Canadian Nuclear Society
Waste Management, Decommissioning and Environmental Restoration
for Canada's Nuclear Activities: Current Practices and Future Needs
Ottawa, Ontario, Canada May 8-11 2005-02-04

NOMINAL RADIO ECOLOGICAL BENCHMARKS FOR THE ECOLOGICAL RISK ASSESSMENT OF RADIOACTIVE WASTE MANAGEMENT FACILITIES

Nava C. Garisto
SENES Consultants Limited
121 Granton Drive, Unit 12, Richmond Hill, Ontario L4B 3N4
email: ngaristo@senes.ca

ABSTRACT

Ecological risk assessments are used to assess potential ecological impacts from contaminated sites, such as radioactive waste management and disposal facilities. These assessments determine the overall significance of the impact of such facilities on non-human biota. Specific indicator species are selected as representative non-human biota at the study sites for the purposes of these risk assessments.

Potential environmental impacts are generally assessed in terms of "screening indices". In simple terms, a screening index is the ratio of an estimated exposure level of the indicator species (or environmental concentration) divided by a level or concentration deemed unlikely to have a significant ecological effect. These latter levels or concentrations are referred to as "estimated no effect value" or ENEVs. Nominal ENEV values for chronic radiation effects based on our current interpretation of literature data are presented in this paper. They are: 5 mGy/d for fish and amphibians; 2.4 mGy/d for aquatic plants; 2 mGy/d for reptiles; 5 mGy/d for benthic and terrestrial invertebrates; 1 mGy/d for slow-growing terrestrial animals that reproduce late in life; 10 mGy/d for short-lived prolific terrestrial animals; 2.4 mGy/d for terrestrial plants; 5 mGy/d for birds. The paper identifies major areas of uncertainty regarding the selection of these nominal ENEVs for practical applications.

I. INTRODUCTION

Ecological risk assessments are used to assess potential ecological impacts from contaminated sites, such as radioactive waste management and disposal facilities. These assessments determine the overall significance of the impact of such facilities on non-human biota. Specific indicator species are selected as representative non-human biota at the study sites for the purposes of these risk assessments.

Potential environmental impacts are generally assessed in terms of "screening indices". In simple terms, a screening index is the ratio of an estimated exposure level of indicator species (or environmental concentration) divided by a level or concentration deemed unlikely to have a significant ecological effect. This latter "benchmark" is referred to as "estimated no effect value" or ENEV.

The screening indices provide a screening-level indication on the potential for environmental harm. The use of conservative assumptions in the derivation of the screening index ensures that if the index is less than one, there is a high level of confidence that, despite any uncertainty in the data, environmental harm is not likely. However, if the screening index is estimated to be greater than one, follow-up work is required to determine whether this is due to conservatism in the assumptions, lack of sufficient data or potential for a real impact.

II. ENDPOINTS OF CONCERN

According to Shpyth *et al.* (2001), the selection of endpoints of concern is a key issue to be resolved when considering the protection of the environment from the effects of ionizing radiation. As noted by the IAEA (1999), there are numerous biological endpoints that might be theoretically considered (ranging from molecular changes in individual cells to complete devastation of the ecosystem). As a consequence, this question must be answered explicitly before any meaningful assessment of "risk" based on "harm" can be completed. Environment Canada's guidance manual for such assessments recognizes this by stating that estimating the probabilities of exceeding an effects threshold or effects of differing magnitudes only fulfills part of the information required for environmental protection. This is because statistically obvious effects (e.g., a high probability of a 10% decline in reproductive fecundity) may or may not be ecologically important. At the community level, a stressor-induced change in microbial species composition is not ecologically significant if there is redundancy in the functions performed by the species.

The assessment endpoint in ecological risk assessment is usually some aspect of population success, such as continuing abundance or persistence of the population, for species or other taxonomic groups of interest. This is in contrast to human health risk assessment where the endpoint of interest is any adverse health effect at the level of the individual. In order to assist in accomplishing the goal of population protection, risk assessors usually focus on specific measurement endpoints that are directly related to population success, and are easy to predict or measure, such as reproductive impairment or mortality of sensitive life stages. For example, Sample *et al.* (1996) focused on endpoints representing actual impairment of reproduction or survival, or developmental effects likely to produce such effects, when they developed benchmark doses for chemical contaminants for wildlife protection. Similarly, Harrison and Anderson (1994) and UNSCEAR (1996) note that the critical radiation effects for non-human biota are those that directly affect reproductive success, via significant impairment of e.g. gametogenesis or embryonic development and survival.

Measurable responses to radiation exposures (e.g., biochemical changes, histological changes in kidney tubules) can occur at exposure levels well below those that actually impair reproduction or survival at any life stage. Such changes are usually regarded as "biomarkers" of exposure, and, in general, are considered as poor endpoints for ecological risk assessment. As pointed out by Environment Canada (1997), "measurement endpoints such as reproductive and developmental toxicity and reduced survival are preferred, as they can be directly related to population-level effects."

III. RADIATION ENEVs FOR FISH AND AQUATIC BIOTA

The lowest ENEV for fish that could be considered based on literature data is from the observations of Makeyeva *et al.* (1995) on silver carp in a cooling pond at Chernobyl, after the accident. That study reported germ cell anomalies and sterile individuals in age classes that have experienced a dose rate of 0.2 Gy/y (0.55 mGy/d); however, the authors acknowledge the possible role of anthropogenic factors other than radiation (thermal and chemical effects), as well as the acute radiation exposures of parents around the time of the accident, as confounding factors in the study. Furthermore, NCRP (1991) noted that such confounding factors can be misleading in studies of accident scenarios.

More relevant experiments on the effects of radiation on fish were conducted by Bonham and Donaldson (1964, 1966, 1970, 1972). They observed opercular defects in salmon at 5 mGy/d and there has been some debate on whether this could lead to population-level effects. The authors themselves concluded that there was no population-level damage at this dose level. The same authors also demonstrated no population-level effects for salmon at a dose rate of 95 mGy/d in a field (sea) study (Hershberger *et al*., 1978).

Knowles (2003) described a study where zebrafish were exposed from an early age to different dose rates of alpha and gamma radiation. The gamma radiation was exposed externally, while the alpha radiation was exposed via ingestion (spiked meals). This study resulted in no significant reproductive effect to those zebrafish exposed to 300 and 1,000 μGy/h (7.2 and 24 mGy/d) of gamma radiation, while radiation damage was seen in those fish exposed to 7,400 μGy/h (177.6 mGy/d). Furthermore, there were no significant reproductive effects seen in zebrafish from those fish exposed to alpha radiation at dose rates of 9.6, 19, 84 and 214 μGy/h (0.23, 0.46, 2.0 and 5.1 mGy/d, respectively).

A literature review including results of a search of the FASSET Radiation Effects Database (www.fasset.org) database was also conducted. Effect levels identified in this database include 5.8 mGy/d (Knowles, 1999), 13 mGy/d (Hyodo-Taguchi, 1980) and a no effect level of 48 mGy/d (Greenwood and Knowles, 1995).

Based on this review, a nominal ENEV for fish and aquatic biota was selected as 5 mGy/day. Insufficient data were identified to derive species-specific ENEV values.

IV. RADIATION ENEVs FOR AQUATIC PLANTS (ALGAE AND MACROPHYTES)

As stated by Thompson and Bird (2003), due to scarcity of data, the ENEV for conifers (terrestrial plants) of 2.4 mGy/d (Amiro, 1994) can be assumed to be the ENEV for algae and macrophytes. This is likely a conservative assumption since conifers are considered to be more sensitive to radiation than lichens and lichens consist of fungus in symbiotic union with algae. This ENEV for algae and macrophytes is also reported in a subsequent paper (Bird *et al*., 2002).

Both UNSCEAR (1996) and the NCRP (1991) report an ENEV of 10 mGy/d for all aquatic organisms to ensure the protection of the population based on no ecologically significant effects below this dose rate. No specific discussion is provided regarding aquatic plants.

A nominal ENEV for aquatic plants (algae and macrophytes) was therefore selected as 2.4 mGy/d.

V. RADIATION ENEVs FOR AMPHIBIANS AND REPTILES

Studies involving chronic exposure by Cs-137 of desert lizards at 20 mGy/d for four years resulted in sterility (Turner, 1975). For these studies, an ENEV of 2 mGy/d was derived by Thompson and Bird (2003) in order to provide a margin of safety for long-lived turtle species and was expected to be conservative for the shorter-lived species that would accumulate lower life-time doses.

There are apparently no studies of chronic radiation exposures of amphibians on which to base an effect threshold, as noted by UNSCEAR (1996). Also, because the responses at high doses may be entirely different from those at low doses, erroneous conclusions may be drawn when acute mortality results (e.g. Sparrow *et al.* 1970) are used to approximate chronic irradiation impacts. In amphibians, acute mortality has usually been associated with haematopoietic damage (UNSCEAR, 1996), whereas the data most relevant to ecological protection are those pertaining to reproduction and development responses (Harrison and Anderson, 1994; UNSCEAR, 1996). Consequently, there is no readily available scientifically sound basis on which to develop an ecologically relevant ENEV specifically for amphibians at this time.

In the absence of chronic radiotoxicity data for amphibians, an ENEV for fish may be considered valid for amphibians, as the early life stages of amphibians are fish-like.

Therefore, a nominal recommended ENEV for amphibians is 5 mGy/d and for reptiles, 2 mGy/d.

VI. RADIATION ENEVs FOR BENTHIC INVERTEBRATES

A study by Harrison and Anderson (1994) developed a dose-response curve for radiological reproductive effects on marine worms. The dose-response curve showed 12% hatch reduction at 50 mGy/d and measurable but essentially insignificant reproductive impairment (1% hatch reduction) at 5 mGy/d. Therefore, the selected ENEV for benthic invertebrates is 5 mGy/d.

VII. RADIATION ENEVs FOR MAMMALS

There are only scarce data on thresholds for radiation effects on slow-growing mammals that reproduce late in life e.g., a study of tritium effect on immature oocytes of the squirrel monkey resulted in a LD_{50} of 3 mGy/d (Dobson, 1982). The ENEVs for terrestrial animals is taken to be 1 mGy/d in several different literature reviews (Jones *et al.,* 2003, Higley *et al.*, 2003 and IAEA, 1992). In addition to these three sources, UNSCEAR (1996) also reports an ENEV of 1 mGy/d for reproductive effects, but an ENEV of 10 mGy/d for protection with respect to mortality.

Therefore, a recommended nominal ENEV for such mammals is 1 mGy/d.

Several studies indicate that short-lived prolific mammals have a higher radioresistance than long-lived slow-reproducing mammals. These studies (e.g., Mihok *et al.* 1985; Mihok, 2003a,b; French *et al.*, 1974) have not observed population-level effects in the 10-100 mGy/d chronic exposure range (Mihok, 2003a). More specifically,

- In papers by Mihok (2003a,b), the results of the 1980s Canadian Zeus Experiment are described. This experiment involved exposing meadow voles to various gamma dose rates (up to 44 mGy/d) and observing the resulting health and demography of all the small mammals living within the facility. This study showed that there were no individual, population or community effects observed at any of the dose rates, including the highest dose rate of 44 mGy/d.
- Studies of pocket mouse in large natural enclosures in Nevada observed no population level effects at a nominal dose rate of 9 mGy/d (French *et al*., 1974).
- Small mammal populations and communities at Chernobyl at a dose rate of 33 mGy/d cannot be distinguished from those in uncontaminated areas (Baker *et al*. 1996; Chesser *et al*. 2001; Rodgers and Baker, 2000; Baker and Chesser, 2000).
- Studies of individual level effects in small rodents in Chernobyl failed to detect long-term effects using sensitive biomarkers for radiation damage in bank voles (Rodgers and Baker, 2000).
- Field irradiator experiments showed no evidence of radiation-specific effects over ten years at a mean exposure rate of 21 mGy/d (Mihok *et al*., 1985).
- According to Mihok (2003a), these experiments *"suggest that populations of short-lived, prolific species can readily accommodate to exposure rates of up to about 100 mGy/d. Any effects of radiation at the individual level are presumably counterbalanced by compensatory mechanisms at the population level, or are simply undetectable relative to natural patterns of variation"*.

A preliminary nominal ENEV value for such mammals is therefore selected as 10 mGy/d. It should be recognized that this value is highly conservative.

VIII. RADIATION ENEVs FOR TERRESTRIAL PLANTS

A population-level radiological benchmark for the protection of terrestrial plants is reported to be 10 mGy/d by Jones *et al.* (2003), Higley *et al.* (2003), IAEA (1992) and UNSCEAR (1996). However, the ENEV for terrestrial plants in reports by ECOMatters (1999), Rose (1992) and Bird *et al*. (2002) are lower. In the ECOMatters report, it was determined that an ENEV of 2.4 mGy/d for chronic exposure to terrestrial plants would not cause any detrimental effects (based on Amiro (1994)), while in the Rose report, an ENEV of 2.7 Gy/y (7.4 mGy/d) resulted in no observable effects for 10 growing seasons of pitch pine. Finally, Bird *et al*. (2002) report that an ENEV of 2.7 mGy/d would result in no significant effects.

A recommended nominal ENEV for terrestrial plants is 2.4 mGy/d.

IX. RADIATION ENEVs FOR TERRESTRIAL INVERTEBRATES

Krivolutsky (1980, 1987) and Krivolutsky *et al.* (1982) reported a seven-fold reduction in the earthworm population at a site contaminated by ^{226}Ra as compared to a control site. Neither site is well described and the source of ^{226}Ra is unclear. It is apparently "caused by the flooding of underground water layers (to) a terrace above a river valley"'.

There are numerous typographical (or translation) errors in the reporting of units. However, between the three papers, it can be deduced that the observed effect occurs in association with l.12E-10 g/g of ^{226}Ra in soil (4.1 Bq/g) and that the γ radiation field measured at some unspecified height above the soil is 100 μR/h. No dosimetry is given in these papers.

Poinsot-Balaguer (1976) reported a decline in springtail populations at dose rates as low as 14 mGy/h (336 mGy/day) after chronic γ irradiation of a Mediterranean oak forest for two to three years. Some other invertebrate species were increased in abundance. Perrault and Castret (1988) reported a reduced number of ant colonies in the same forest after 18 years of chronic irradiation at dose rates as low as 5 mGy/h (120 mGy/day). It is possible that these were indirect effects related to radiation effects on the plant communities.

It should be noted that in a recent paper by Bird *et al.* (2002), it was suggested to base the ENEV for terrestrial invertebrates on the ENEV for benthic invertebrates.

Therefore, our recommended nominal ENEV for terrestrial invertebrates is 5 mGy/d.

X. RADIATION ENEVs FOR BIRDS

A field study by Zach and Mayoh (1982) of breeding birds exposed to γ irradiation reported no effects on breeding, hatching or fledgling in tree swallows and house wrens at dose rates of 5 mGy/day. Another study at the same site (Zach and Mayoh, 1986) reported 56% hatching success at 1,000 mGy/day as compared to 82 to 91% for control nests, or approximately a 35% reduction in hatching success. In a subsequent paper by Zach *et al.* (1993), it was determined that there was no effect on breeding tree swallows that were exposed to a dose rate that is 45 times the background (6 μGy/h, corresponds to 0.14 mGy/d).

UNSCEAR (1996) reviewed this study and others involving chronic irradiation of birds. Buech (1977) observed increased embryonic mortality in birds irradiated at approximately 300 mGy/day in a Wisconsin forest, while Mraz and Woody (1972) impaired gametogenesis by irradiating chicken embryos at 240 mGy/day in a laboratory study. In conjunction with the Zach and Mayoh (1982) data, these studies begin to narrow the gap between no-effect and effect levels. However, there is still a gap in the range of 5 mGy/d to 240 mGy/d.

Therefore, our recommended nominal ENEV for birds is 5 mGy/day.

XI. CONCLUSION

Nominal radiological ENEVs in the range of 1 to 10 mGy/d were derived for various taxonomic groups for population-level effects based on our current interpretation of literature data. The limited amount of information regarding dose-response (i.e., the determination of an upper bound on no-effect values) implies that the ENEVs are generally conservative. The scarcity of data on inter-species variability implies that there is some uncertainty associated with the application of these values to site-specific situations. Therefore, slight numerical differences between ENEVs of different taxonomic groups, e.g., in the range 2-5.5 mGy/d, may be convenient for documentation purposes, but are not very meaningful.

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