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ENVIRONMENTAL RISK ASSESSMENT FOR URANIUM MINES AND MILLS IN CANADA

Prepared by Dr. Douglas Chambers[1], Dr. Nava Garisto[1] and Dr. Harriet Phillips[1]
[1)]SENES Consultants Limited
121 Granton Drive, Unit 12, Richmond Hill, Ontario L4B 3N4
email: dchambers@senes.ca

SUMMARY

In the past, the concern with radiation exposures arising from human activities has been with the protection of human health. The concept was that, if humans were adequately protected, then “other living things are also likely to be sufficiently protected” (ICRP 1977) or “other species are not put at risk” (ICRP 1991). In recent years, the general validity of this view has been challenged (e.g., IAEA 1999), in part, because of increased worldwide concern over sustainability of the environment, including maintaining biodiversity and protecting habitats, rather than because of actual observation of biological effects in non-human species. With the passing of the new *Nuclear Safety and Control Act* of May 2000, the Canadian Nuclear Safety Commission (CNSC) was required to regulate nuclear facilities in such a way as “…to prevent unreasonable risk to the environment.” This was a new challenge for both the CNSC and the industries which it regulates, especially the uranium mining industry.

The former Advisory Committee on Radiological Protection (ACRP) was a group of experts whose role was to provide the CNSC with independent advice on matters relating to health or environmental aspects of ionizing radiation. In view of the new importance of the environment to the CNSC’s regulatory framework, the ACRP established a Working Group to report on current scientific matters pertaining to the potential risks to non-human biota from ionizing radiation and on possible frameworks for the protection of non-human biota. The findings of the ACRP are described in INFO 0703 (ACRP 2002).

A key Canadian regulatory initiative was the inclusion of releases of radionuclides from nuclear facilities (impact on non-human biota) in the second Priority Substances List (PSL-2). A draft report released in July 2001 (EC/HC 2001) generated considerable dialogue among the various stakeholders. The final report of May 2003 concluded that there is little evidence to suggest that current releases of radionuclides from nuclear facilities are harmful to the environment and that it is in fact the chemical properties of uranium that are the issue. While a great deal of debate over the findings of the PSL-2 report remains, the PSL-2 report concluded that *“releases of uranium and uranium compounds contained in effluent from uranium mines and mills are entering the environment in quantities or concentrations that may have a harmful effect on the environment and its biological diversity”*.

Nevertheless, it is still important to evaluate the potential adverse effects on non-human biota exposed to ionizing radiation. In considering how to assess the potential effects of ionizing radiation on the environment, it should be remembered that the ultimate goal of environmental

protection is to ensure that communities and populations of organisms can reproduce and survive and that all higher organisms in the food-chain will be self-sustaining. Thus, the focus of a strategy for environmental protection must be on the collective response of the population or the community rather than the response of a single individual within the community.

It is also important to understand that in assessing risks to the environment, there are many sources of uncertainty, which need to be addressed, or as a minimum acknowledged. Some of these sources of uncertainty include identifying the population at risk, defining what adverse effect is to be assessed, spatial and temporal averaging of exposures, the dose calculation procedure, and the role of natural background variability, among other factors. Each of these aspects introduces uncertainty into the assessment of environmental risk. The presence of such uncertainties is an important consideration in deciding whether or not a true environmental risk is present and how to use the results of the environmental assessments which encompasses uncertainty as part of a risk (-informed) management strategy, consistent with the federal government initiatives in Smart Regulation (www.pco-bcp.gc.ca/smartreg-regint/en/index.html).

Since the passing of the new *Nuclear Safety and Control Act* in 2000, environmental risk assessments have been carried out at various nuclear sites across the country, including uranium mining sites, resulting in extensive dialogue between the CNSC and industry. This dialogue has helped the Canadian process to evolve. At the same time, there have been, and continue to be, several important international initiatives in the area of environmental risk assessment. A continuing challenge to both regulators and practitioners is to participate in, or at least to monitor, such international initiatives and to incorporate relevant information and procedures into the Canadian approach. Thus, this paper attempts to provide an overview of key international initiatives and how these and other initiatives as considered within the Canadian regulatory framework.

1. CURRENT AND ONGOING INTERNATIONAL ACTIVITIES

The current International Commission on Radiological Protection (ICRP) system of radiation protection, while indirectly protecting non-human biota through the protection of people, does not specifically address the potential effects of ionizing radiation on non-human biota. In 2000, the ICRP set up a Task Group to address the protection of the environment, and in January 2003, the Task Group's Report (www.icrp.org) was presented and adopted.

The Stockholm Environment Conference on the Protection of the Environment from the Effects of Ionizing Radiation (October 2003), at which Canada was well represented by regulators and industry, concluded that:

- UNSCEAR, the United Nations Scientific Committee on the Effects of Atomic Radiation, should provide findings on the sources and effects of ionizing radiation in relation to non-human species.
- ICRP should continue to issue recommendations on radiation protection, including specific recommendations for the protection of non-human species.

- IAEA, the International Atomic Energy Agency, should mediate the application of this work internationally.

Subsequently, the ICRP decided to establish a fifth standing committee, Committee 5, on Protection of Non-Human Species. The concept is that the ICRP will take a leading role in policy development in this area (www.icrp.org/docs/2003_Ann_Rep_52_249_04a.pdf).

The European Framework for the Assessment of Environmental Impact (FASSET) project was launched in November 2000 under the EU 5th Framework Programme, to develop a framework for assessing the effects of ionizing radiation to European ecosystems (http://www.fasset.arrakis.es/erk/main38.html). According to the FASSET Final Report of May 2004, the objective of FASSET was to investigate four broad areas:

1. Dosimetry: To provide radiation dosimetry models for a set of reference organisms relevant to different exposure situations.
2. Exposure: To assess transfer, uptake and turnover of radionuclides in European ecosystems and identify components of the ecosystems where exposures (external and internal) may be high.
3. Effects: To critically examine reported data on biological effects on individual, population and ecosystem levels, as a point of departure for characterising the environmental consequences of, e.g., a source releasing radioactive substances into the environment. It is of interest to note that FASSET organized their analysis on four effects categories (umbrella effects), Morbidity, Mortality, Reduced reproductive success (including fertility and fecundity), and Mutation (induced in germ and somatic cells).
4. Framework: To review existing frameworks for environmental assessment used in different environmental management or protection programmes and to integrate project findings into an assessment framework.

The 2003 ERICA project (Environmental Risk from Ionizing Contaminant: Assessment and Management) (www.info@erica-project.org)) is a targeted research program under the 6th EU Framework Programme and ensures the follow-up to FASSET. The key objectives of the ERIC project are:

- to provide an assessment tool;
- to provide risk characterization methodologies;
- to bring together the assessment tool and the risk characterization methods to provide an integrated approach to assessing risk to non-human biota; and
- to test the assessment tool with case studies.

The ERICA project has just completed its first year of work and is currently targeted to be completed by February 2007.

In addition, as part of its current document cycle, UNSCEAR has initiated a new document on the efforts of ionizing radiation on non-human biota and a new report, updating its 1996 evaluation of the effects of ionizing radiation on non-human biota can be anticipated in the next 2 to 3 years.

From the above discussion, it is evident that much work towards improving our understanding of the effects of ionizing radiation on non-human biota is underway. Consequently, it is important that both Canadian regulators and Canadian industry participate in these discussions, where possible, in order to be able to make an informed decision about what knowledge derived from international studies should be adapted for application in the Canadian setting. This becomes especially important in view of the Federal government's initiatives towards "Smart Regulations" (www.pco-bcp.gc.ca/smartreg-regint/en/index.html) which support a learning regulatory culture and a "need for a more strategic international regulatory approach."

2. OVERVIEW OF INTERNATIONAL INITIATIVES

The effects of ionizing radiation on non-human biota, as well as the assessment and management of these effects, has been of interest to scientists for many years and has been reviewed many times by national and international authorities, including, among others, UNSCEAR, (1996), the National Council on Radiological Protection (NCRP, 1991), IAEA (1976, 1988 and 1992), Bird *et al.* (2000), the U.S. DOE (2002), Jones *et al.* (2003), Environment Canada and Health Canada (PSL-2 EC/HC 2003), the report of the former ACRP (ACRP 2002), Copplestone *et al.* (2001), and the various reports developed under FASSET, among others. There are common key elements that are present in all these documents. Table 1 provides a summary of five of the key elements that are discussed in all of these documents and which the authors think merit some discussion.

Table 1: Key Elements in Framework for Protection of Non-Human Biota

• Reference Biota	– not possible to evaluate all biota; - need to select appropriate "reference" biota or indicator species and indicate basis for selection; - possible need to consider individual biota *per se* when species are endangered.
• Exposure of Biota	Need to consider: – spatial and temporal patterns; – uptake by organism; – non-uniform distribution within organism.
• Endpoints in Radiological Assessment	– need to select appropriate population level deterministic effect either on mortality or reproductive capacity.
• Dosimetry Model for (Reference) Biota	Some considerations are: – absorbed dose (by whole body or by time/organ?); – geometry correction; – radiation weighting factor for biota.
• Effects on Biota	– need to select appropriate reference doses from UNSCEAR, IAEA, NCRP, etc. for "umbrella" effects of morbidity, mortality, reproductive capacity; – connection between radiation effects on umbrella endpoint in individual and consequent "possible" effects on population; – role of background radiation levels; – natural population variability.

Three of the five key elements discussed in Table 1 are explored further in this paper.

Exposure of Biota

In considering effects to non-human biota, it should be noted that effects on animal populations can be reduced by considering their mobility (in terms of moving from areas of high exposure to areas of low exposure). Spatial and temporal effects are a key component in assessing exposure to non-human biota. The most significant source of exposure to most terrestrial animals is by ingestion of deposited radioactivity on vegetation or soil. A particular example of this in Canada is the transfer of radionuclides through air, deposition on lichen and subsequent uptake by caribou and reindeer. Lichens do not have a root system but are highly efficient at collecting and retaining nutrient material deposited on their surfaces. Furthermore, lichens do not turn over annually but integrate all deposited materials, including radionuclides, over several decades. The main diet of caribou and reindeer during the winter months is lichen. Therefore, the caribou and reindeer graze on lichen that have absorbed radioactivity over a period of time but also forage over a large area to obtain food as lichen are generally not plentiful in a particular area. Hence, the assessment of exposure to lichen integrates radioactivity both over time and spatial area.

On the other hand, comparatively stationary soil and sediment invertebrates do not have such mobility and can receive higher doses than other more mobile biota, particularly because the soil and sediment is a sink for most radioactive contamination. However, the extent of the relatively highly contaminated sediments or soils may be quite limited and of little practical concern for population level effects.

It is also important to understand that natural radiation is present in many part of the world, for example, ^{210}Po occurs naturally in northern Canada in concentrations of about 15 Bq/kg in muscle and up to 500 Bq/kg in bone (Thomas 1994). Doses to the caribou from natural background radiation can be quite high as illustrated in the example calculation shown below in Table 2. In this example, the background dose is calculated using the internationally acceptable relative biological effectiveness factor (RBE) of 10, as well as the new proposed RBE of 40, as suggested by the CNSC. As seen in the example, the difference in the RBE factor results in a 14-fold difference in the dose. This will be discussed in greater detail in a subsequent section.

Table 2: Background ^{210}Po Dose to Caribou

- Levels of ^{210}Po
  - 15 Bq/kg muscle
  - 500 Bq/kg bone
- Dose Conversion Factor 2.73 x 10^{-5} Gy/y per Bq/kg (Amiro 1997)
- For alpha RBE = 10 (ACRP 2002)
  - Whole body dose ~ 10 mGy/year
  - Bone dose ~ 40 mGy/year
- For alpha RBE = 40 (EC/HC 2001)
  - Whole body dose ~ 40 mGy/year
  - Bone dose ~ 560 mGy/year

Effects of Biota

Scientific reviews such as those carried out by UNSCEAR (1996), IAEA (1992) and Whicker (1997), indicate that mammals are the most sensitive organisms and that reproduction is a more sensitive endpoint than mortality. For acute exposures of mammals, mortality generally occurs at doses > 3 Gy while reproduction is affected at doses < 0.3 Gy. Chronic exposures alter the responses, with mortality occurring at >0.1 Gy d^{-1} and reproduction effected at < 0.01 Gy d^{-1}. Among aquatic organisms, fish are the most sensitive, with gametogenesis and embryo development being the most sensitive stages.

The CNSC (Bird *et al*. 2002) have recommended dose limits for Canadian sites. They recommend that a dose limit value of 0.6 mGy/d be used for fish, a value of 3 mGy/d be used for aquatic plants and a value of 6 mGy/d be applied for benthic invertebrates. These levels are referred to as “estimated no effects values” or ENEVs.

Recently, Garisto (2005) has reviewed the literature on radiation effects on non-human biota and has developed recommendations for “nominal” radiological benchmarks (Garisto 2005). Garisto suggests nominal ENEV values for chronic radiation effects of 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.

These values are quite different from those recommended by the CNSC. This discussion indicates that there still needs to be consensus within international and Canadian regulatory bodies to develop appropriate dose limits for use in risk assessments for non-human biota.

Dosimetry Models

Dosimetry models are needed to assess the impact of environmental radioactivity on non-human biota and to demonstrate compliance with radiation dose guidelines. Realistic dosimetry models for non-human biota are much less well developed compared to human dosimetry. In practice, simplifying assumptions have to be made especially for the practical purpose of demonstrating compliance with regulatory standards or criteria. The degree of simplification depends on the purpose of the application. For example, Amiro (1997) has used the concept of a single generic biota, which represents all plants and animals irrespective of size, shape and composition. Somewhat more sophisticated models take account of dose distributions within reference organisms of assumed shapes and sizes and the fractions of radiation energies absorbed in the organisms (Woodhead, 1979). More recently since it is not possible, nor even necessarily desirable, to assess every individual species, FASSET analyzed an approach based on reference organisms and a corresponding approach to dosimetry for reference organisms (FASSET Deliverable 3, 2003a).

A number of factors contribute to uncertainty in biota dosimetry, among them, organism, population relevant end-point(s), the range of doses under consideration and the choice of a modifying factor for application to absorbed dose used to account for the relative effectiveness of different types of radiation. This modifying factor is often referred to as the *radiation weighting factor* (alternatively RBE) in environmental evaluations.

Several authors have reported data and evaluations of published data on radiation weighting factors, nominal values from these reviews are summarized in Table 3. In considering these values, it is important to understand that data are limited; that experimental radiation weighting factors/RBEs are specific to the endpoint studied; the biological, environmental and exposure conditions in reality (e.g. reference radiation, dose – rate, dose, etc.) are different from laboratory conditions. Thus, as noted in the recent FASSET Deliverable 4 (FASSET 2003b), it is a challenge to develop a generally valid radiation weighting factor/RBE for use in environmental risk assessment. For such reasons, the ACRP (2002) and FASSET (2003) have proposed ranges of radiation weighting factor/RBE values for such general application. Coincidentally, the ACRP and FASSET both selected an alpha radiation weighting factor/RBE of 10, as a notional central value of the radiation weighting factor/RBE as well as "in order to illustrate" the impact of radiation weighting factor/RBE for an internally deposited alpha emitter in the case of FASSET.

Table 3: Summary of Radiation Weighting Factors for RBE Internal Alpha Radiation (Relative to Low LET Radiation)

Source	Nominal Value	Comment
NCRP (1991)	1	Built-in conservatism in dose model
IAEA (1992)	20	Keep same as for humans
Barendsen (1992)	2-10	Non-stochastic effect of neutrons and heavy-ions
UNSCEAR (1996)	5	Average for deterministic effects
Trivedi & Gentner (2002)	10	Deterministic population relevant endpoints
Copplestone *et al*. (2001)	20	Likely to be conservative for deterministic effects
Environment Canada (2001)	40	Includes studies with high RBEs
ACRP (2002)	5-20 (10)	5-10 deterministic effects (cell killing, reproductive) 10-20 cancer, chromosome abnormalities 10, nominal central value
FASSET Deliverable #4 (2003)	5-50 (10)	10 to illustrate effect of α RBE

A very recent evaluation of available information on alpha radiation weighting factors recommends a nominal radiation weighting factor of the order of 5 for alpha radiation population relevant endpoint (Chambers in preparation). Thus, at present a nominal alpha radiation weighting factor in the range of about 5 to 10 seems reasonable.

3. CANADIAN PRACTICE

In Canada, the assessment of potential effect of ionizing radiation continues to be an important consideration, especially to those licensed by the CNSC. A great deal of work has been done by CNSC licencees in support of licence application and environmental assessment. This work will, when published in the open literature provide valuable insight concerning the data, methods, and results of Canadian assessments of the effects of ionizing radiation on non-human biota.

Often, ecological risk assessments are conducted in a tiered manner, with an increasing level of refinement at each tier, with effort concentrated on those issues (e.g., particular ecological entities, habitats, exposure pathways) that the preceding tier was not able to conclusively rule out as possible risk factors. Typically, these issues would be carried forward within a conservative, yet realistic, quantitative assessment that includes a high level of site-specific refinement.

Site-specific data is used extensively to derive model inputs (e.g., operational emissions data, site meteorology and surface hydrology). In turn, a combination of models and measurements are used to develop multi-media environmental concentrations. For example, air dispersion models are used to predict spatial patterns of radon and dust from mining, milling and waste management activities. Similarly, water quality models are used with measurements of effluent from the tailings basin to estimate the downstream concentration of radionuclides in water and sediment. Available data are used to benchmark model predictions.

In many instances, the potential effect of mining and milling operations in the distant future must be assessed, using appropriate models in support of a waste management or decommissioning project. Since no model is a perfect reflection of reality and there are many uncertainties associated with modeling into the future, probabilistic models which allow specific evaluation of uncertainties arising from lack of data, natural variability and other sources are often used to develop best estimates of concentrations and provide a measure of confidence in the model predictions. In order to calculate concentrations in non-human biota (aquatic plants, benthic organisms fish), if no measurements are available, site-specific or regional-specific transfer factors are used where available, in the absence of this information generic transfer factors from referenced literature sources are used. Site-specific Valued Ecosystem Components (VECs) which are representative of the non-human biota at the site are also used in the assessment. The selection of these VECs are sometimes based on stakeholder input. Although, there appears an interest in organ-specific uptake and organ doses, no reference dose levels are available to support the use of such guidance.

Most often, a screening index (SI) of the form:

$$SI = \frac{\text{estimate of biota concentration (dose)}}{\text{reference biota concentration (dose)}}$$

is used to assess the potential adverse effect to an exposed population. The reference biota concentration is often based on individual exposure dose limits or measurement endpoints. Where the screening index exceeds 1, more detailed follow-up may be suggested.

Two important, as yet unresolved issues in assessing effects to non-human biota from mining activities in Canada are reference effects level for non-human biota exposed to ionizing radiation and the radiation weighting factor (RBE) for use in dosimetry of internally incorporated alpha radiation. Thus, for assessment of mining activities in Canada, a range of reference dose limits (benchmarks) for the assessment of effects to aquatic biota, for example fish, are commonly used to reflect varying scientific and regulatory views. For example, recent environmental assessments have used the following range of effect levels for fish, 0.6 mGy/d and 10 mGy/d.

Similarly, in an attempt to reflect the current range of views concerning alpha radiation weighting factor/RBE, values of 5 to 40 are used to address the greater effectiveness of alpha particles in biota with internally deposited radionuclides.

It is self evident, that in the future, it would be desirable to reach a consensus as to nominal values for effect levels and radiation weighting factor/RBE. Agreement concerning the likely effect of uncertainty in those values is also desirable.

4. CONCLUDING REMARKS

A great deal of effort has been, and will continue, to be expended into assessing potential environmental effects of uranium mines, mills and waste management facilities. There is no question that it is very important to protect our natural environment. However, it is also important to use the best available information in assessing potential effects of mining activities on the environment. Thus, it seems evident that it is very important for Canadian regulators and industry to maintain and where appropriate participate in international assessments and apply relevant knowledge gained from such participation to the Canadian setting.

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