitive, followed by birds, fish, reptiles and insects. Plants show a wide range of sensitivity that generally overlaps that of animals. Least sensitive to acute radiation exposures are mosses, lichens, algae and micro-organisms, such as bacteria and viruses.

263. Sensitivity of the organism to radiation depends on the life stage at exposure. Embryos and juvenile forms are more sensitive than adults. Fish embryos, for example, have been shown to be quite sensitive. The various developmental stages of insects are quite remarkable for the range of sensitivities they present. Overall, the available data indicate that the production of viable offspring through gametogenesis and reproduction is a more radiosensitive population attribute than the induction of individual mortality.

264. In the most sensitive plant species, the effects of chronic irradiation were noted at dose rates of 1,000-3,000 μGy h^{-1}. It was suggested that chronic dose rates less than 400 μGy h^{-1} (10 mGy d^{-1}) would have effects, although slight, in sensitive plants but would be unlikely to have significant deleterious effects in the wider range of plants present in natural plant communities.

265. For the most sensitive animal species, mammals. there is little indication that dose rates of 400 μGy h^{-1} to the most exposed individual would seriously affect mortality in the population. For dose rates up to an order of magnitude less (40-100 μGy h^{-1}), the same statement could be made with respect to reproductive effects. For aquatic organisms, the general conclusion was that maximum dose rates of 400 μGy h^{-1} to a small proportion of the individuals and, therefore, a lower average dose rate to the remaining organisms would not have any detrimental effects at the population level. The radiation doses necessary to produce a significant deleterious effect are very difficult to estimate because of long-term recovery (including natural regeneration and the migration of individuals from surrounding less affected areas), compensatory behaviour and the many confounding factors present in natural plant and animal communities in both terrestrial and aquatic environments.

Table 1
Internal dose rates to leaves and needles of trees from natural radionuclides in the plant material [J1]

Radionuclide	*Half-life*	*Effective energy (MeV)*		*Dose rate per unit concentration (nGy h⁻¹ per Bq kg⁻¹)*	
		α	β, γ	α	β, γ
H-3	12.4 a	-	0.0057	-	0.0033
C-14	5730 a	-	0.048	-	0.028
K-40	1.28 10^9 a	-	0.068	-	0.039
U-238	4.47 10^9 a	4.18	-	2.42	-
Th-234 [a]	24.1 d	-	0.10	-	0.057
U-234	2.45 10^5 a	4.76	-	2.76	-
Th-230	7.7 10^4 a	4.67	-	2.71	-
Ra-226	1600 a	4.76	-	2.76	-
Rn-222 [b]	3.82 d	19.2	0.22	11.1	0.13
Pb-210 [a]	22.3 a	-	0.12	-	0.068
Po-210	138 d	5.30	-	3.07	-
Th-232	1.41 10^{10} a	4.00	-	2.32	-
Ra-228 [a]	5.75 a	-	0.22	-	0.13
Th-228 [a]	1.91 a	11.1	-	6.42	-
Rn-220 [b]	55 s	20.9	0.21	12.10	0.12

a Including decay product.
b Including short-lived decay products in equilibrium with the parent radionuclide.

Table 2
Dose rates to leaves and needles of trees from natural background radiation

Source	*Absorbed dose rate ($\mu Gy\ h^{-1}$)*		
	α	β, γ	*Total*
	External radiation		
Cosmic radiation at sea level	0.0004 [a]	0.032	0.032
Terrestrial gamma radiation		0.01-0.18	0.01-0.18
	Internal radiation		
H-3	-	0.000001	0.000001
C-14	-	0.0016	0.0016
K-40	-	0.001-0.006	0.001-0.006
U-238-Ra-226 + Th-232-Ra-224	0.0001-0.001	-	0.0001-0.001
Rn-222 in air	-	0.007-0.035	0.007-0.035
Rn-222 in groundwater	0.005-0.54	-	0.005-0.54
Pb-210-Po-210	0.013-0.025	-	0.013-0.025
Total	0.02-0.57	0.05-0.26	0.07-0.8

a From cosmic-ray neutrons.

Table 3
Estimated maximum total absorbed dose rates to aquatic organisms from various sources [a]

Source	Dose rate ($\mu Gy\ h^{-1}$)							
	Fresh water			*Coastal seas*			*Deep ocean (> 4,000 m)*	
	Phyto-plankton	*Pelagic fish*	*Benthic molluscs*	*Phyto-plankton*	*Pelagic fish*	*Benthic molluscs*	*Bathypelagic fish*	*Benthic molluscs*
Natural background								
Cosmic radiation [b]	0.027	0.022	0.022	0.027	0.022	0.022	-	-
Internal radionuclides	-	0.049 (0.013)	-	0.073 (0.072)	0.047 (0.022)	0.15 (0.12)	0.06 (0.03)	0.19 (0.16)
Radionuclides in water	0.062	0.007	0.0035	0.0043 (0.0002)	0.001	0.0005	-	-
Radionuclides in sediment [c]	-	-	0.16	-	-	0.16	-	-
Total	0.089	0.078	0.19	0.1	0.070	0.33	0.06	0.19
Global weapons fallout								
Internal radionuclides	-	0.26	0.0015	0.25 (0.003)	0.018	0.080	-	-
Radionuclides in water	0.0053	0.0026	0.0013	0.00016 (0.00001)	0.00007	0.00003	-	-
Radionuclides in sediment [c]	-	-	0.058	-	-	-	-	-
Total	0.0053	0.26	0.061	0.25	0.018	0.080	-	-
Waste disposal								
Columbia River								
Internal radionuclides	2.0	21	240	-	-	-	-	-
Radionuclides in water	0.026	0.023	0.011	-	-	-	-	-
Radionuclides in sediment [c]	-	-	8.6	-	-	-	-	-
Northeast Irish Sea								
Internal radionuclides	-	-	-	21	0.015	0.59	-	-
Radionuclides in water	-	-	-	0.033	0.024	0.012	-	-
Radionuclides in sediment [c]	-	-	-	-	-	33	-	-
Northeast Atlantic dump site								
Internal radionuclides	-	-	-	-	-	-	0.0068 (0.0024)	0.40 (0.39)
Radionuclides in water	-	-	-	-	-	-	-	-
Radionuclides in sediment [c]	-	-	-	-	-	-	-	0.025
Total	2.0	21	250	21	0.039	34	0.0068	0.42

a Values in parentheses are the contribution to the absorbed dose rates from high-LET radiation.
b At 1 m depth for phytoplankton and 2 m depth for fish and molluscs.
c Gamma radiation only.

Table 4
Dose rates to leaves and needles of trees from noble gas radionuclides in air [J1]

Radionuclide	*Half-life*	*Decay mode*	*Effective energy (MeV)*		*Dose rate per unit concentration in air (10^{-12} Gy h^{-1} per Bq m^{-3})*	
			External	*Internal*	*External*	*Internal*
Ar-41	1.83 h	β	0.25	0.083	110	0.004
		γ	1.3	-	580	-
Kr-85m	4.48 h	β	0.080	0.086	36	0.008
		γ	0.16	-	72	-
Kr-85	10.7 a	β	0.08	0.10	40	0.01
Kr-87	76.3 min	β	1.2	0.040	540	0.004
		γ	0.80	-	360	-
Kr-88 [a]	2.86 h	β	0.57	0.26	250	0.025
		γ	2.1	-	950	-
Xe-131m	11.9 d	γ	0.04	0.16	18	0.04
Xe-133m	2.2 d	γ	0.06	0.20	30	0.05
Xe-133	5.25 d	β	0.004	0.12	2	0.03
		γ	0.046	-	21	-
Xe-135m	15.6 min	γ	0.43	0.10	190	0.025
Xe-135	9.1 h	β	0.12	0.10	54	0.025
		γ	0.25	-	110	-
Xe-138 [a]	14.2 min	β	0.8	0.13	360	0.03
		γ	1.8	-	810	-

a Including decay products.

Table 5
Estimated doses to leaves and needles of trees from normalized discharge to the atmosphere of noble gases from nuclear reactors

Radionuclide	*Normalized discharge* [a] *[TBq (GW a)$^{-1}$]*	*Integrated concentration in air at 1 km* [b] *[Bq h m^{-3} (GW a)$^{-1}$]*	*Dose factor* [c] *[nGy h^{-1} per Bq m^{-3}]*	*Absorbed dose per unit energy generated [μGy (GW a)$^{-1}$]*
		Pressurized water reactors		
Ar-41	0.87	72	0.69	0.050
Kr-85m	0.24	20	0.11	0.002
Kr-85	3.5	290	0.04	0.012
Kr-87	0.04	33	0.90	0.003
Kr-88	0.16	13	1.2	0.016
Xe-131m	0.69	57	0.018	0.001
Xe-133m	0.53	44	0.03	0.001
Xe-133	82	6830	0.023	0.16
Xe-135m	0.062	5.2	0.19	0.001
Xe-135	3.5	290	0.16	0.047
Xe-138	0.17	14	1.2	0.017
Total				0.3
		Boiling water reactors		
Ar-41	0.15	12	0.69	0.009
Kr-85m	4.0	330	0.11	0.037
Kr-85	1.3	110	0.04	0.004
Kr-87	4.0	330	0.90	0.30
Kr-88	6.5	540	1.2	0.65
Xe-131m	0.22	18	0.018	0.0003
Xe-133m	0.28	23	0.03	0.0007
Xe-133	26	2170	0.023	0.050
Xe-135m	3.8	320	0.19	0.060
Xe-135	12	1000	0.16	0.16
Xe-138	13	1080	1.2	1.3
Total				2.6
		Gas-cooled reactors		
Ar-41	2150	180000	0.69	120

a Data from UNSCEAR 1993 Report [U2].
b Assumes dispersion factor of 3 10^{-7} Bq s m^{-3} per Bq [U4].
c From Table 4 [J1].

Table 6
Estimated dose rates to organisms from controlled discharges of radionuclides that would each result in a dose rate of 1 mSv a⁻¹ to man residing in the same environment
[I4, N1]

Radionuclide	Dose rate (μGy h⁻¹)		
	Plants [a]	Animals [a b]	Fish [c]
H-3	5.8	5.8	0.59
C-14	18	11	
P-32	32	28	4.8
Co-60			0.53
Sr-90	2.0	0.042	67
Zr-95	38	2.0	
Tc-99			3.8
I-131	1.2	0.058	
Cs-137	5.4	3.1	0.72
Ra-226 [d]			3.6
U-235 [d]			2.6
U-238 [d]			4.7
Pu-239 [d]	0.023	0.00055	0.49
Am-241 [d]			0.71

a Discharges to atmosphere.
b Domestic sheep.
c Discharges to water (lakes).
d High-LET radiation.

Table 7
Cumulative absorbed doses in agricultural animals following single intakes of radionuclides and for similar periods of chronic intakes of radionuclides
[K9]

Animal species	*Type of exposure* [a]	Cumulative absorbed dose (µGy)						
		After 10 days	*After 20 days*	*After 30 days*	*After 60 days*	*After 90 days*	*After 180 days*	*After 365 days*
Iodine-131 [b]								
Cattle	Single	200	300	340	370	370		
	Chronic	900	2,000	3,000	4,200	4,300		
Sheep	Single	1,100	1,600	1,800	2,000	2,000		
	Chronic	4,900	11,800	16,600	22,200	23,000		
Swine	Single	420	600	700	740	740		
	Chronic	1,800	4,400	6,200	8,300	8,300		
Strontium-90 [c]								
Cattle	Single	0.6	1	1.2		2.4	4	6
	Chronic	2	10	20		128	420	1,360
Sheep	Single	4	8	10		20	32	52
	Chronic	22	82	166		1,080	3,420	11,320
Swine	Single	8	14	20		40	60	100
	Chronic	40	140	300		1,920	6,180	20,400
Caesium-137 [d]								
Cattle	Single	0.07	0.12	0.17		0.37	0.50	0.56
	Chronic	0.32	1.25	2.7		19.7	60	160
Sheep	Single	0.5	1	1.4		3.1	4.2	4.7
	Chronic	2.8	10.5	22.6		165	500	1,330
Swine	Single	0.32	0.6	0.9		1.9	2.5	2.8
	Chronic	1.6	6.3	13.5		98.5	300	800

a Intake of 1 kBq on the first day for both single and chronic exposures; for chronic exposure the intakes declined according to the radioactive decay rates; radionuclides administered orally in experimental setting.
b Absorbed dose in thyroid.
c Absorbed dose in bone.
d Absorbed dose in muscle.

Table 8
Absorbed dose and period in organogenesis for radiation-induced, externally detectable malformations
[C22]

Radiosensitive organ	*Animal species*	*Main induction period (days after conception)*	*Lowest reported dose to cause effect*	*Main dose range to cause effect* [a]
Central nervous system	Mouse (strain-dependent)	8-13	0.25 Gy	1.0-2.0 Gy
	Rat	9-14	0.50 Gy [b]	1.0-2.0 Gy
Eye	Mouse	7-8	0.25-0.50 Gy	1.0-2.0 Gy
	Rat	9-10	0.25 Gy	1.0-2.0 Gy
	Hamster	8-9	>1.0 Gy	
	Rabbit	-10	>1.0 Gy	
Skull	Mouse	7-10	0.5 Gy	1.0-2.0 Gy
	Rat	9-12	1.0 Gy	1.5-2.5 Gy
	Hamster	7-8		>2.0 Gy
	Rabbit	9-11		>4.0 Gy
	Monkeys	8-12		>2.5 Gy
Trunk	Mouse	6-13		>0.25 Gy
	Sheep	-23		>1.0 Gy
	Cattle	-32		>1.0 Gy
Extremities	Mouse	10-3		>1.5 Gy
	Rat	>9		>2.0 Gy
	Hamster	>9		>2.0 Gy
	Dog	25-28		>1.3 Gy

a Single x-ray exposure.
b Histological findings from 0.1 to 0.4 Gy.

Table 9
Dose levels from short-term irradiation producing damage to plant communities [a]
[W5]

Plant community	*Dose range to produce effects (Gy)*		
	Minor effects	*Intermediate effects*	*Severe effects*
Coniferous forest	1-10	10-20	>20
Deciduous forest	10-100	50-350	>100
Shrubland	10-50	50-200	>200
Tropical rain forest	40-100	100-400	>400
Rock outcrop	80-100	100-400	>400
Old field	30-100	100-1,000	>1,000
Herbaceous forest understorey	200-400	400-600	>600
Grassland	80-100	100-1,000	>1,000
Herbaceous invaders	400-600	600-1,000	>1,600
Moss lichen	100-1,000	500-5,000	>2,000

a Exposures of 8-30 days. Dose range may be 2-4 times less for more acute exposures. Equivalent daily dose ranges for chronic effects are 1%-4% of the listed values.

Table 10
Primary composition of radionuclides deposited in a contaminated area following the southeastern Urals accident [T21]

Radionuclides	*Half-life*	*Fraction of total activity (%)*						
		October 1957	*March 1958*	*July 1958*	*July 1959*	*July 1960*	*July 1961*	*July 1962*
^{144}Ce - ^{144}Pr	265 d	66.3	78.2	80.0	68.6	49.6	29.6	15.0
^{90}Sr - ^{90}Y	28 a	5.15	8.4	12.3	26.0	45.6	66.6	82.7
^{106}Ru - ^{106}Rh	1 a	3.45	4.6	4.9	5.3	4.8	3.8	2.3
^{95}Zr - ^{95}Nb	65 d	25.1	9.0	2.8	0.1	0	0	0

Table 11
Vertical distribution of dose rates from beta and gamma radiation to components of a pine forest in an area of contamination from the southeastern Urals accident normalized to deposition density of ^{90}Sr of 1 MBq m^{-2} [T17]

Months after deposition	*Absorbed dose rate (μGy h^{-1})*				
	At soil surface	*At litter surface (2 cm)*	*At bottom part of crowns (3 m)*	*At middle part of crowns (6-7 m)*	*At top part of crowns (9-10 m)*
0	67	270	2,200	3,000	1,700
1	1,700	9,400	3,300	1,700	1,200
7	2,300	12,000	1,300	1,500	830
21	2,300	10,000	830	670	330
33	6,300	4,000	250	83	50
45	9,400	2,000	130	50	25

Table 12
Normalized radiation dose rates to organisms during the acute period following the accident in the southeastern Urals [a]
[T17]

Organism	*Component, location or specific type of organism*	*Maximum normalized absorbed dose rates (μGy h^{-1} per MBq m^{-2} ^{90}Sr)*	*Absorbed doses during the acute period*	
			Normalized doses (Gy per MBq m^{-2} ^{90}Sr)	*Maximum doses near release point (Gy)*
Pine trees	Bud meristem	1,300-2,100	3-5	100-800
	Seeds in the canopy	830-1,300	2-3	50-400
	Seeds on the soil	420-830	0.5-1	20-200
Birch trees	Bud meristem	830-1,300	0.5-2	20-200
	Seeds in the canopy	420-830	0.3-0.7	10-100
Herbaceous plants	Dormant buds	0-4,200	0-10	0-2,000
	Seeds on the soil	830-4,200	2-10	70-2,000
Soil invertebrates	In the leaf litter	130-830	0.5-5	200-800
	At 1 cm depth in the soil	83	3	10-40
Mammals	Large herbivores (GI tract)	1,300	3	100-400
	Small rodents (whole body)	130-210	1-2	10-100
	Carnivores (GI tract)	420	3	30-100
Birds	Small, overwintering	830-1,300	2-3	50-400
	Carnivorous, overwintering (GI tract)	420	1	30-100

a The dose rates have been normalized to a strontium-90 contamination density of 1 MBq m^{-2}, because there was a relatively constant relationship between all the radionuclides throughout the deposition.

Table 13
Radiation damage to trees in the contaminated area of the southeastern Urals

^{90}Sr contamination density (MBq m^{-2})	*Average absorbed dose (Gy)*		*Radiobiological effect*
	Needles	*Bud meristem*	
1.5-1.8	5-10	2-4	Pine: desiccation of needles in the lower part of the crown, non-viability of pollen and seeds, reduction in growth increment
3.7-4.4	10-20	5-10	Pine: desiccation of 95% of the crown, growth retardation
6.3-7.4	20-40	10-20	Pine: complete death (LD_{100})
37-59	-	40-60	Birch: desiccation of the upper storey in 1% of trees, up to 30% reduction of young growth, low germination capacity of seeds, reduction in growth increment
92-140	-	100-150	Birch: desiccation of the upper storey in 30% of trees, up to 75% reduction of young growth (LD_{50})

Table 14
Numbers of the main groups of soil mesofauna in ^{90}Sr-contaminated and control sites in the southeastern Urals [K15]

Type of invertebrate	*Species*	*Absolute number per m²*		*Proportion of control*
		At contaminated site	*Control*	
Saprophage	Earthworms	0.1	9.4	0.01
	Millipedes		6.0	
	Total	0.1	15.4	0.01
Phytophage	Snails/slugs	0.7	3.0	0.23
	Herbivorous insect larvae	9.0	14.5	0.62
	Total	9.7	17.5	0.55
Predators	Spiders	2.0	7.0	0.29
	Insect larvae	5.0	6.5	0.75
	Beetles	12.5	8.5	1.47
	Centipedes	1.4	9.0	0.16
	Total	20.9	30.0	0.70

Table 15
Changes in numbers of the main groups of soil mesofauna in ^{90}Sr-contaminated sites in the southeastern Urals [K15]

Type of invertebrate	*Species*	*Absolute number per m² in 1988*		*Proportion of control*	
		At contaminated site	*Controls*	*In 1969*	*In 1988*
Saprophage	Earthworms	3.7 ± 0.9	8.8 ± 3.7	0.08	0.42
Phytophage	Click beetles	4.3 ± 1.8	25.5 ± 10.7	0.59	0.17
	Weevils	1.8 ±0.7	12.3 ± 5.1	0.44	0.15
Predators	Carabid beetles	5.8 ± 0.6	7.8 ± 2.5	0.48	0.77
	Staphylinid beetles	1.7 ± 0.6	4.3 ± 1.3	0.83	0.40
Other	Lithobiidae	0.3 ± 0.1	2.0 ± 0.8	0.10	0.15
	Diptera	2.0 ± 0.6	2.0 ± 0.6	0.24	No difference

Table 16
Degree of contamination and external dose rates at sites where farm animals were grazing following the accident in the southeastern Urals [A11]

Site	*Contamination density on day 20 (MBq m⁻²)*	*Concentration of beta emitters in grass (MBq kg⁻¹)*	*External dose rate at 1 m (μGy h⁻¹)*	*Total absorbed dose over 12 days (Gy)*
1	1,100	360	15,000	2.9
2	1,100	340	11,000	2.0
3	930	28	6,300	1.4
4	170	-	920	0.13

Table 17
Total concentration for all radionuclides in animal tissues near sites of the accident in the southeastern Urals [A11]

Animal	*Mass (kg)*	*Number of animals*	*Concentration (kBq kg⁻¹)*						
			Muscle	*Lung*	*Liver*	*Kidney*	*Skeleton*	*Large intestine*	*Wool, feathers*
Site 1 [a]									
Cow	300	1	19		150		370	200	
Cow fetus	30	1	20	14	37	39	1,200	21	
Goat	30	1	24	240	98	230	1,100	410	160,000
Sheep	30	1	58	56	170	510	190	190	46,000
Geese	3.2	3	1.1	10	3.3	5.6	59	3.3	1,700
Hens	1.2	3	3.0	20	28	37	250		12,000
Site 4 [a]									
Cow									
Day 11	300	1		14	7.0	8.1	24		
Day 120	380	1	0.33	8.1	24	2.9	63	0.33	
Sheep									
Day 11	30	1	6.7	34	1.5		74	19	2,100
Day 120	48	1	1.9	5.2	5.6	4.1	310	59	9,300
Geese									
Day 11	4	3	1.2	41	1.4	2.8	41	170	1,800
Day 120	5.1	2	0.44	19	31	1.1	240	19	520
Hens									
Day 11	1.2	3	0.96	5.9	0.93	2.1	81	27	220
Day 120	1.4	5	0.22	2.1	0.26	0.26	85	5.6	85

a Contaminated sites defined in Table 16.

Table 18
Estimated absorbed dose over 12 days to different segments of the gastro-intestinal tract and to the skeleton of sheep and cows at three sites contaminated by the accident in the southeastern Urals [A11]

Organ	*Absorbed dose (Gy)*					
	Sheep			*Cows*		
	Site 1	*Site 2*	*Site 3*	*Site 1*	*Site 2*	*Site 3*
Segment of GI tract						
Rumen (1)	9.1	9.0	2.5	9.3	8.9	2.5
Rumen (2)	7.5	7.1	2.0	6.2	5.9	1.6
Omasum	11	10	2.5	16	15	4.2
Abomasum	4.5	4.3	1.2	3.8	3.7	1.0
Duodenum	3.8	3.6	1.0	2.2	2.2	0.61
Jejenum	4.9	4.7	1.3	2.6	2.5	0.69
Ileum	7.6	7.3	2.0	5.6	5.4	1.5
Large colon	30	29	8.0	14	13	3.7
Small colon	34	33	9.2	17	17	4.6
Rectum	54	52	15	23	22	6.0
Skeleton	1.9	1.9	0.53	1.9	1.8	0.48

Table 19
Distribution of radiation damage in the forest around Chernobyl nuclear power plant
[K24, K25]

Damage zone/area	*Type of damage*	*Absorbed dose from external gamma radiation (Gy)*	*Absorbed dose rate on 1 October 1986 (μGy h⁻¹)*	*Absorbed dose in needles (Gy)*
Lethal zone, 4 km²	Complete death of pine trees Partial damage of deciduous trees	>80-100	>5,000	>100
Sublethal zone, 38 km²	Death of most growth points, partial dieback of coniferous trees Morphological changes in deciduous trees	10-20	2,000-5,000	50-100
Zone of medium damage, 120 km²	Suppressed reproductive ability, desiccated needles, morphological changes	4-5	500-2,000	20-50
Zone of minor damage	Disturbances in growth and reproduction, morphological disturbances in coniferous trees	0.5-1.2	<200	<10

Table 20
Chromosomal aberrations at meiosis in pine microsporocytes in an area close to the Chernobyl nuclear power reactor
[K25]

Estimated absorbed dose (Gy)	*Number of cells analysed*		*Chromosomal aberrations (%)*	
	1987	*1988*	*1987*	*1988*
0.7-1.1	4,200	1,800	22.0	14.4
1.7-2.3	6,300	2,200	30.2	9.6
Control	3,000	1,000	5.7	5.8

Table 21
Estimates of quantities of radionuclides in the Chernobyl nuclear power plant cooling pond on 20 May 1986
[K27]

Radionuclide	*Activity (10^{12} Bq)*	
	Sediments	*Water*
Cs-137	110 ± 50	60 ± 30
Cs-134	60 ± 40	30 ± 15
Ce-144	860 ± 400	30 ± 20
Ce-141	640 ± 280	50 ± 30
Ru-106	220 ± 100	20 ± 10
Ru-103	700 ± 360	40 ± 15
Zr-95	1200 ± 500	50 ± 30
Nb-95	1100 ± 400	70 ± 40
Ba-140	400 ± 140	120 ± 70
La-140	280 ± 120	80 ± 40
I-131	30 ± 10	250 ± 60
Sr-90	50 ± 20	6 ± 4

Table 22
Effects of radiation on silver carp fish surviving in the Chernobyl nuclear power plant cooling pond after the accident
[B33]

Year of sampling	*Number of fish analysed*				*Proportion of fish with abnormalities in generative cells (%)*		
	Females	*Males*	*Sterile*	*Total*	*Females*	*Males*	*Total*
	Caged silver carps [a]						
1989	17	8	2	27	0	25	-
1990	11	6	3	20	55	33	47
1991	9	7	0	16	78	57	69
1992	3	4	0	7	33	100	71
Total	40	25	5	70	35	48	44
	Uncaged silver carps [b]						
1992	9	10	2 [c]	19	89	90	90

a Confined in aquaculture pens.
b At large in the cooling pond.
c Partial sterility.

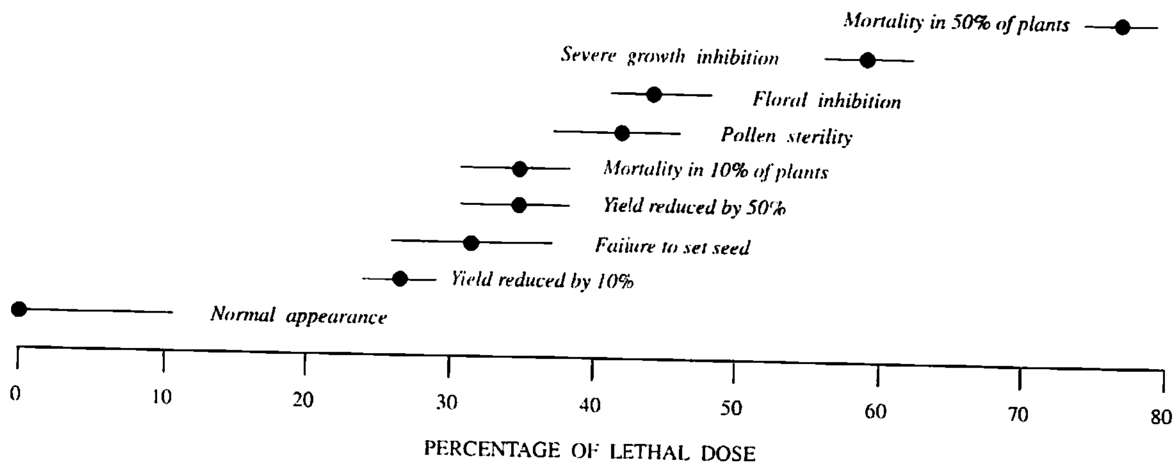

Figure I.
General range of radiation response in herbaceous plants in comparison to the lethal dose (LD_{100}).
[S8]

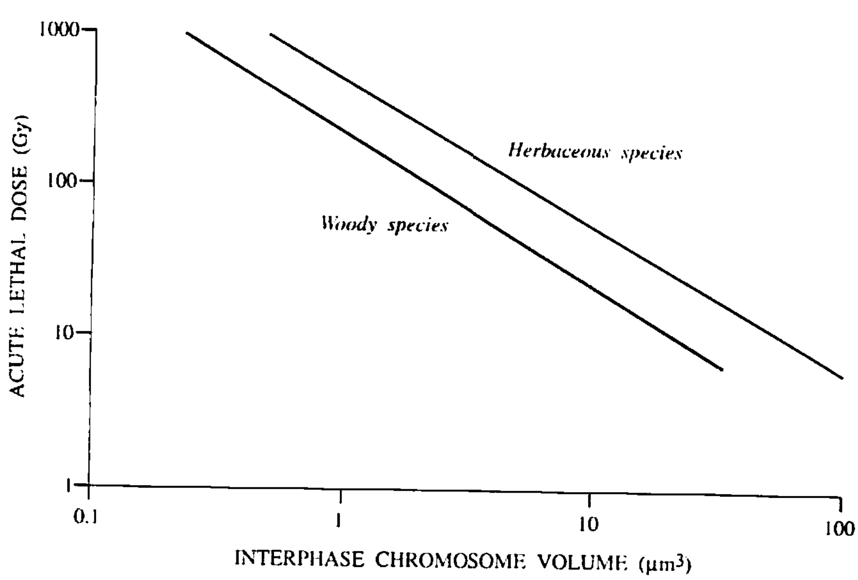

Figure II.
The acute lethal exposure to high-dose-rate, low-LET radiation in relation to the volume of interphase (non-dividing) chromosomes of angiosperms.
[S12]

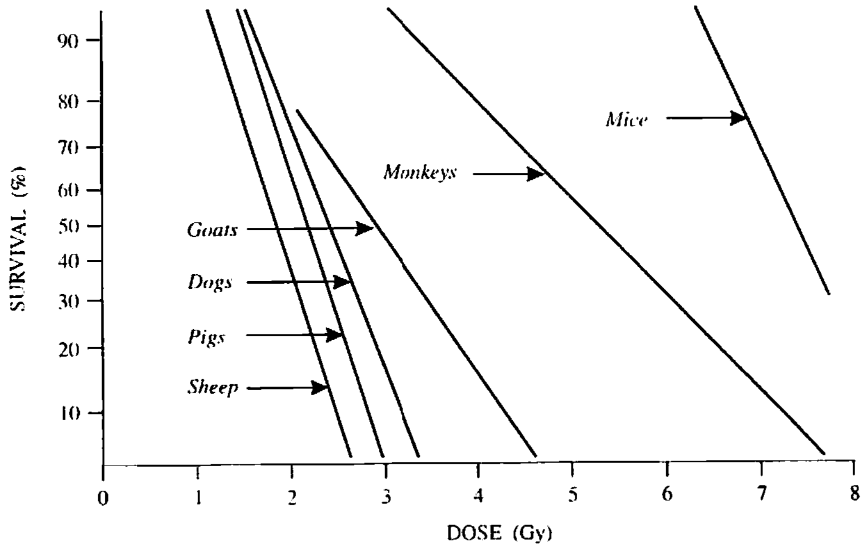

Figure III.
Midline dose-survival curves for various species of animals irradiated bilaterally.
[T10]

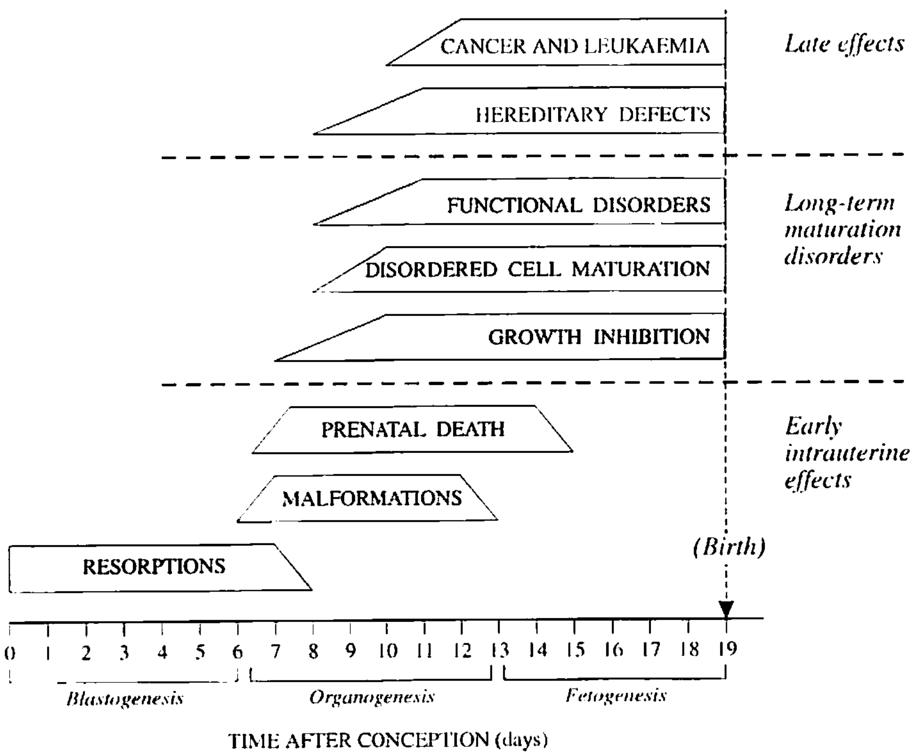

Figure IV.
Prenatal phases for induction of radiation effects in the mouse
[C22]

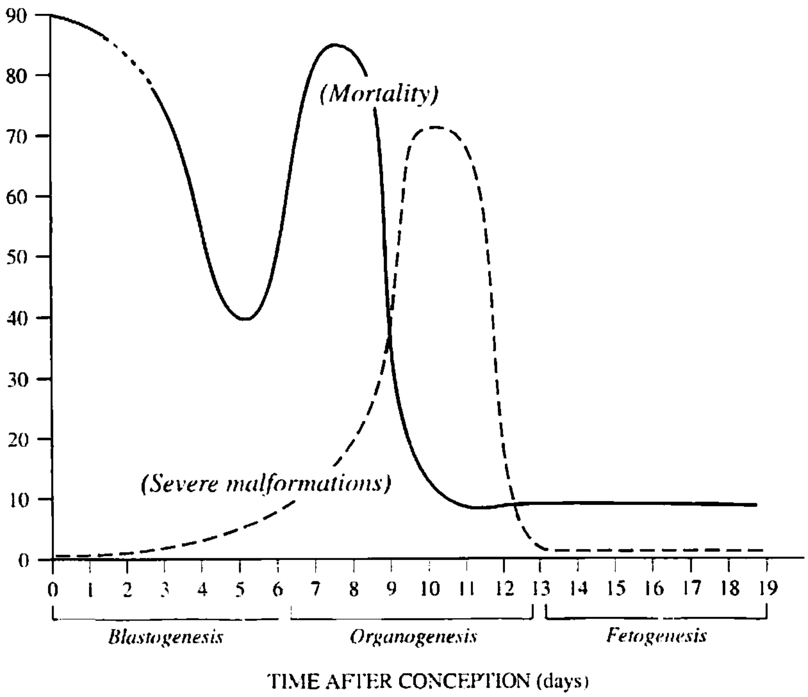

Figure V.
Relative occurrence of intrauterine injuries in the mouse after acute x irradiation with 1.9 Gy. For irradiation following day 14 after conception, there is no radiation-induced injury, and the spontaneous rates are observed.
[C22]

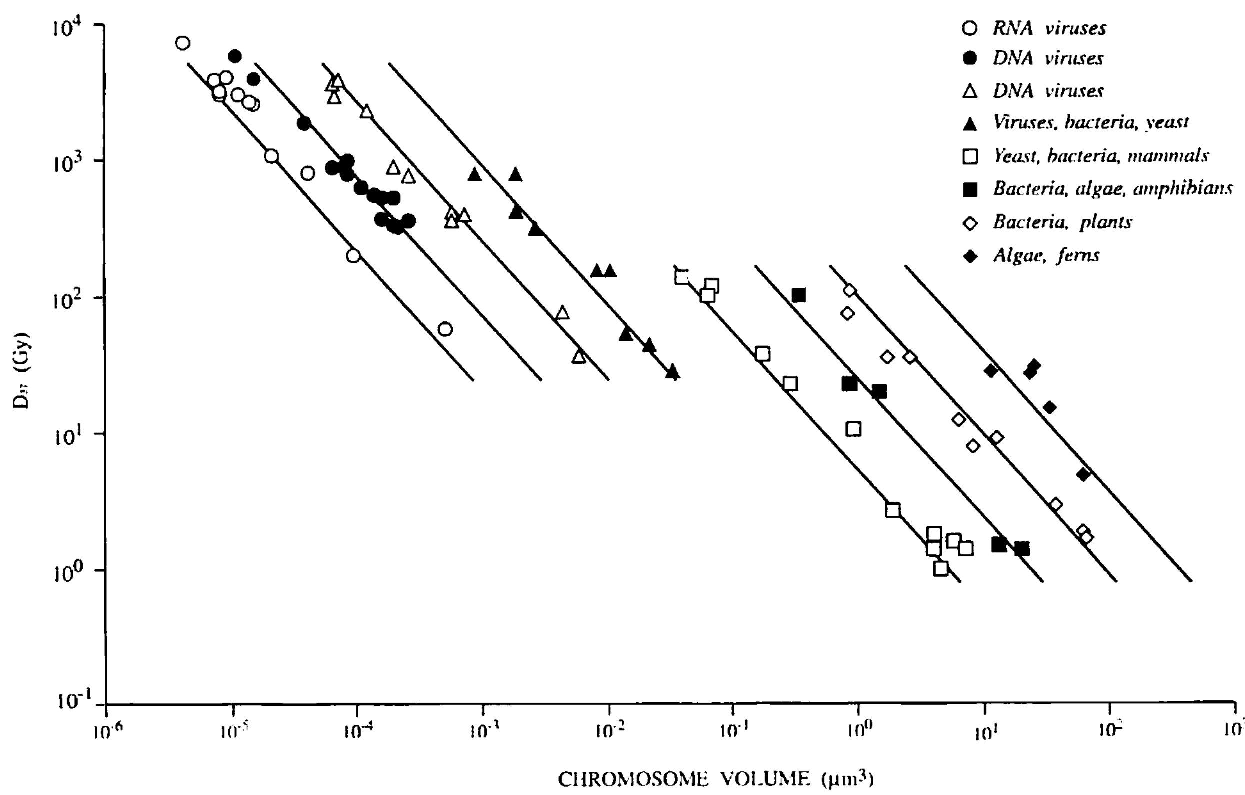

Figure VI.
Cell radiosensitivity based on correlation between D_{37} (37% survival dose) and chromosome volume.
[S1]

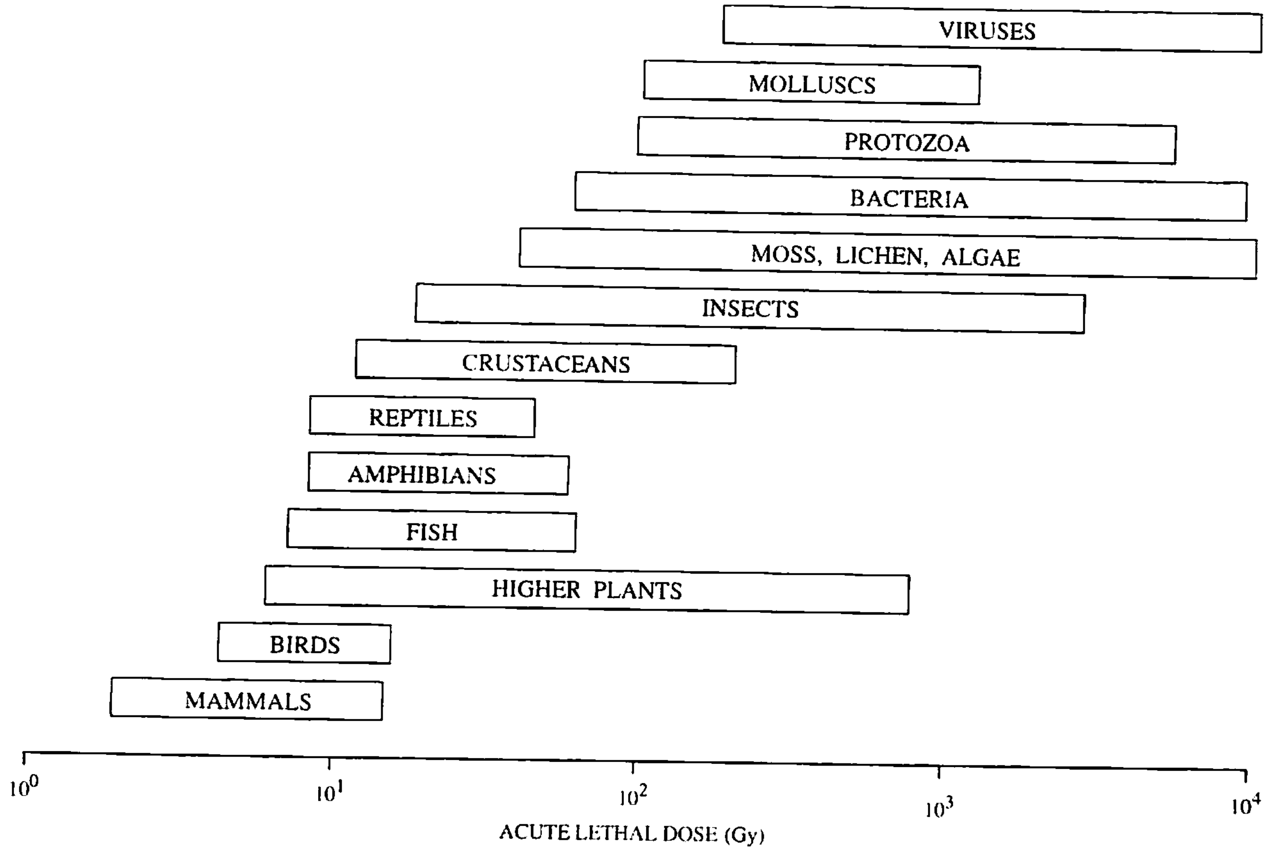

Figure VII.
Approximate acute lethal dose ranges for various taxonomic groups.
[S1, W5]

References

A1 Arena, V. Ionizing Radiation and Life. C.V. Mosby, St. Louis, 1971.

A2 Anderson, S.L. and F.L. Harrison. Effects of radiation on aquatic organisms and radiobiological methodologies for effects assessment. USEPA EPA-520/1-85-016 (1986).

A3 Andersen, A.C., A.G. Hendrickx and M.H. Momeni. Effects of prenatal fractionated x-ray exposures on the ovary of the bonnet monkey. Radiat. Res. 67: 526 (1976).

A4 Amiro, B.D. and J.R. Dugle. Temporal changes in a boreal forest tree canopy cover along a gradient of gamma radiation. Can. J. Bot. 63: 15-20 (1985).

A5 Amiro, B.D. Effect of gamma-radiation dose rate and total dose on stem growth of *Pinus banksiana* (Jack pine) seedlings. Environ. Exp. Bot. 26: 253-257 (1986).

A6 Armentano, T.V. and G.M. Woodwell. The production and standing crop of litter and humus in a forest exposed to chronic gamma irradiation for twelve years. Ecology 57: 360-366 (1976).

A7 Auerbach, S.I., D.A. Crossley and M.D. Engelman. Effects of gamma radiation on Collembola population growth. Science 126: 614 (1957).

A8 Abrahamson, S., M.A. Bender, A.D. Conger et al. Uniformity of radiation-induced mutation rates among different species. Nature 245: 460-462 (1973).

A9 Alexakhin, R.M. Nuclear Power and the Biosphere. Energoatomizdat, Moscow, 1982.

A10 Alexakhin, R.M. and M.A. Naryshkin. Migration of Radionuclides in Forest Biogeocenoses. Nauka Publishers, Moscow, 1977.

A11 Alexakhin, R.M., A.P. Povalyayev, V.A. Sokolov et al. Radiation accidents and the agricultural industry. p. 316-365 in: Agricultural Radioecology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers, Moscow, 1991.

A12 Alexakhin, R.M., I.A. Sarapultsev, Y.V. Spirin et al. Formation of dose burdens in agricultural animals following the Chernobyl nuclear power plant accident and the effect of their relocation on the absorbed doses. Proc. USSR Acad. Sci. 323(3): 576-579 (1992).

A13 Atkinson, G.F. Report on some preliminary experiments with Roentgen rays on plants. Science 7: 7 (1895).

A14 Antropova, Z.G., E.I. Belova, I.K. Dibobes et al. A Review of Studies and Experience in Eliminating the Consequences of the Accidental Contamination of the Territory with Uranium Fission Products (A.I. Burnazyan, ed.). Energoatomizdat, Moscow, 1990.

B1 Bacq, Z.M. and P. Alexander. Fundamentals of Radiobiology, 2nd Edition. page 562. Pergamon Press, Elmsford, New York, Oxford, 1961.

B2 Bell, M.C., L.B. Sasser and J.L. West. Simulated fallout radiation effects on livestock. p. 193 in: Survival of Food Crops and Livestock in the Event of Nuclear War (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).

B3 Blaylock, B.G. Chromosomal polymorphism in irradiated natural populations of Chironomus. Genetics 53: 131-136 (1966).

B4 Blaylock, B.G. and J.R. Trabalka. Evaluating the effects of ionizing radiation on aquatic organisms. p. 103 in: Advances in Radiation Biology, Volume 7 (J.T. Lett and H. Adler, eds.). Academic Press, New York, 1978.

B5 Blinks, L.R. Effects of radiation on marine algae. J. Cell. Comp. Physiol. 39 (Suppl. 2): 11 (1952).

B6 Brisbin, I.L. Responses of broiler chicks to gamma-radiation exposures: changes in early growth parameters. Radiat. Res. 39: 36-44 (1969).

B7 Buech, R.R. Observations of nesting avifauna under gamma radiation exposure. p. 181 in: The Enterprise, Wisconsin. Radiation Forest: Radioecological Studies. ERDA TID-26113-P2 (1977).

B8 Bond, V.P., T.M. Fliedner and J.O. Archambeau. Mammalian Radiation Lethality. Academic Press, New York, 1965.

B9 Bell, M.C. Radiation effects on farm animals: a review. p. 656-669 in: Survival of Food Crops and Livestock in the Event of Nuclear War (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).

B10 Baverstock, K.F., D.G. Papworth and K.M. Townsend. Man's sensitivity to bone marrow failure following whole body exposure to low-LET ionizing radiation: inferences to be drawn from animal experiments. Int. J. Radiat. Biol. 47: 397-411 (1985).

B11 Berger, M.J. Distribution of absorbed dose around point sources of electrons and beta-particles in water and other media. J. Nucl. Med. 12 (Suppl. 5): 5-23 (1971).

B12 Berger, M.J. Energy deposition in water by photons from point isotropic sources. J. Nucl. Med. 9 (Suppl. 1): 15-25 (1968).

B13 Brownell, G.L., W.H. Ellett and A.R. Reddy. Absorbed fractions for photon dosimetry. J. Nucl. Med. 9 (Suppl. 1): 27-39 (1968).

B14 Bakker, K. Some general remarks on the concepts of "population" and "regulation". p. 565-567 in: Proc. Adv. Study Inst. Dynamics and Numbers of Populations, Oosterbeek, 1970. Centre for Agricultural Publishing and Documentation, Wageningen, 1971.

B15 Brown, S.O., G.M. Krise, H.B. Pace et al. Effect of continuous radiation on reproductive capacity and fertility of the albino rat and mouse. p. 103-110 in: Effects of Ionizing Radiation on the Reproductive System (W.D. Carlson and F.X. Gassner, eds.). MacMillan, New York, 1964.

B16 Belot, Y. Tritium in plants: a review. Radiat. Prot. Dosim. 16: 101-105 (1986).

B17 Berry, R.J. Genetic effects of radiation on populations. At. Energy Rev. 10 (1): 67-100 (1972).

B18 Blair, W.F. Radiation-induced genetic damage in the Mexican toad (*Bufo valliceps*). Tex. J. Sci. 12: 216-227 (1960).

B19 Bornhausen, M., A. Burgmeier, A. Matthes et al. Effects of prenatal treatment with ionizing radiation and/or heavy metal compounds on the conditioned behaviour of rats. p. 309-312 in: Developmental Effects of Prenatal Irradiation. Gustav Fischer, Stuttgart, 1982.

B20 Bourdeau, P.F. and G.M. Woodwell. Field measurements of carbon dioxide exchange by *Pinus rigida* trees exposed to chronic gamma irradiation. Ecology 45: 403-406 (1964).

B21 Brayton, R.D. and G.M. Woodwell. Effects of ionizing radiation and fire on *Gaylussacia baccata* and *Vaccinium vacillans*. Am. J. Bot. 53: 816-820 (1966).

B22 Brodo, I.M. Field studies of the effects of ionizing radiation on lichens. Bryologist 67: 76-87 (1964).

B23 Bonham, K. and A.D. Welander. Increase in radioresistance of fish to lethal doses with advancing embryonic development. p. 353-358 in: Radioecology (V. Schultz and A.W. Klement, eds.). Reinhold Publishing Corp., New York, 1961.

B24 Baptist, J.P., D.A. Wolfe and D.R. Colby. Effects of chronic gamma radiation on the growth and survival of juvenile clams (*Mercenaria mercenaria*) and scallops (*Argopecten irradians*). Health Phys. 30: 79-83 (1976).

B25 Brower, J.H. Developmental success of two species of *Ips* (Coleoptera: Scolytidae) in a chronically irradiated forest community. Can. Entomol. 106: 233-238 (1974).

B26 Brower, J.H. Behavioral changes in an ant colony exposed to chronic irradiation. Am. Midl. Nat. 75: 530-534 (1966).

B27 Bigot, L., A. Grauby, N. Poinsot et al. Influence d'une irradiation gamma chronique sur la faune et sur la microflore d'un écosystème forestier à Cadarache. Radioprotection 8: 243-256 (1973).

B28 Bickham, J.W., B.G. Hanks, M.J. Smolen et al. Flow cytometric analysis of the effects of low-level radiation exposure on natural populations of slider turtles (*Pseudemys scripta*). Arch. Environ. Contam. Toxicol. 17: 837-841 (1988).

B29 Bickham, J.W. Flow cytometry as a technique to monitor the effects of environmental genotoxins on wildlife populations. p. 97-108 in: *In Situ* Evaluations of Biological Hazards of Environmental Pollutants (S. Sandhu, W.R. Lower et al., eds.). Plenum Press, New York, 1990.

B30 Burnazyan, A.I. (ed.). The Results of Investigation and Experience of Liquidation of the Land with Fission Products of Uranium. Energoatomizdat, Moscow, 1990.

B31 Begg, F.H., M.S. Baxter, G.T. Cook et al. Anthropogenic ^{14}C as a tracer in western UK coastal waters. p. 52 in: Radionuclides in the Study of Marine Processes (P.J. Kershaw and D.S. Woodhead, eds.). Elsevier Applied Science, London/New York, 1991.

B32 Barr, R.E. and X.J. Musacchia. The effect of body temperature and post-irradiation cold exposure on the radiation response of the hibernator, *Citellus tridecemlineatus*. Radiat. Res. 38: 437-448 (1969).

B33 Belova, N.V., B.V. Verigin, N.G. Emelianova et al. Radiobiological analysis of silver carp (*Hypophthalmichthys molitrix*) from the Chernobyl NPP cooling pond in the post-accident period. I. The state of the reproductive system of fish surviving the accident. Vopr. Ichtiologii 33(6): 814-828 (1993).

C1 Chipman, W.A. Ionizing radiation. p. 1578 in: Marine Ecology, A Comprehensive Integrated Treatise on Life in Oceans and Coastal Waters, Volume 1/3 (O. Kinne, ed.). Wiley, Inter-science, 1972.

C2 Cadwell, L.L. Colony formation of the western harvester ant in a chronic gamma radiation field. Am. Midl. Nat. 89/2: 446 (1973).

C3 Casarett, A.P. Radiation Biology. Prentice-Hall, Englewood Cliffs, New Jersey, 1968.

C4 Castet, R. Evolution des activités microbiennes dans un ecosystème mediterranéen soumis à une irradiation gamma chronique. Etude particulière des transferts azotés par marquage isotopique. CEA/R-5402 (1987).

C5 Coughtrey, P.J. Effect of ionizing radiation on native plant and animal communities. ANS-305 (1983).

C6 Committee on Biological Effects of Ionizing Radiation (BEIR III). The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980. United States National Academy of Sciences, National Research Council. National Academy Press, Washington, 1980.

C7 Cherry, R.D. and M. Heyraud. Evidence for high natural radiation doses in certain mid-water oceanic organisations. Science 218: 54-56 (1982).

C8 Carvalho, F.P. ^{210}Po in marine organisms: a wide range of natural radiation dose domains. Radiat. Prot. Dosim. 24: 113-117 (1988).

C9 Cahill, D.F. and C.L. Yuile. Tritium: some effects of continuous exposure in utero on mammalian development. Radiat. Res. 44: 727-737 (1970).

C10 Cahill, D.F., L.W. Reiter, J.A. Santalucito et al. Biological assessment of continuous exposure to tritium and lead in the rat. p. 65-76 in: Biological and Environmental Effects of Low-level Radiation, Volume 2. IAEA, Vienna, 1976.

C11 Cristaldi, M., E. D'Arcangelo, L.A. Ieradi et al. ^{137}Cs determination and mutagenicity tests in wild *Mus musculus domesticus* before and after the Chernobyl accident. Environ. Pollut. 64: 1-9 (1990).

C12 Cristaldi, M., L.A. Ieradi, D. Mascanzoni et al. Environmental impact of the Chernobyl accident: mutagenesis in bank voles from Sweden. Int. J. Radiat. Biol. 59 (1): 31-40 (1991).

C13 Cosgrove, G.E. The radiosensitivity of snakes and box turtles. Radiat. Res. 25: 706-712 (1965).

C14 Conger, A.D. and J.H. Clinton. Nuclear volumes. DNA contents and radiosensitivity in whole-body-irradiated amphibians. Radiat. Res. 54: 69-101 (1973).

C15 Coffigny, H. and C. Pasquier. Etude chez le rat adulte des effets d'une irradiation pre- ou post-natale de 150 rads. Trav. Scient. CRSSA ..: 48-51 (1976).

C16 Cooley, J.L. Effects of chronic environmental radiation on a natural population of the aquatic snail *Physa heterostropha*. Radiat. Res. 54: 130-140 (1973).

C17 Cosgrove, G.E. and B.G. Blaylock. Acute and chronic irradiation effects in mosquito fish at 15 or 25°C. p. 579-584 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P1 (1971).

C18 Cooley, J.L. and F.L. Miller. Effects of chronic irradiation on laboratory populations of the aquatic snail *Physa heterostropha*. Radiat. Res. 47: 716-724 (1971).

C19 Cooley, J.L. Effects of temperature and chronic irradiation on populations of the aquatic snail *Physa heterostropha*. p. 585-590 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P1 (1971).

C20 Chakrabarti, S., G. Streisinger, F. Singer et al. Frequency of γ-ray induced specific locus and recessive lethal mutations in mature germ cells of the zebrafish, *Brachydanio rerio*. Genetics 103: 109-123 (1983).

C21 Cherdantsev, V.Y., S.M. Lyapkov, Y.M. Cherdantseva et al. Methods and results of an analysis of the ecological stability of a population of brown frogs under conditions of radioactive contamination. p. 303-307 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

C22 Commission on Radiological Protection (Federal Republic of Germany). Effects of Prenatal Irradiation, 2nd Edition. Gustav Fischer Verlag, Stuttgart, 1989. (in German)

D1 Delpoux, M. La radioactivité naturelle et les végétaux. p. 221-237 in: Congrès sur les Données Actuelles sur la Radioactivité Naturelle. Monte Carlo, 1984.

D2 De Rooij, D.G. and C. Rönnbäck. The effect of ^{90}Sr given to pregnant mice on spermatogenesis in the male offspring: a comparison with the effect on the ovaries in the female offspring. Int. J. Radiat. Biol. 56: 151-159 (1989).

D3 Dunaway, P.B. and S.V. Kaye. Effects of ionizing radiation on mammal populations on the white oak lake bed. p. 333-338 in: Proceedings of the First National Symposium on Radioecology (V. Schultz and A.W. Klement, eds.). Reinhold Publishing Corp., New York and American Institute of Biological Sciences, Washington, 1963.

D4 Davey, D.R. and R.A. Jeffree. Ocean dumping of low-level radioactive waste. p. 245-254 in: Radiation Protection in Nuclear Energy, Volume 2. IAEA, Vienna, 1988.

D5 Dobson, R.L. and C. Kwan. The tritium RBE at low level exposure: variation with dose rate and exposure duration. Curr. Top. Radiat. Res. Quart. 12: 44-62 (1977).

D6 Dunaway, P.B., L.L. Lewis, J.D. Story et al. Radiation effects in the Soricidae, Cricetidae and Muridae. p. 173-184 in: Symposium on Radioecology. Proceedings of the Second National Symposium, Ann Arbor, 1967 (D.J. Nelson and F.C. Evans, eds.). CONF-670503 (1969).

D7 Dobson, R.L. and M.F. Cooper. Tritium toxicity: effect of low-level ^{3}HOH exposure on developing female germ cells in the mouse. Radiat. Res. 58: 91-100 (1974).

D8 Dobson, R.L. Low-level chronic exposure to tritium: an improved basis for hazard evaluation. p. 57-63 in: Biological and Environmental Effects of Low-level Radiation, Volume 2. IAEA, Vienna, 1976.

D9 Dana, S.W. and D.W. Tinkle. Effects of x-radiation on the testes of the lizard, *Uta stansburiana stejnegeri*. Int. J. Radiat. Biol. 9 (1): 67-80 (1965).

D10 Drew, R.T. and M. Eisenbud. The natural radiation dose to indigenous rodents on the Morro do Ferro, Brazil. Health Phys. 12: 1267-1274 (1966).

D11 Drew, R.T. and M. Eisenbud. The pulmonary dose from ^{220}Rn received by indigenous rodents of the Morro do Ferro, Brazil. Radiat. Res. 42: 270-281 (1970).

D12 Dugle, J.R. Growth and morphology in balsam fir: effects of gamma radiation. Can. J. Bot. 64: 1484-1492 (1986).

D13 Dugle, J.R. and J.L. Hawkins. Leaf development and morphology in ash: influence of gamma radiation. Can. J. Bot. 63: 1458-1468 (1985).

D14 Dugle, J.R. and K.R. Mayoh. Responses of 56 naturally-growing shrub taxa to chronic gamma irradiation. Environ. Exp. Bot. 24: 267-276 (1984).

D15 Dugle, J.R. and K.R. Mayoh. Boreal forest canopy cover changes after eighteen months of chronic gamma irradiation. Manit. Entomol. 8: 70-79 (1974).

D16 Dobson, R.L. and T.C. Kwan. The RBE of tritium radiation measured in mouse oocytes: increase at low exposure levels. Radiat. Res. 66: 615-625 (1976).

D17 Dubinin, N.P. and V.A. Shevchenko. Mutation processes in irradiated natural populations. p. 265-291 in: Mechanisms of Genetic Processes: Mutagenesis and Repair. Nauka Publishers, Moscow, 1976.

D18 Dobson, R.L. Low exposure tritium radiotoxicity in mammals. p. 120-134 in: Proceedings of Workshop on Tritium Radiobiology and Health Physics (H. Matsudaira, T. Yamaguchi, T. Nakazawa et al., eds.) NIRS-M-41 (1982).

D19 Diabaté, S. and S. Strack. Organically bound tritium. Health Phys. 65: 698-712 (1993).

D20 Dong, J., X. Zhou and C. Zhang. RBE of tritium beta rays for oocyte survival in female mice. Radiat. Prot. 5: 123-128 (1985).

E1 Egami, N. and K. Ijiri. Effects of irradiation on germ cell and embryonic development in teleosts. Int. Rev. Cytol. 59: 195-248 (1979)

E2 Epstein, H.T. Identification of radiosensitive volume with nucleic acid volume. Nature 171: 394-395 (1953).

E3 Ellett, W.H. and R.M. Humes. Absorbed fractions for small volumes containing photon-emitting radioactivity. J. Nucl. Med. 12 (Suppl. 5): 25-32 (1971).

E4 Ershoff, B.H. Comparative effects of prenatal gamma irradiation and x-irradiation on the reproductive system of the rat. Am. J. Physiol. 198: 1119-1122 (1960).

E5 Erickson, B.H. and P.G. Martin. Effects of continuous pre-natal gamma-radiation of the pig and rat. p. 111-118 in: Biological and Environmental Effects of Low-level Radiation, Volume 1. IAEA, Vienna, 1976.

E6 Edwards, C.A. Effects of gamma irradiation on populations of soil invertebrates. p. 68-77 in: Symposium on Radioecology. Proceedings of the Second National Symposium, Ann Arbor, 1967 (D.J. Nelson and F.C. Evans, eds.). CONF-670503 (1969).

E7 Ennis, T.J. The sterile male approach to the control of the spruce budworm, *Choristoneura fumiferana*. p. 389-393 in: Sterile Insect Technique and Radiation in Insect Control. IAEA, Vienna, 1982.

E8 Engel, D.W. The radiation sensitivities of three species of fiddler crabs (*Uca pugilator, U. pugnans* and *U. minax*). Chesapeake Sci. 14: 289-291 (1973).

E9 Egami, N. and K. Aoki. Effects of x-irradiation of a part of the body on the ovary in the loach, *Misgurnus anguillicaudatus*. Annot. Zool. Jpn. 39: 7-15 (1966).

E10 Egami, N. and Y. Hyodo-Taguchi. Hermaphroditic gonads produced in *Oryzias latipes* by x-irradiation during embryonic stages. Copeia 1: 195-196 (1969).

E11 Engel, D.W. Effect of single and continuous exposures of gamma radiation on the survival and growth of the blue crab, *Callinectes sapidus*. Radiat. Res. 32: 685-691 (1967).

E12 Etoh, H. and Y. Hyodo-Taguchi. Effects of tritiated water on germ cells in medaka embryos. Radiat. Res. 93: 332-339 (1983).

E13 Emery, R.M. and M.C. McShane. Nuclear waste ponds and streams on the Hanford site: an ecological search for radiation effects. Health Phys. 38: 787-809 (1980).

E14 Eliseyev, K.G., A.M. Voytovich, M.V. Ploskaya et al. Cytogenetic damage in amphibians inhabiting regions of Byelorussia contaminated with radionuclides. p. 151 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

F1 Fabries, M., A. Grauby and J.L. Trochain. Study of a mediterranean type phytocenose subjected to chronic gamma irradiation. Radiat. Bot. 12: 125 (1972).

F2 French, N.R. and H.W. Kaaz. The intrinsic rate of natural increase of irradiated *Peromyscus* in the laboratory. Ecology 49: 1172 (1968).

F3 French, N.R., B.G. Maza and H.W. Kaaz. Mortality rates in irradiated rodent populations. p. 46-52 in: Symposium on Radioecology. Proceedings of the Second National Symposium, Ann Arbor, 1967 (D.J. Nelson and F.C. Evans, eds.). CONF-670503 (1969).

F4 French, N.R., B.G. Maza, H.O. Hill et al. A population study of irradiated desert rodents. Ecol. Monogr. 44 (1): 45-72 (1974).

F5 French, N.R. Radiation and animal populations: problems, progress and projections. Health Phys. 11: 1557-1568 (1965).

F6 Filipas, A.S., Ye.A. Morgunova and V.G. Dikarev. Effects of ionizing radiation on agricultural crops. p. 156-174 in: Agricultural Radioecology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers, Moscow, 1992.

F7 Flaccus, E., T.V. Armentano and M. Archer. Effects of chronic gamma radiation on the composition of the herb community of an oak-pine forest. Radiat. Bot. 14: 263-271 (1974).

F8 Fraley, L. and F.W. Whicker. Response of a native short-grass plant stand to ionizing radiation. p. 999-1006 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

F9 Franz, E.H. and G.M. Woodwell. Effects of chronic gamma irradiation on the soil algal community of an oak-pine forest. Radiat. Bot. 13: 323-329 (1973).

G1 Gannutz, T.P. A study of the lichens of an irradiated rain forest. p. 227-231 in: A Tropical Rain Forest (H.T. Odum and R.F. Pigeon, eds.). TID-24270 (1970).

G2 Greig-Smith, P. Quantitative Plant Ecology. Butterworth, London, 1964.

G3 Guthrie, J.E. and J.R. Dugle. Gamma-ray irradiation of a boreal forest ecosystem: the field irradiator-gamma (FIG) facility and research programmes. Can. Field-Nat. 97: 120 (1983).

G4 Golley, F.B. and J.B. Gentry. Response of rodents to acute gamma radiation under field conditions. p. 166-172 in: Symposium on Radioecology. Proceedings of the Second National Symposium, Ann Arbor, 1967 (D.J. Nelson and F.C. Evans, eds.). CONF-670503 (1969).

G5 Green, E.L. Reproductive fitness of irradiated populations of mice. Genetics 50: 423-434 (1964).

G6 Green, E.L. and E.P. Les. Persistence of populations of mice exposed to sub-sterilizing doses of spermatogonial X-irradiation. Genetics 50: 497-507 (1964).

G7 Greig-Smith, P. Quantitative Plant Ecology, 3rd Edition. Blackwell Scientific Public, Oxford, 1983.

G8 Gschenaur, S.E. and G.M. Woodwell. The soil micro-fungi of a chronically-irradiated oak-pine forest. Ecology 55: 1004-1016 (1974).

G9 Green, E.L. Genetic effects of radiation in mammalian populations. Annu. Rev. Genet. 2: 87-120 (1968).

G10 Griffin, C.S. and C. Tease. Gamma-ray-induced numerical and structural chromosome anomalies in mouse immature oocytes. Mutat. Res. 202: 209-213 (1988).

G11 Geraskin, S.A., V.G. Dikarev, A.A. Oudalova et al. Combined action of ionizing radiation and heavy metal compounds on induction of chromosome aberrations in leaf meristem of summer barley. Russ. J. Genet. 32: (1996).

G12 Gilyarov, M.S. and D.A. Krivolutsky. Radioecological studies in soil zoology. Zool. J. 50(3): 329 (1971).

H1 Hines, N.O. Proving Ground. University Washington Press, Seattle, 1962.

H2 Hinckley, A.D. Infestation of irradiated white oaks by the solitary oak leafminer. Ann. Entomol. Soc. Am. 64: 1094 (1971).

H3 Holtzman, R.B. Application of radiolead to metabolic studies. p. 37-96 in: The Biogeochemistry of Lead in the Environment, Part B (J.O. Nriagu, ed.). Elsevier, Amsterdam, 1978.

H4 Hess, C.T., R.E. Casparius, S.A. Norton et al. Investigation of natural levels of Radon-222 in groundwater in Maine for assessment of related health effects. p. 529-546 in: The Natural Radiation Environment III (T.F. Gesell and W.M. Lowder, eds.). CONF-780422 (1980).

H5 Hetherington, J.A., D.F. Jefferies, N.T. Mitchell et al. Environmental and public health consequences of the controlled disposal of transuranic elements to the marine environment. p. 139-153 in: Transuranium Nuclides in the Environment. IAEA, Vienna, 1976.

H6 Heyraud, M., P. Domansk, R.D. Cherry et al. Natural tracers in dietary studies: data for ^{210}Po and ^{210}Pb in decapod shrimp and other pelagic organisms in the northeast Atlantic Ocean. Mar. Biol. 97: 507-519 (1988).

H7 Heaslip, M.B. Factors affecting the radiosensitivity of *Fraxinus americana* L. seedlings and seed. p. 978-982 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

H8 Hadley, E.B. and G.M. Woodwell. Effects of ionizing radiation on rates of CO_2 exchange of pine seedlings. Radiat. Res. 24: 650-656 (1966).

H9 Holt, B.R. and P.J. Bottino. Structure and yield of a chronically irradiated winter rye-weed community. Radiat. Bot. 12: 355-359 (1972).

H10 Holt, B.R. Radiosensitivity and distribution of common macro-fungi in a chronically irradiated oak-pine forest. Radiat. Bot. 12: 339-342 (1972).

H11 Hinckley, A.D. Concentration of oak aphids, *Myzocallis spp*, on irradiated white oaks. Environ. Entomol. 2: 697-700 (1973).

H12 Hyodo-Taguchi, Y. and N. Egami. Effect of x-irradiation on spermatogonia of the fish, *Oryzias latipes*. Radiat. Res. 67: 324-331 (1976).

H13 Hamaguchi, S. and N. Egami. Post-irradiation changes in oocyte populations in the fry of the fish *Oryzias latipes*. Int. J. Radiat. Biol. 28: 279-284 (1975).

H14 Hamaguchi, S. Changes in the radiation responses of oogonia in the embryos and fry of the fish *Oryzias latipes*. Int. J. Radiat. Biol. 29: 565-570 (1976).

H15 Hyodo-Taguchi, Y. and H. Etoh. Effects of tritiated water on germ cells in medaka. II. Diminished reproductive capacity following embryonic exposure. Radiat. Res. 106: 321-330 (1986).

H16 Hyodo-Taguchi, Y. and H. Etoh. Vertebral malformations in medaka (teleost fish) after exposure to tritiated water in the embryonic stage. Radiat. Res. 135: 400-404 (1993).

H17 Harrison, F.L. and S.L. Anderson. Reproductive success as an indicator of genotoxicity in the polychaote worm, *Neanthes arenaceodentata*. Mar. Environ. Res. 28: 313-316 (1989).

I1 International Commission on Radiation Units and Measurement. Quantitative concepts and dosimetry in radiobiology. ICRU Report 30 (1979).

I2 International Atomic Energy Agency. Effects of ionizing radiation on aquatic organisms and ecosystems. Technical Reports Series No. 172. IAEA, Vienna (1976).

I3 International Atomic Energy Agency. Assessing the impact of deep sea disposal of low level radioactive waste on living marine resources. Technical Reports Series No. 288. IAEA, Vienna (1988).

I4 International Atomic Energy Agency. Effects of ionizing radiation on plants and animals at levels implied by current radiation protection standards. Technical Reports Series No. 332. IAEA, Vienna (1992).

I5 Ingram, M. Biological effects on ionizing radiation. An annotated bibliography covering the years 1898-1957. TID-3097 (1966).

I6 Indeka, L. Incorporation of tritiated water from the atmosphere into aqueous and organic components of plants. p. 21-27 in: Biological Incorporation of Tritium. Central Laboratory for Radiological Protection, Report No. CLOR-115/D, Warsaw (1981).

I7 Ilyenko, A.I. and T.P. Krapivko. Hypoxigenia in populations of mammals-radionuclidofores. Proc. USSR Acad. Sci. 300(2): 503-504 (1988).

I8 International Commission on Radiological Protection. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Annals of the ICRP 21(1-3). Pergamon Press, Oxford, 1991.

I9 International Atomic Energy Agency. Methodology for assessing impacts of radioactivity on aquatic ecosystems. Technical Reports Series No. 190. IAEA, Vienna (1979).

I10 Ijiri, K. and N. Egami. Effects of γ-ray irradiation on primordial germ cells in embryos of *Oryzias latipes*. Radiat. Res. 72: 164-173 (1977).

I11 International Atomic Energy Agency. Summary report on the post-accident review meeting on the Chernobyl accident. Safety Series No. 75-INSAG-1. IAEA, Vienna (1986).

I12 International Atomic Energy Agency. The International Chernobyl Project, An Overview. IAEA, Vienna, 1991.

I13 Ilyenko, A.I. Radioisotope Accumulation by Animals and Effects on Populations. Nauka Publishers, Moscow, 1977.

I14 Ilyenko, A.I. and T.P. Krapivko. Ecological consequences of radioactive contamination for populations of small mammals. p. 171-180 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

I15 Ilyenko, A.I. and T.P. Krapivko. Ecology of Animals in Radiation Biogeocenoses. Nauka Publishers, Moscow, 1989.

J1 Jacobi, W. and H.G. Paretzke. Consideration of radiation exposure of trees by natural and artificial sources. GSF 5/86 (1986).

J2 Juntunen, R. Uranium and Radon in Wells Drilled Into Bedrock in Southern Finland. Report 98. Geological Survey of Finland, Espoo, 1991. (in Finnish)

J3 Jacobi, W. Communication to the UNSCEAR Secretariat (1996).

J4 Jaroslow, B.N., D.E. Smith, M. Williams et al. Survival of hibernating ground squirrels (*Citellus tridecemlineatus*) after single and fractionated doses of cobalt-60 gamma radiation. Radiat. Res. 38: 379-388 (1969).

K1 Kaplan, H.S. and L.E. Moses. Biological complexity and radiosensitivity. Science 145: 21-25 (1964).

K2 Krivolutsky, D.A. Radiation ecology of soil animals. Biol. Fertil. Soils 3: 51 (1987).

K3 Kozubov, G.M. and A.I. Taskaev (eds.). The Radiation Influence on the Coniferous Forests in the Region of the Catastrophe at the Chernobyl Atomic Power Station. Siktivkar, USSR, 1990.

K4 Kaye, S.V. Assessing potential radiological impacts to aquatic biota in response to the National Environmental Policy Act (NEPA) of 1969. p. 649-659 in: Environmental Behaviour of Radionuclides Released in the Nuclear Industry. IAEA, Vienna, 1973.

K5 Karaban, R.T., N.N. Mishenkov, D.A. Spirin et al. The effects of acute gamma-irradiation on forest trees at different seasons. Dokl. Akad. Nauk SSSR 252 (3): 766-768 (1980).

K6 Karaban, R.T., N.N. Mishenkov, B.S. Prister et al. Radiation effects in woody plants in the first year after acute gamma-irradiation of a forest. Lesovedeniye 1: 39-45 (1978).

K7 Kakushina, E.A. and L.A. Plodovskaya. The effects of x rays on the fertility of irradiated animals. p. 111-119 in: Influence of Ionizing Radiation During Pregnancy on the Condition of the Fetus and Newborn Offspring. Moscow, 1960. (in Russian)

K8 Kirchmann, R. and G. Berino. Behaviour of ^{222}Rn in pea plants, *Pisum sativum L.* Phyton 22 (2): 137-139 (1965).

K9 Kozmin, G.V., I.A. Sarapultsev, I.K. Khvostunov et al. Basic regularities of formation of absorbed doses in the irradiation of agricultural animals. p. 128-156 in: Agricultural Radioecology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers, Moscow, 1992.

K10 Kruglikov, B.P., A.V. Vasilyev and A.S. Shevchenko. Effects of ionizing radiations on agricultural animals. p. 174-195 in: Agricultural Radioecology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers, Moscow, 1992.

K11 Konno, K. and N. Egami. Notes on effects of x-irradiation of the male of *Oryzias latipes* (Teleostei, Cyprinodontidae). Annot. Zool. Jpn. 39: 63-70 (1966).

K12 Konno, K. Effects of gamma-irradiation on the gonads of the rainbow trout, *Salmo gairdnerii irideus*, during embryonic stages. p. 129-133 in: Radiation Effects on Aquatic Organisms. Japan Scientific Societies Press, Tokyo, 1980.

K13 Knowles, J.F. and L.N. Greenwood. The effects of chronic irradiation on the reproductive performance of *Ophryotrocha diadema* (Polychaeta, Dorvilleidae). Mar. Environ. Res. 38: 207-224 (1994).

K14 Komarov, V.I. Radioactive contamination and decontamination in the 30 km zone surrounding the Chernobyl nuclear power plant. p. 3-16 in: Environmental Contamination Following a Major Nuclear Accident. Volume 2. IAEA, Vienna, 1990.

K15 Krivolutsky, D.A., B.L. Usachev, A.I. Arkhireyeva et al. Changes in the structure of animal populations (above-ground and soil invertebrates) as affected by contamination of land with strontium-90. p. 241-249 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

K16 Krivolutsky, D.A. and A.D. Pokarzhevsky. Changes in the population of soil fauna caused by the Chernobyl nuclear power plant accident. p. 78 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

K17 Kupriyanova, Y.B. On the wood-lice fauna (Crustacea, Isopoda) of the Chernobyl nuclear power plant zone. p. 94 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

K18 Krapivko, T.P. and A.I. Ilyenko. The first signs of radioadaptation in populations of the red field vole (*Clethrionomus glareolus*) in radiation biogeocenosis. Proc. USSR Acad. Sci. 302(5): 1272-1274 (1988).

K19 Krapivko, T.P. and A.I. Ilyenko. Investigation of the processes of radioadaptation in the red field vole (*Clethrionomus glareolus*) - caesiumfores. Proc. USSR Acad. Sci. 315(5): 1275-1277 (1990).

K20 Kryshev, I.I. Estimation of radiation doses for members of biological communities in the regions contaminated by the Chernobyl NPP accident. p. 115 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

K21 Kirchmann, R., P. Charles, R. van Bruwaene et al. Distribution of tritium in the different organs of calves and pigs after ingestion of various tritiated feeds. Curr. Top. Radiat. Res. 12: 291-312 (1977).

K22 Kozubov, G.M. and A.J. Taskaev. Radiobiological and Radioecological Investigations of Trees in the Vicinity of the Chernobyl NPS Accident. page 256. Nauka, St. Petersburg, 1994.

K23 Karaban, R.T., N.N. Mishenkov, B.S. Prister et al. The effect of acute gamma-radiation on the forest biogeocenosis. p. 27-52 in: The Problems of Forest Radioecology. Transactions of the Institute of Applied Geophysics, Number 38. Division of Hydrometeoizdat, Moscow, 1979.

K24 Kryshev, I.I., R.M. Alexakhin, K.P. Makhon'ko et al. Radioecological Consequences of the Chernobyl Accident. Nuclear Society, Moscow, 1992.

K25 Kozubov, G.M., A.I. Taskaev, E.I. Ignatenko et al. Radiation exposure of the coniferous forest in the area exposed to the Chernobyl contamination. Komy Scientific Centre of the Academy of Sciences, Syktyvkar, 1990.

K26 Kudaesheva, A.G., L.N. Shishkina, N.A. Zagorskaya et al. The impact of technogenic pollutants on regulatory cell systems. Scientific Reports, Issue 248. Komy Scientific Centre of the Academy of Sciences, Syktyvkar, 1990.

K27 Kryshev, I.I. Radioactive contamination of aquatic ecosystems following the Chernobyl accident. J. Environ. Radioact. 27(3): 207-219 (1995).

K28 Kryshev, I.I. and T.G. Sazykina. Mathematical Modelling of Radionuclide Migration in Aquatic Ecosystems. page 152. Energoatomizdat, Moscow, 1986.

K29 Kryshev, I.I. and T.G. Sazykina. Assessment of radiation doses to aquatic organisms in the Chernobyl contaminated area. J. Environ. Radioact. 28(1): 91-103 (1995).

K30 Kryshev, I.I., I.N. Ryabov and T.G. Sazykina. Using a bank of predatory fish samples for the bioindication of radioactive contamination of aquatic food chains in the area affected by the Chernobyl accident. Sci. Total Environ. 139/140: 279-285 (1993).

L1 Leonard, A., M. Delpoux, J. Chameaud et al. Biological effects observed in mammals maintained in an area of very high natural radioactivity. Can. J. Genet. Cytol. 23: 321 (1981).

L2 Leonard, A., R. Meyer, M. Delpoux et al. Influence d'une radioactivité naturelle élevée sur la fécondité des souris males. C.R. Seances Soc. Biol. Fil. 177: 234 (1983).

L3 Leonard, A., M. Delpoux, R. Meyer et al. Effect of an enhanced natural radioactivity on mammal fertility. Sci. Total Environ. 45: 535 (1985).

L4 Ledney, G.D. and R. Wilson. Protection induced by bacterial endotoxin against whole-body x-irradiation in germ-free and conventional mice. Proc. Soc. Exp. Biol. Med. 118: 1062-1065 (1965).

L5 Loevinger, R., E.M. Japha and G.L. Brownell. Discrete radioisotope sources. in: Radiation Dosimetry, Chapter 16 (G.J. Hine and G.L. Brownell, eds.). Academic Press, New York, 1956.

L6 Lewis, B.G. and M.M. McDonell. Release of Rn-222 by vascular plants: effect of transpiration and leaf area. J. Environ. Qual. 19: 93-97 (1990).

L7 Lappenbusch, W.L., D.G. Watson and W.L. Templeton. In situ measurement of radiation dose in the Columbia River. Health Phys. 21: 247-251 (1971).

L8 Lemaire, G. and J. Maas. Irradiation chronique du tissu germinal du rat mâle. Trav. Scient. CRSSA 3: 110-114 (1982).

L9 Landreth, H.F., P.B. Dunaway and G.E. Cosgrove. Effects of whole-body gamma irradiation on various life stages of the toad, *Bufo woodhousei fowleri*. Radiat. Res. 58: 432-438 (1974).

L10 Lystsov, V.N., O.Y. Skotnikova, O.P. Bolshakov et al. Estimation of dose burdens of aquatic organisms of the Chernobyl NPP cooling water reservoir in 1989. p. 107 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

L11 Ludwików, G. Radiotoxicity of ^{125}I Bound to Thyroid Hormone - The Micronucleus Test in Assessments of Radiation-induced Damage, Ph.D. Thesis. Uppsala University, 1992.

L12 Lu, H., X. Zhou, L. Li et al. Distribution and materno-fetus and materno-suckling transfer of tritium after single injection of tritiated water in mice. Chin. Med. J. 106: 366-369 (1993).

L13 Lu, H. and H. Takeda. Biokinetics of tritium incorporation into the tissues of rats during continuous ingestion of tritiated water or tritium-labeled food. Chin. Med. J. 105: 594-597 (1992).

M1 Maslov, V.I., K.I. Maslova and I.N. Verkhovskaya. Characteristics of the radioecological groups of mammals and birds of biogeocenoses with high natural radiation. p. 561 in: Radioecological Concentration Processes (B. Aberg and F.P. Hungate, eds.). Pergamon Press, Oxford, 1967.

M2 Mellinger, P.J. and V. Schultz. Ionizing radiation and wild birds: a review. CRC Crit. Rev. Environ. Control 5/3: 397 (1975).

M3 Mihok, S., B. Schwartz and S.L. Iverson. Ecology of red-backed voles (*Clethrionomys gapperi*) in a gradient of gamma radiation. Ann. Zool. Fennici 22: 257 (1985).

M4 Muller, H.J. Our load of mutations. Am. J. Hum. Genet. 2/2: 111 (1950).

M5 Myers, D.K. The general principles and consequences of environmental radiation exposure in relation to Canada's nuclear fuel waste management concept. AECL-9917 (1989).

M6 Murphy, P.G. and J.F. McCormick. Ecological effects of acute beta irradiation from simulated fallout particles on a natural plant community. p. 454-481 in: Survival of Food Crops and Livestock in the Event of Nuclear War (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).

M7 Mitchell, N.T. Radioactivity in surface and coastal waters of the British Isles 1971. Technical Report FRL-9. Ministry of Agriculture, Fisheries and Food, Lowestoft (1973).

M8 Medawar, P. and J. Medawar. Aristotle to Zoos. A Philosophical Dictionary of Biology. Oxford University Press, Oxford, 1985.

M9 Max, C. Cytological investigation of embryos in low dose x-irradiated young and old female inbred mice. Hereditas 85: 199-206 (1977).

M10 Mishenkov, N.N., D.A. Spirin, R.M. Alexakhin et al. Radiation-induced and post-irradiation changes in the forest biogeocenosis after acute gamma-irradiation. Comparison of seasonal radiosensitivity of a mixed pine-birch stand after acute gamma-irradiation. Radiobiology 23: 220-222 (1983).

M11 Murphy, P.G. and J.F. McCormick. Effects of beta radiation from simulated fallout on the reproductive potential of a dominant plant species in a natural community. p. 983-987 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

M12 Mraz, F.R. and M.C. Woody. Effect of continuous gamma irradiation of chick embryos upon their gonadal development. Radiat. Res. 50: 418-425 (1972).

M13 Menhinick, E.F. and D.A. Crossley. Radiation sensitivity of twelve species of arthropods. Ann. Entomol. Soc. Am. 62: 711-717 (1969).

M14 Michibata, H. The role of spermatogonia in the recovery process from temporary sterility induced by gamma-ray irradiation in the teleost, *Oryzias latipes*. J. Radiat. Res. 17: 142-153 (1976).

M15 Marshall, J.S. The effect of continuous γ-radiation on the intrinsic rate of natural increase of *Daphnia pulex*. Ecology 43: 598-607 (1962).

M16 Marshall, J.S. Population dynamics of *Daphnia pulex* as modified by chronic radiation stress. Ecology 47: 561-571 (1966).

M17 Muntyan, S.P. Investigation of fish populations under conditions of radioactive contamination of the environment. p. 187-191 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

M18 Müller, W.-U., C. Streffer and S. Pampfer. The question of threshold doses for radiation damage: malformations induced by radiation exposure of unicellular or multicellular preimplantation stages of the mouse. Radiat. Environ. Biophys. 33: 63-68 (1994).

M19 Matsuda, Y., I. Tobari, J. Yamigiwa et al. Dose-response relationship of gamma-ray-induced reciprocal translocations at low doses in spermatogonia of the crab-eating monkey (*Macaca fascicularis*). Mutat. Res. 151: 121-127 (1985).

M20 Murphy, G.E. Tritium transport and cycling in the environment. Health Phys. 65: 683-697 (1993).

M21 Musacchia, X.J. and R.E. Barr. Survival of whole-body-irradiated hibernating and active ground squirrels, *Citellus tridecemlineatus*. Radiat. Res. 33: 348-356 (1968).

M22 Makeeva, A.P., N.G. Yemelianova, N.V. Belova et al. Radiobiological analysis of silver carp (*Hypophthalmichthys molitrix*) from the Chernobyl NPP cooling pond in the post-accident period. II. Development of the reproductive system of the fish in the 1st generation. Vopr. Ichtiologii 34(5): 681-696 (1994).

N1 National Council on Radiation Protection and Measurements. Effects of ionizing radiation on aquatic organisms. NCRP Report No. 109 (1991).

N2 National Academy of Sciences, National Research Council. The effects on populations of exposure to low levels of ionizing radiation. Report of Advisory Committee on Biological Effects of Ionizing Radiation (1972).

N3 National Research Council of Canada. Radioactivity in the Canadian aquatic environment. NRCC Report No. 19250 (1983).

N4 National Council on Radiation Protection and Measurements. Some aspects of strontium radiobiology. NCRP Report No. 110 (1991).

N5 Nakatsuchi, Y. and N. Egami. Radiation injury and acute death in *Armadillidium vulgare* (terrestrial isopod, Crustacea) subjected to ionizing radiation. Radiat. Res. 85: 135-149 (1981).

N6 Nikipelov, B.V., G.N. Romanov, L.A. Buldakov et al. Accident in the Southern Urals on 29 September 1957. IAEA-INFCIRC-368 (1989).

O1 O'Brien, R.D. and L.S. Wolfe. Nongenetic effects of radiation. in: Radiation, Radioactivity and Insects. Volume 23. Academic Press, New York, 1964.

O2 Odum, E.P. Fundamentals of Ecology. W.B. Saunders, Philadelphia, 1971.

O3 Oakberg, E.F. Gamma-ray sensitivity of oocytes in immature mice. Proc. Soc. Exp. Biol. Med. 109: 763-767 (1962).

O4 Organization for Economic Co-operation and Development: Nuclear Energy Agency. Review of the Continued Suitability of the Dumping Site for Radioactive Waste in the North-East Atlantic. OECD/NEA, Paris, 1985.

P1 Page, N.P. The effect of dose-protraction on radiation lethality of large animals. p. 12.1-12.19 in: Proceedings of Symposium on Dose Rate in Mammalian Radiation Biology. CONF-680410 (1968).

P2 Purdom, C. Radiation and mutation in fish. p. 861 in: Disposal of Radioactive Wastes into Seas, Oceans and Surface Waters. Proceedings of a Symposium. IAEA, Vienna, 1966.

P3 Pierce, C.M. The effects of radiation and radioisotopes on the life processes. An annotated bibliography. TID-3098 (1963).

P4 Polikarpov, G.G. Radioecology of Aquatic Organisms. (Translated from Russian by Scripta Technica, English translation edited by V. Schultz and A.W. Klement) p. 314. Reinhold, New York, 1966.

P5 Pentreath, R.J. and D.S. Woodhead. Towards the development of criteria for the protection of marine fauna in relation to the disposal of radioactive wastes into the sea. p. 213-243 in: Radiation Protection in Nuclear Energy, Volume 2. IAEA, Vienna, 1988.

P6 Phillips, L.J. and J.E. Coggle. The radiosensitivity of embryos of domestic chickens and black-headed gulls. Int. J. Radiat. Biol. 53: 309-317 (1988).

P7 Pelton, M.R. and E.E. Provost. Effects of radiation on survival of wild cotton rats (*Sigmodon hispidus*) in enclosed areas of natural habitat. p. 39-45 in: Symposium on Radioecology. Proceedings of the Second National Symposium, Ann Arbor, 1967 (D.J. Nelson and F.C. Evans, eds.). CONF-670503 (1969).

P8 Platteau, B., H. Bazin, M. Janowski et al. Failure to detect immune deficiency in rats after prenatal or early postnatal irradiation. Int. J. Radiat. Biol. 55: 7-14 (1989).

P9 Proverbs, M.D. Sterile insect technique in codling moth control. p. 85-99 in: Sterile Insect Technique and Radiation in Insect Control. IAEA, Vienna, 1982.

P10 Perrault, G.H. and R. Castret. Recensement du peuplement en fourais d'un écosystème forestier méditerranéen soumis à une irradiation gamma chronique. Radioprotection 23: 45-64 (1988).

P11 Poinsot-Balaguer, N. Résponse des communautés de Collemboles à l'irradiation gamma chroniques d'une forêt méditerranéenne. Rev. Ecol. Biol. Sol 13: 365-379 (1976).

P12 Poinsot-Balaguer, N., R. Castet and E. Tabone. Impact of chronic gamma irradiation on a mediterranean forest ecosystem in Cadarache. J. Environ. Radioact. 14: 23-36 (1991).

P13 Pampfer, S. and C. Streffer. Prenatal death and malformations after irradiation of mouse zygotes with neutrons or x-rays. Teratology 37: 599-607 (1988).

P14 Pietrzak-Flis, Z. and M. Wasilewska-Gomutka. Effect of lifetime intake of organically bound tritium and tritiated water on the oocytes of rats. Radiat. Environ. Biophys. 23: 61-68 (1984).

P15 Pechkurenkov, V.L. Effect of Chernobyl NPP accident in 1986 on fish populations in the cooling water reservoir. p. 143 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

P16 Pietrzak-Flis, Z., I. Radwan and L. Indeka. Tritium in rabbits after ingestion of freeze-dried tritiated food and tritiated water. Radiat. Res. 76: 420-428 (1978).

P17 Pietrzak-Flis, Z., I. Radwan, Z. Major et al. Tritium incorporation in rats chronically exposed to tritiated food or tritiated water for three successive generations. J. Radiat. Res. 22: 434-442 (1982).

P18 Pietrzak-Flis, Z. Effects of chronically ingested tritium on the oocytes of two generations of rats. p. 111-115 in: Developmental Effects of Prenatal Irradiation (H. Kriegel, W. Schmahl, G. Kistner et al., eds.) .Gustav Fischer, New York, 1982.

P19 Petrova, N.A. Frequency of chromosome aberrations for Chironomids from the Chernobyl zone. p. 159 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

R1 Ross, H.A. Genetic changes in an irradiated population of wild meadow voles (*Microtus pennsylvanicus*). Can. J. Zool. 64: 698 (1986).

R2 Rönnbäck, C. Disturbances of fertility in female mice Sr-90 - contaminated as fetuses. Acta Radiol. Oncol. 20: 337-343 (1981).

R3 Reichle, D.E., J.P. Witherspoon, M.J. Mitchell et al. Effects of beta-gamma radiation of earthworms under simulated-fallout conditions. p. 527-534 in: Survival of Food Crops and Livestock in the Event of Nuclear War (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).

R4 Rapport, D.J., H.A. Regier and T.C. Hutchinson. Eco-system behaviour under stress. Am. Nat. 125: 617-640 (1985).

R5 Rönnbäck, C. Effects of continuous irradiation during gestation and suckling periods in mice. Acta Radiol. 3: 169-176 (1965).

R6 Rudolph, T.D. Seed yield and quality in white spruce cross-pollinated with gamma-irradiated pollen. p. 972-977 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

R7 Reiners, W.A. and G.M. Woodwell. Water budget of a forest damaged by ionizing radiation. Ecology 47: 303-306 (1966).

R8 Roed, K.H., I.M.H. Eikelmann, M. Jacobsen et al. Chromosome aberrations in Norwegian reindeer calves exposed to fallout from the Chernobyl accident. Hereditas 115: 201-206 (1991).

R9 Rahalkar, G.W., K. Shantaram, M.R. Harwalkar et al. Mating competitiveness and effective life of the radiation-sterilized male red palm weevil, *Rhyncho-phorus ferrugineus* oliv. p. 395-400 in: Sterile Insect Technique and Radiation in Insect Control. IAEA, Vienna, 1982.

R10 Rackham, B.D. and D.S. Woodhead. Effects of chronic γ-irradiation on the gonads of adult *Ameca splendens* (Osteichthyes: Teleostei). Int. J. Radiat. Biol. 45: 645-656 (1984).

R11 Radwan, I. and Z. Pietrzak-Flis. Retention of tritium in rats after ingestion of tritiated food or tritiated water. Nukleonika 30: 215-226 (1985).

S1 Sparrow, A.H., A.G. Underbrink and R.C. Sparrow. Chromosomes and cellular radiosensitivity. I. The relationship of D_0 to chromosome volume and complexity in seventy-nine different organisms. Radiat. Res. 32: 915-945 (1967).

S2 Saas, A., P. Bovard and A. Grauby. The effect of chronic gamma irradiation on decay of oak (*Quercus pubescens*) and dogwood (*Cornus mas*) leaves and subjacent litter. Radiat. Bot. 15: 1941 (1975).

S3 Stearner, S.P. and E.J.B. Christian. Late effects of ionizing radiation in the chicken: survival, body weight and pathology. Radiat. Res. 52: 179-196 (1972).

S4 Smirnov, E.G., G.P. Shein, N.V. Guro et al. Effect of acute gamma radiation on meadow vegetation. J. Sov. Ecol. 14: 329 (1983). Transl. from Ekologiya 6: 34 (1983).

S5 Smith, R.F. The vegetation structure of a Puerto Rican rain forest before and after short-term gamma irradiation. p. D103-D140 in: A Tropical Rain Forest (H.T. Odum and R.F. Pigeon, eds.). TID-24270 (1970).

S6 Styron, C.E. Effects of beta and gamma radiation on a population of springtails, *Sinella curviseta* (Collembola). Radiat. Res. 48: 53-62 (1971).

S7 Sparrow, A.H., S.S. Schwemmer and P.J. Bottino. The effects of external gamma radiation from radioactive fallout on plants with special reference to crop production. Radiat. Bot. 11: 85-118 (1971).

S8 Sparrow, A.H. and G.M. Woodwell. Prediction of the sensitivity of plants to chronic gamma irradiation. p. 257-270 in: Proceedings of the First National Symposium on Radioecology (V. Schultz and A.W. Klement, eds.). Reinhold Publishing Corp., New York and American Institute of Biological Sciences, Washington, 1963.

S9 Sparrow, A.H. and J.E. Gunckel. The effects on plants of chronic exposure to gamma radiation from radiocobalt. p. 52-59 in: Proceedings of International Conference on Peaceful Uses of Atomic Energy, Volume 12. United Nations, 1956.

S10 Sparrow, A.H., L.A. Schairer, R.C. Sparrow et al. The radiosensitivity of Gymnosperms. I. The effect of dormancy on the response of *Pinus strobus* seedlings to acute gamma radiation. Radiat. Bot. 3: 169-173 (1963).

S11 Stadler, J. and J.W. Gowen. Observations on the effects of continuous irradiation over ten generations on reproductivities of different strains of mice. p. 111-122 in: Effects of Ionizing Radiation on the Reproductive System (W.D. Carlson and F.X. Gassner, eds.). MacMillan, New York, 1964.

S12 Sparrow, R.C. and A.H. Sparrow. Relative radio-sensitivities of woody and herbaceous spermatophytes. Science 147: 1449-1451 (1965).

S13 Sparrow, A.H., S.S. Schwemmer, E.E. Klug et al. Woody plants: changes in survival in response to long-term (8 years) chronic gamma irradiation. Science 169: 1082-1084 (1970).

S14 Spirin, D.A., N.N. Mishenkov, R.T. Karaban et al. The effects of acute gamma-irradiation on photo-synthetic functions of pine and birch trees. Lesovedeniye 4: 75-82 (1981).

S15 Spirin, D.A., N.N. Mishenkov, R.M. Alexakhin et al. The effects of acute gamma-irradiation in Scots pine trees of different vigours. Lesovedeniye 3: 87-89 (1983).

S16 Spirin, D.A. and R.T. Karaban. The quantitative estimation of the combined effects of ionizing radiation and chemical pollutants on plants. Radiobiologiya 26 (1): 99-102 (1986).

S17 Spirin, D.A., V.L. Usachev, R.M. Alexakhin et al. Radiation-induced and post-irradiation changes in a forest biogeocenosis after acute gamma-irradiation: damage of irradiated trees by xylophagous insects. Radiobiologiya 25 (2): 278-280 (1985).

S18 Smirnov, E.G. and P.N. Melankholin. The effects of acute gamma-irradiation on the herbaceous layer in a pine-birch forest. Lesovedeniye 2: 85-90 (1979).

S19 Spiridonov, S.I., S.V. Fesenko, R.M. Alexakhin et al. A mathematical simulation of the consequences of acute irradiation on the trees of a forest biogeocenosis. Radiobiologiya 29 (4): 544-549 (1989).

S20 Spirin, D.A., E.G. Smirnov, L.I. Suvorova et al. The effect of radioactive contamination on natural systems. Priroda 5: 58-63 (1990).

S21 Sankaranarayanan, K. Ionizing radiation and genetic risks. IV. Current methods, estimates of risk of Mendelian disease, human data and lessons from biochemical and molecular studies of mutations. Mutat. Res. 258: 99-122 (1991).

S22 Shevchenko, V.A., M.D. Pomerantseva, L.K. Ramaiya et al. Genetic disorders in mice exposed to radiation in the vicinity of the Chernobyl nuclear power station. Sci. Total Environ. 112: 45-56 (1992).

S23 Spirin, Ye.E. Basic regularities of formation of absorbed doses in the irradiation of agricultural crops. p. 116-128 in: Agricultural Radioecology (R.M. Alexakhin and N.A. Korneyev, eds.). Ecologia Publishers, Moscow, 1992.

S24 Sheppard, S.C. and W.G. Evenden. Factors controlling the response of field crops to very low doses of gamma irradiation of the seed. Can. J. Plant Sci. 66: 431-441 (1986).

S25 Sheppard, S.C. and P.J. Regitnig. Factors controlling the hormesis response in irradiated seed. Health Phys. 52: 599-605 (1987).

S26 Sheppard, S.C., C.L. Gibb, J.L. Hawkins et al. Investigation of hormetic stimulation in strawberry plants using ionizing radiation. Can. J. Plant Sci. 67: 1181-1192 (1987).

S27 Spirin, D.A., R.M. Alexakhin, R.T. Karaban et al. Radiation-induced and post-irradiation changes in a forest biogeocenosis after acute gamma-irradiation. Influence of acute gamma-irradiation on productivity of a mixed pine-birch forest. Radiobiology 25: 125-128 (1985).

S28 Spirin, D.A., N.N. Mishenkov, R.T. Karaban et al. Radiation-induced and post-irradiation changes in a forest biogeocenosis after acute gamma-irradiation. Post-irradiation effects in the grass cover of an irradiated forest. Radiobiology 25: 122-124 (1985).

S29 Sparrow, A.H., L.A. Schairer and G.M. Woodwell. Tolerance of *Pinus rigida* trees to a ten-year exposure to chronic gamma irradiation from cobalt-60. Radiat. Bot. 5: 7-22 (1965).

S30 Sheppard, M.I., D.H. Thibault and J.E. Guthrie. Radiosensitivity and the role of *Pinus sylvestris* in the revegetation of radioactive waste disposal areas. Environ. Exp. Bot. 22: 193-198 (1982).

S31 Samuels, L.D. Effects of polonium-210 on mouse ovaries. Int. J. Radiat. Biol. 11: 117-129 (1966).

S32 Spalding, J.F., M.R. Brooks and R.F. Archuleta. Genetic effects of x-irradiation of 10, 15 and 20 generations of male mice. Health Phys. 10: 293-296 (1964).

S33 Sparrow, A.H., C.H. Nauman, G.M. Donnelly et al. Radiosensitivities of selected amphibians in relation to their nuclear and chromosome volumes. Radiat. Res. 42: 353-371 (1970).

S34 Suzuki, J. and N. Egami. Mortality of the earthworms, *Eisenia foetida*, after γ-irradiation at different stages of their life history. J. Radiat. Res. 24: 209-220 (1983).

S35 Suyama, I. and H. Etoh. Chromosomal effects of tritium on lymphocytes of the teleost, *Umbra limi*. p. 146-156 in: Tritium Radiobiology and Health Physics (H. Matsudaira, T. Yamaguchi and H. Etoh, eds.). NIRS-M-52 (1985).

S36 Smirnov, Y.G. Living forms and radioecology of plants. p. 103-119 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

S37 Schevchenko, V.A., V.I. Abramov and V.L. Pechkurenkov. Genetic investigations in the southern Urals radioactive trail. p. 258-303 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

S38 Schevchenko, V.A. Radiation Genetics of Unicellular Algae. Nauka Publishers, Moscow, 1979.

S39 Spirin, D.A., V.Z. Martyushov, Y.G. Smirnov et al. Effect of radioactive contamination on living organisms of the 30 km zone of the Chernobyl nuclear power plant. p. 71 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

S40 Suvorova, L.I., Y.G. Smirnov, G.P. Shein et al. Evaluation of biological consequences of radioactive contamination of phytocenoses. p. 6 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

S41 Sokolov, V.E., I.N. Ryabov, I.A. Ryabtsev et al. Effects of radioactive contamination on the flora and fauna in the vicinity of the Chernobyl nuclear power plant. Physiol. General Biol. Rev. 8(2): (1994).

S42 Schalet, A. and K. Sankaranarayanan. Evaluation and re-evaluation of genetic radiation hazards in man. I. Interspecific comparisons of estimates of mutation rates. Mutat. Res. 35: 341-370 (1976).

S43 Selby, P. Experimental induction of dominant mutations in mammals by ionizing radiation and chemicals. Teratology 5: 181-253 (1990).

S44 Shima, A. and A. Shimada. Development of a possible non-mammalian test system for radiation-induced germ-cell mutagenesis using a fish, the Japanese medaka (*Oryzias latipes*). Proc. Natl. Acad. Sci. USA 88: 2545-2549 (1991).

S45 Sarapultsev, B.I. and S.A. Geraskin. Genetic Principles of Radioresistance and Evolution. Energoatomizdat, Moscow, 1993.

S46 Sparrow, A.H. and J.P. Miksche. Correlation of nuclear volume and DNA content with higher plant tolerance to chronic irradiation. Science 134: 282-283 (1961).

S47 Sparrow, A.H., L.A. Schairer and R.C. Sparrow. Relationship between nuclear volumes, chromosome numbers and relative radiosensitivities. Science 141: 163-166 (1963).

S48 Sparrow, A.H., A.F. Rogers and S.S. Schwemmer. Radiosensitivity studies with woody plant. I. Acute irradiation survival data for 28 species and predictions for 190 species. Radiat. Bot. 8: 149-186 (1968).

S49 Sokolov, V.E. and D.A. Krivolutzkii (eds.). Ecological After-effects of the Radioactive Contamination of the Southern Urals. page 336. Nauka, Moscow, 1993.

S50 Searle, A.G., C.V. Beechey, D. Green et al. Cytogenetic effects of protracted exposures to alpha-particles from Pu-239 and to gamma rays from Co-60 compared in male mice. Mutat. Res. 41: 297-310 (1976).

T1 Thompson, P.M. Environmental monitoring for radio-nuclides in marine ecosystems: are species other than man protected adequately? J. Environ. Radioact. 7: 275-283 (1988).

T2 Terzi, M. Comparative analysis of inactivating efficiency of radiation on different organisms. Nature 191: 461-463 (1961).

T3 Terzi, M. Radiosensitivity and genetic complexity. J. Theor. Biol. 8: 233-243 (1965).

T4 Tabone, E. Influence d'une irradiation gamma chronique sur le système sol d'une chênaie mixte mediterranéenne à Cadarache. p. 1-65 in: Thèse Doct. Troisième Cycle. Université de Provence, 1986.

T5 Taskayev, A.I., N.P. Frolova, O.N. Popova et al. The monitoring of herbaceous seeds in the 30 km zone of the Chernobyl nuclear accident. Sci. Total Environ. 112: 57-67 (1992).

T6 Templeton, W.L., R.E. Nakatani and E.E. Held. Radiation effects. p. 223 in: Radioactivity in the Marine Environment. National Academy of Sciences, Washington, 1971.

T7 Testov, B.V. and A.I. Taskayev. Dynamics of numbers of mouse-type rodents in the Chernobyl nuclear power plant zone. p. 86 in: Biological and Radioecological Consequences of the Accident at the Chernobyl Nuclear Power Plant. Proceedings of the 1st International Conference, Zeleny Mys, September 1990. Moscow, 1990.

T8 Turner, F.B., P.A. Medica, J.R. Lannom et al. A demographic analysis of continuously irradiated and nonirradiated populations of the lizard, *Uta stansburiana*. Radiat. Res. 38: 349-356 (1969).

T9 Turner, F.B. Effects of continuous irradiation on animal populations. p. 83 in: Advances in Radiation Biology, Volume 5. Academic Press, New York, 1975.

T10 Thames, H.D. and J.H. Hendry. Fractionation in Radiotherapy. p. 297. Taylor and Francis, London, 1987.

T11 Tikhomirov, F.A., I.S. Fedotov, R.T. Karaban et al. The effects of acute gamma-irradiation on the reproductive organs of Scots pine. Lesovedeniye 4: 75-83 (1978).

T12 Turner, F.B., J.R. Lannom, H.J. Kania et al. Acute gamma irradiation experiments in the lizard *Uta stansburiana*. Radiat. Res. 31: 27-35 (1967).

T13 Tinkle, D.W. Effect of radiation on the natality, density and breeding structure of a natural population of lizards, *Uta stansburiana*. Health Phys. 11: 1595-1599 (1965).

T14 Turner, F.B., G.A. Hoddenbach and J.R. Lannom. Growth of lizards in natural populations exposed to gamma radiation. Health Phys. 11: 1585-1593 (1965).

T15 Turner, F.B., P. Licht, J.D. Thrasher et al. Radiation-induced sterility in natural populations of lizards (*Crotaphytus wislizenii* and *Cnemidophorus tigris*). p. 1131-1143 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

T16 Török, P. and G. Kistner. Reproductive performance of mice after injection of tritiated water at different embryonic development stages. p. 91-96 in: Develop-mental Effects of Prenatal Irradiation. Gustav Fischer, Stuttgart, 1982.

T17 Tikhomirov, F.A. and G.N. Romanov. Doses of radiation to organisms under conditions of radioactive contamination of a forest. p. 13-20 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

T18 Tester, J.R., M.A. Ewert and D.B. Siniff. Effects of ionizing radiation on natural and laboratory populations of Manitoba toads, *Bufo hemiophrys*. Radiat. Res. 44: 379-389 (1970).

T19 Tabone, E., R. Castet and N. Poinsot-Balaguer. Influence d'une irradiation gamma chronique sur le système sol d'une chenaie mixte méditerranéenne à Cadarache (Bouches du Rhône). Bull. Soc. Ecophysiol. 11: 195-206 (1986).

T20 Tabone, E. and N. Poinsot-Balaguer. Dynamique de la matière organique dans un sol de fôret mixte méditerranéenne soumis à une irradiation gamma chronique. Pedobiologia 30: 113-126 (1987).

T21 Tikhomirov, F.A. Distribution and migration of radionuclides in the forests within the south Urals radioactive trail of fallout. p. 21-39 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

T22 Tikhomirov, F.A. Effects of Ionising Radiations on Ecological Systems. Atomizdat, Moscow, 1972.

T23 Tikhomirov, F.A. and R.T. Karaban. Radiation damage of a forest under conditions of radioactive contamina-tion. p. 85-95 in: Ecological Consequences of Radioactive Contamination in the Southern Urals. Nauka Publishers, Moscow, 1993.

T24 Tarkhanov, I. Experiments upon the action of Roentgen's x-rays on organisms. Izv. S-Peterb. Biol. Lab. 1: 47-52 (1896).

T25 Thomas, P.A., J.W. Sheard and S. Swanson. Transfer of ^{210}Po and ^{210}Pb through the lichen-caribou-wolf foodchain of northern Canada. Health Phys. 66: 666-677 (1994).

T26 Thomas, P.A. Dosimetry of ^{210}Po in humans, caribou and wolves in northern Canada. Health Phys. 66: 678-690 (1994).

T27 Takeda, H. and T. Iwakura. Incorporation and distribution of tritium in rats exposed to tritiated rice or tritiated soybean. J. Radiat. Res. 33: 309-318 (1993).

U2 United Nations. 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. United Nations sales publication E.94.IX.2. United Nations, New York, 1993.

U3 United Nations. Sources, Effects and Risks of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 Report to the General Assembly, with annexes. United Nations sales publication E.88.IX.7. United Nations, New York, 1988.

U4 United Nations. Genetic and Somatic Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1986 Report to the General Assembly, with annexes. United Nations sales publication E.86.IX.9. United Nations, New York, 1986.

U5 United Nations. Ionizing Radiation: Sources and Biological Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 1982 Report to the General Assembly, with annexes. United Nations sales publication E.82.IX.8. United Nations, New York, 1982.

U6 United Nations. Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, 1977 Report to the General Assembly, with annexes. United Nations sales publication E.77.IX.1. United Nations, New York, 1977.

U7 United Nations. Ionizing Radiation: Levels and Effects. Volume I: Levels, Volume II: Effects. United Nations Scientific Committee on the Effects of Atomic Radiation, 1972 Report to the General Assembly, with annexes. United Nations sales publication E.72.IX.17 and 18. United Nations, New York, 1972.

U13 Ushakova, A.P., I.A. Likhtarev and A.A. Moiseev. Influence of pesticide (DDT) intoxication on the dynamics of caesium and sodium metabolism in rats. UNSCEAR Document A/AC.82/G/L.1500 (1973).

V1 Van Hook, R.I. Gamma radiation profiles for the migratory grasshopper *Melanoplus sanguinipes* (Fab.). p. 1150-1157 in: Radionuclides in Ecosystems. Proceedings of the Third National Symposium on Radioecology, Oak Ridge, 1971 (D.J. Nelson, ed.). CONF-710501-P2 (1971).

V2 Van Hook, R.I. Survival of crickets *Acheta domesticus* (L.), as affected by variations in gamma dose rate. p. 521-526 in: Survival of Food Crops and Livestock in the Event of Nuclear War (D.W. Bensen and A.H. Sparrow, eds.). AEC Symposium Series 24 (1971).

V3 Vriesendorp, H.M. and D.W. van Bekkum. Susceptibility to total body irradiation. p. 43-57 in: Response of Different Species to Total Body Irradiation (J.J. Broerse and T.J. MacVittie, eds.). Martinus Nijhoff Publishers, Dordrecht, 1984.

W1 Welander, A.D., B. Kelshaw, R.F. Palumbo et al. Bikini Eniwetok Studies, 1964, Parts I and II. USAEC Report, UWFL-93. Clearing House for Federal Scientific and Technical Information, NBS, Springfield, 1967.

W2 Wells, J.W. Recent corals of the Marshall Islands, Bikini and nearby atolls, Part 2. Oceanography (biologic), Geol. Surv. Prof. 260/I: 385 (1954).

W3 Whicker, F.W. and L. Fraley. Effects of ionizing radiation on terrestrial plant communities. p. 317 in: Advances in Radiation Biology, Volume 4. Academic Press, New York, 1974.

W4 Willard, W.K. Relative sensitivity of nestlings of wild passerine birds to gamma radiation p. 345-349 in: Proceedings of the First National Symposium on Radioecology (V. Schultz and A.W. Klement, eds.). Reinhold Publishing Corp., New York and American Institute of Biological Sciences, Washington, 1963.

W5 Whicker, F.W. and V. Schultz. Radioecology: Nuclear Energy and the Environment, Volume II. CRC Press, Inc., Boca Raton, Florida, 1982.

W6 Whittaker, R.H. A study of summer foliage insect communities in the Great Smoky Mountains. Ecol. Monogr. 22: 1 (1952).

W7 Woodhead, D.S. Methods of dosimetry for aquatic organisms. p. 43-96 in: Methodology for Assessing Impacts of Radioactivity on Aquatic Ecosystems. Technical Reports Series No. 190. IAEA, Vienna (1979).

W8 Woodhead, D.S. The estimation of radiation dose rates to fish in contaminated environments, and the assessment of the possible consequences. p. 555-575 in: Population Dose Evaluation and Standards for Man and His Environment. IAEA, Vienna, 1974.

W9 Woodhead, D.S. Contamination due to radioactive materials. p. 1111 in: Pollution and Protection of the Seas - Radioactive Materials, Heavy Metals and Oil, Volume 5, Part 3 (O. Kinne, ed.). John Wiley and Sons, New York, 1984.

W10 Whicker, F.W. and T.B. Kirchner. PATHWAY: a dynamic food chain model to predict radionuclide ingestion after fallout deposition. Health Phys. 52 (6): 717-737 (1987).

W11 Woodwell, G.M. Radiation and the patterns of nature. Sensitivity of natural plant populations to ionizing radiation seems to follow known ecological patterns. Science 156: 461-470 (1967).

W12 Woodwell, G.M. and J.K. Oosting. Effects of chronic irradiation on the development of old field plant community. Radiat. Bot. 5/3: 205 (1965).

W13 Woodwell, G.M. and J.H. Brower. An aphid population explosion induced by chronic gamma irradiation of a forest. Ecology 48: 680 (1967).

W14 Wagner, R.H. and T.G. Marples. The breeding success of various passerine birds under chronic gamma irradiation stress. Auk 83: 437-440 (1966).

W15 White, J.C. and J.W. Angelovic. Tolerances of several marine species to Co-60 irradiation. Chesapeake Sci. 7: 36-39 (1966).

W16 Woodwell, G.M. and L.N. Miller. Chronic gamma radiation affects the distribution of radial increment in *Pinus rigida* stems. Science 139: 222-223 (1963).

W17 Woodwell, G.M. and T.P. Gannutz. Effects of chronic gamma irradiation on lichen communities of a forest. Am. J. Bot. 54: 1210-1215 (1967).

W18 Wagner, R.H. The annual seed rain of adventive herbs in a radiation damaged forest. Ecology 46: 517-520 (1965).

W19 Wagner, R.H. Herbaceous recolonization of the Brookhaven irradiated forest: the first three years. Radiat. Bot. 6: 561-565 (1966).

W20 Woodwell, G.M. and A.L. Rebuck. Effects of chronic gamma radiation on the structure and diversity of an oak-pine forest. Ecol. Monogr. 37: 53-69 (1967).

W21 Woodwell, G.M. and R.H. Whittaker. Effects of chronic gamma irradiation on plant communities. Q. Rev. Biol. 43: 42-55 (1968).

W22 Ward, F., S.A. Beach and E.D. Dyson. The effect of acute x-irradiation on the development of the plaice, *Pleuronectes platessa*. J. Fish Biol. 3: 251-260 (1971).

W23 Walker, C. and G. Streisinger. Induction of mutations by γ-rays in pregonial germ cells of zebrafish embryos. Genetics 103: 125-136 (1983).

W24 Woodwell, G.M. and A.H. Sparrow. Predicted and observed effects of chronic gamma radiation on a near-climax forest ecosystem. Radiat. Bot. 3: 231-237 (1963).

W25 Woodwell, G.M. and R.A. Houghton. The experimental impoverishment of natural communities: effects of ionizing radiation on plant communities, 1961-76. p. 9-24 in: The Earth in Transition: Patterns and Processes of Biotic Impoverishment (G.M. Woodwell, ed.) .Cambridge University Press, Cambridge, 1990.

W26 Wang, B. and X. Zhou. Effects of prenatal exposure to low dose ß-radiation from tritiated water on neuro-behaviour in mice. J. Radiat. Res. (1996, in press).

W27 Woodhead, D.S. The effects of chronic irradiation on the breeding performance of the guppy, *Poecilia reticulata* (Osteichthyes: Teleostei). Int. J. Radiat. Biol. 32: 1-22 (1977).

Y1 Yamada, T., O. Yukawa, K. Asami et al. Effect of chronic HTO β or ^{60}Co γ radiation on pre-implantation mouse development in vitro. Radiat. Res. 92: 359-369 (1982).

Z1 Zoetelief, J., L.A. Hennen and J.J. Broerse. Some practical aspects of dosimetry and dose specification for whole body irradiation. p. 3-28 in: Response of Different Species to Total Body Irradiation (J.J. Broerse and T.J. MacVittie, eds.). Martinus Nijhoff Publishers, Dordrecht, The Netherlands, 1984.

Z2 Zach, R. and K.R. Mayoh. Gamma-radiation effects on nestling house wrens: a field study. Radiat. Res. 105: 49-57 (1986).

Z3 Zach, R. and K.R. Mayoh. Gamma irradiation of tree swallow embryos and subsequent growth and survival. Condor 88: 1-10 (1986).

Z4 Zach, R. and K.R. Mayoh. Gamma radiation effects in nestling tree swallows. Ecology 65: 1641-1647 (1984).

Z5 Zach, R. and K.R. Mayoh. Breeding biology of tree swallows and house wrens in a gradient of gamma radiation. Ecology 63: 1720-1728 (1982).

Z6 Zach, R., J.L. Hawkins and S.T. Sheppard. Effects of ionizing radiation on breeding swallows at current radiation protection standards. Environ. Toxicol. Chem. 12: 779-786 (1993).

Z7 Zhou, X., J. Dong, X. Geng et al. Tritium beta-ray and ^{60}Co gamma-ray caused dominant lethal mutation in mice. Chin. Med. J. 99: 420-423 (1986).