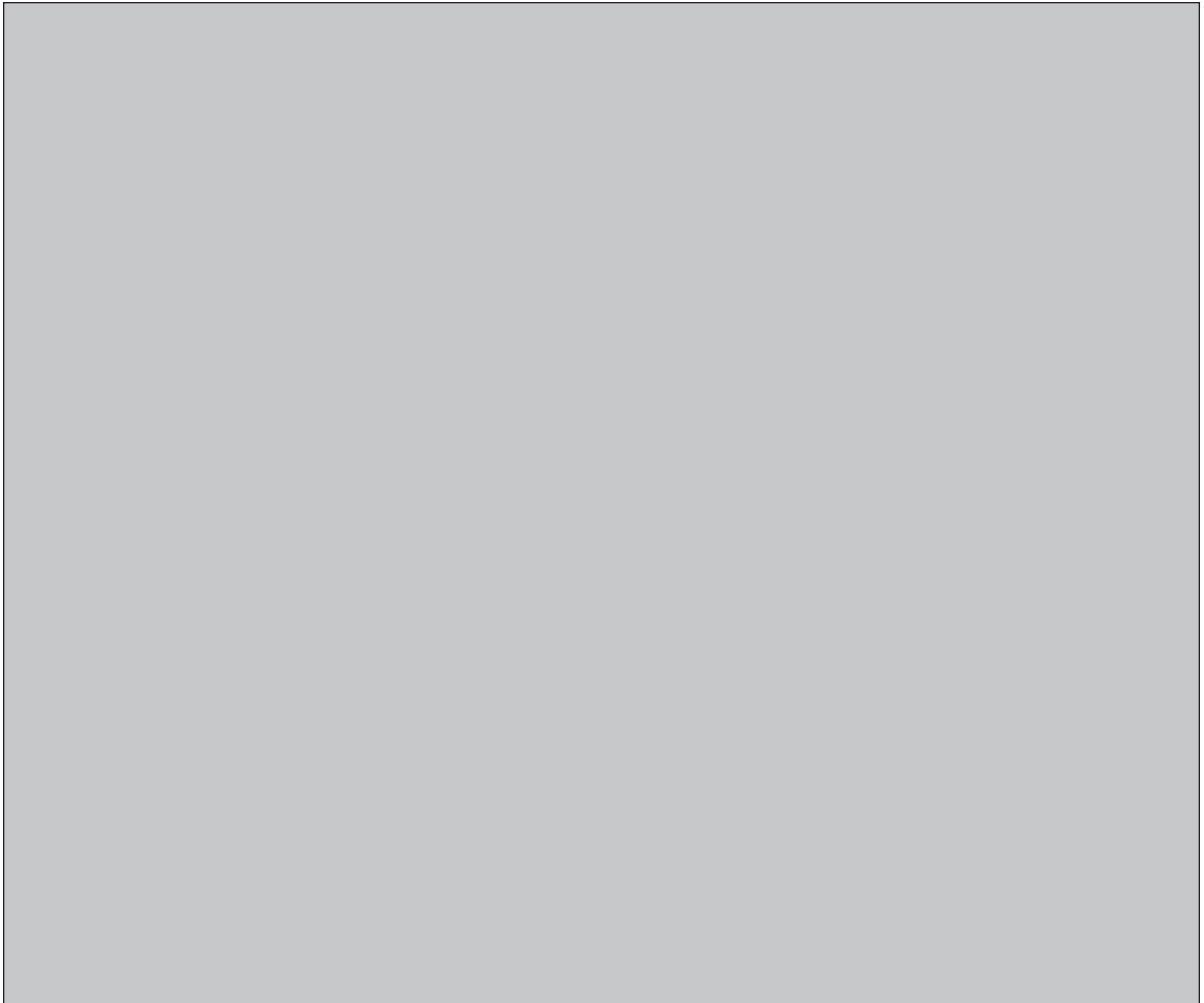


NWMO BACKGROUND PAPERS
4. SCIENCE AND ENVIRONMENT

**4-1 CURRENT STATUS OF BIOSPHERE RESEARCH RELATED TO HIGH-LEVEL
RADIOACTIVE WASTE MANAGEMENT (HLRWM)**

ECOMatters Inc.



NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts** – describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety** – provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment** – provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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Background Paper on the Current Status of Biosphere Research Related to High-Level Radioactive Waste Management (HLRWM)

July 21, 2003

SUMMARY

The biosphere is anywhere organisms live. The biosphere research related to high-level radioactive waste management (HLRWM) deals entirely with the potential effects of the various management options that might be considered. Effects in the biosphere on humans or other biota are the ultimate performance criteria for these HLWRM options, so related biosphere research is quite important. The biosphere cannot be a barrier to the spread of contamination, because by definition there are organisms present everywhere in the biosphere, and any of them could be impacted. Thus the biosphere is the potential receptor of contamination or other impacts from a HLRWM facility. We must understand the severity of these impacts and be able to engineer facilities to prevent or minimize them.

Historically, the emphasis in biosphere research related to nuclear environmental contamination was on the protection of humans, especially from contamination in agricultural settings. Since about 1996, there have been rapid developments worldwide to include predictions of effects on non-human biota. Canada has at times been a leader in issues related to biosphere aspects of HLRWM, and continues to play a role with contributions to the scientific literature and involvement in international programs.

The underlying scientific discipline, radioecology, has particular strengths in dealing with the transport and dispersion of radioactive contaminants in soil, water and air. It borrows from human health and safety research and is well advanced in the estimation of the additive effects of multiple radioactive contaminants. Radioecology is now adapting scientific methods from other ecological disciplines to deal with the multiple organisms present in natural settings.

Although the biosphere is not usually conceived as a manageable barrier, biosphere research has additional importance because the public identifies with biosphere issues. This aspect is becoming increasingly more important as the HLWRM programs worldwide progress and facilities are built.¹

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OBJECTIVES OF THIS PAPER

The objective of this paper is to describe the current status of biosphere research related to HLRWM. It will examine biosphere programs in Canada and worldwide, with particular emphasis on the last decade (1993/2003). Although it will include information relevant to the three possible management approaches for HLRWM as defined in the Nuclear Fuel Waste Act, the emphasis will be on potential long-term impacts, which are somewhat similar for the three approaches.

INTRODUCTION

Biosphere implies any environment where something lives, but the focus is on organisms in water, soil and air at the earth's surface.

Biosphere **research**² for high-level radioactive waste management (HLRWM) focuses on the potential effects of releases of contamination on living organisms. The emphasis is on the surface environment (water, soil, air, and associated organisms) even though micro-organisms can live deep underground. The emphasis is often on very long-term **impacts** (thousands to ten of thousands of years in the future), because long-term impacts are less easily controlled than are more immediate ones, and there are existing regulations and methods to ensure protection for present-day surface facilities. The long-term perspective means the biosphere is considered in a rather generic way, because no one can be sure what the environment will be like that far in the future. Of particular interest to biosphere research are the **radionuclides** found in the high-level waste, their ability to move in the environment, and their radioactive emissions (radiation). Fortunately, most biosphere research related to nuclear waste is relevant to all HLRWM options, and additionally can very effectively draw from research on other nuclear facilities such as emissions from power reactors.

For HLRWM, the major requirement is for information on how organisms absorb and are affected by radionuclides.

Biosphere research is a broad term, and implies the study of any and all organisms and the environment they need for sustained survival. For HLRWM, the research emphasis is on the interactions of **biota** with radionuclides and radiation. It is important to note that a great deal of basic information from the earth and ecological sciences is available to understand many of the more fundamental biosphere

² words in bold have specific meanings in this context, and are more fully defined in the GLOSSARY.

processes. For example, there is information in the literature on the diet of specific biota such as a muskrat, so that in the context of HLRWM the biosphere research can emphasize the **uptake** of radionuclides and the **effects** they might cause.

Biosphere research supports estimation of the effects against which HLRWM will be judged.

The role of the biosphere in HLRWM is not as a barrier to the spread of contamination. The engineered facilities (and the surrounding rock if it is underground) are the barriers to contamination. Zero emission of contaminants and radiation to the environment is the best protection, and is the engineering objective of HLRWM. However, there is always the possibility of some escape of contamination to the environment. As a result, biosphere research has been conducted to understand the impacts of potential releases. This is why biosphere research is important to HLRWM: the ultimate performance criterion for all possible options is the effect they could have on the biosphere.

Potential releases are more probable over very long time periods, and some of the wastes will remain hazardous for thousands of years. Because of this perspective, the role of biosphere research is not to ‘manage’ the problem of contamination, but to estimate the potential effects against which management of other aspects will be judged.



In the 1970's, research was on the survivability of nuclear war.

Previous Research Priorities

The biosphere research relevant to HLRWM began in the 1970's, with rather different objectives. With the proliferation of nuclear weapons, scientists around the world investigated the impacts of radiation on the environment. Considerable effort was directed to understanding the effects on plants, because all life depends on plants as the ecological primary producers. In one line of research, large irradiators were set up, usually powerful radiation sources mounted on poles above natural or agricultural plots. The effects of this radiation on plants and other biota was reported, and these data are still some of the best available (e.g., Sparrow et al. 1971). Canada participated with the Field Irradiator Gamma (FIG) experiment (Guthrie and Dugle 1983, photo opposite), which irradiated a plot of boreal forest in Manitoba, and this was found to be a particularly sensitive ecological system (Amiro and Sheppard 1994; Dugle 1986; Sheppard et al. 1982).

Food chain models were forefront in the 1980's, to calculate dose to humans as a result of reactor operations.

By the 1980's, biosphere research in the nuclear industry emphasized the movement and fate of specific radionuclides, information that was needed to assess the many new nuclear power developments. Information was acquired and simple food-chain models were established (Baker 1977; Fletcher and Dotson 1971; Hoffman et al. 1977; Kaye et al. 1982; Moore et al. 1979; Napier et al. 1980; Shaeffer and Ethnier 1979) and followed later by Canada's own standard for operating reactors (CSA 1987). The radionuclides to be assessed were from almost every element in the periodic table (Figure 1). Where necessary, extrapolations were made to extend the assessment capability to scenarios and radionuclides for which there were few underlying data (e.g., Baes et al. 1984). These extrapolations were thought by some to have led to decreased funding for biosphere research, because they gave the impression that the required knowledge was complete.

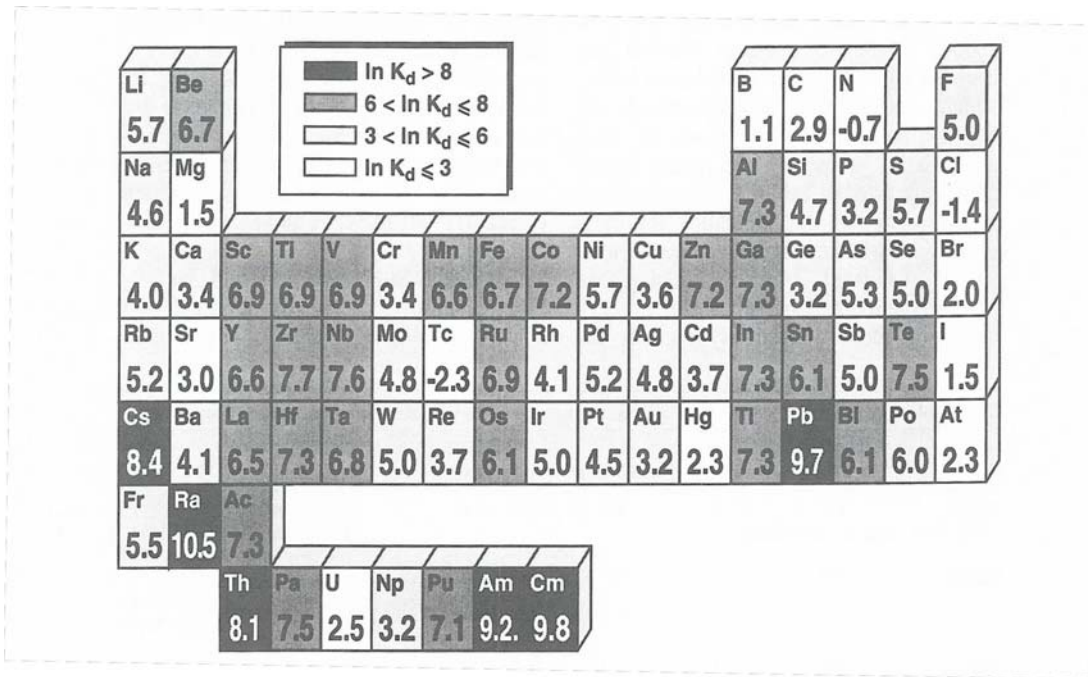


Figure 1. An illustration of the interpolation to provide data for almost every element in the periodic table. Shown are soil solid/liquid partition coefficients in units of $\ln(L/kg)$, from Sheppard et al. (1992).

Chernobyl and glasnost

The Chernobyl accident happened in April 1986, and the contamination consequences became an unfortunate global opportunity to validate our understanding of biosphere processes (see photo opposite). Funding levels markedly



The former 'Red Forest', highly impacted by the Chernobyl accident.

increased, and thousands of research papers have been published on this topic. Shortly after, with the fall of the Soviet Union, western scientists gained access to several other catastrophic nuclear accident sites and widely contaminated regions. Most important to HLRWM are the papers on biological effects of low-level environmental radiation and some cases of unexpected radionuclide behaviour. As one example, there is evidence of **developmental instability** in plants (Moller 1998) and field mice (Oleksyk et al. 2003) in the exclusion zones around Chernobyl. As another example, it has become evident that in nutrient-poor environments, contaminants such as cesium (which mimics the essential nutrient potassium) are very effectively cycled between soils and plants. As a result, radioactive cesium is not leached out of the soil as quickly as might otherwise be the case, and remains an ecological hazard (Desmet et al. 1990).

The future for research will be for waste management and decommissioning of nuclear facilities.

Recently, and following the bursts of research activity related to threat of nuclear weapons and Chernobyl, emphasis is moving toward waste management and decommissioning issues, and especially toward the potential for impacts on non-human biota. There is also some research on biological technologies (plants or micro-organisms) to decontaminate soil. The level of research activity could increase again if nuclear power gains momentum under clean energy strategies.

The Canadian biosphere research has been thoroughly published in the scientific literature.

In Canada, research related to disposal of fuel waste began in the late 1970's, much of it conducted by the environmental research scientists at Atomic Energy of Canada Limited (AECL) Whiteshell Laboratories, with specific inputs from colleagues at Chalk River Laboratories. This contributed to an Environmental Impact Statement (an EIS, AECL 1994). The assessment and research programs were initially funded entirely by the Federal government. In about 1986 there was a shift to 50% co-funding from other owners of nuclear fuel waste (COG, the CANDU Owners Group), and this evolved so that by the late 1990's the research was, and continues to be, fully and directly funded by Ontario Power Generation (OPG). A Technical Review Group, funded by AECL and with reviewers drawn from prominent Canadian professional scientific societies, initially provided scientific review. After submission of the EIS, the Seaborn Panel was established to provide independent and multi-stakeholder review, and they established Scientific Review Groups to critique various aspects of the EIS, including the biosphere components. In addition to this formalized review process, the biosphere

research was extensively published in the open scientific literature, and over 300 papers and reports received international peer review in this process.

The Biosphere Research Community

Radioecology is the discipline that studies radioactive materials and radiation effects in the environment.

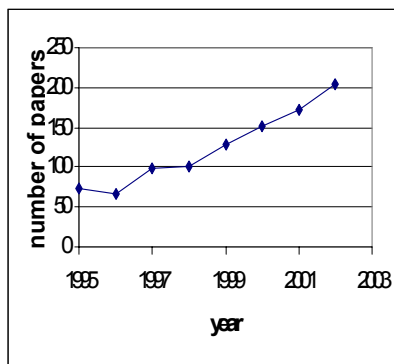


Figure 2. Numbers of papers published in the Journal of Environmental Radioactivity 1995 to 2002, as an indication in the growth of radioecology (from Sheppard 2003).

The relevant biosphere research is carried out throughout the world by scientists in government, university and industry establishments, with funding from governments and industry. The university researchers tend to deal with more theoretical aspects, and orient their research towards publication in the peer-reviewed scientific literature. Their research priorities balance the academic need for originality with the specific requirements of funding agencies. The other researchers span a broader spectrum, including excellent theoretical work along with rather pragmatic modifications from previous knowledge. Their research may be published in peer-reviewed journals, but there is a tendency to also, or to only, produce internal institutional reports. In general, these reports are made publicly available. The major underlying discipline is called radioecology, and is the study of radioactive materials and radiation effects in the environment. The International Union of Radioecologists (IUR web link³) and the South Pacific Environmental Radioactivity Association (SPERA web link) are two prominent related scientific societies. Several peer-reviewed scientific journals publish relevant articles, and the Journal of Environmental Radioactivity (Elsevier Science) has been solely devoted to radioecology for over 20 years (Figure 2). There are a series of regular international conferences that are specific to or include specific sessions on radioecology (e.g., ICOBTE, ECORAD web links).

There is a long history of international cooperation in radioecology.

The International Atomic Energy Agency (IAEA) provides some international coordination role, especially in transferring biosphere information and technology from well-developed to less-developed nations (e.g., IAEA 1992, 1994). Other international agencies such as the Organization for Economic Cooperation and Development (OECD), Food and Agriculture Organization (FAO) and Nuclear Energy Agency (NEA) include some aspects of

³ web links to the internet are given in the REFERENCE section.

radioecology in their mandates. In addition to these established institutes, various national agencies collaborate in specific programs to collectively advance the science (e.g., BIOMOVs: International programme on the BIOSpheric Model Validation Study; BIOMASS: IAEA project on BIOSphere Modelling and Assessment; BIOCLIM: on-going European Community project (2000-2003) 5th Euratom Framework Programme- Modelling Sequential Biosphere Systems under Climate Change for Radioactive Waste Disposal; and BIOPROTA: on-going cooperative project among international waste owners). In general, radioecology is a relatively strong and stable discipline in Europe, and it is growing in Asia. There are several radioecology graduate and post-graduate programs in radioecology in Europe and Japan. Radioecology has lost ground as a discipline in North America, and there are almost no formal training programs. The schematic of the globe (Figure 3) illustrates the relative effort by country, based on papers published in the *Journal of Environmental Radioactivity*.



Figure 3. Schematic where the size of the country outline is proportional to the numbers of papers published in the *Journal of Environmental Radioactivity*, which is an index of the amount of biosphere research being done for the nuclear industry (not just HLRWM), from Sheppard (2003).

Linkage of Research to Assessment

Assessment needs set the priorities for biosphere research.

Biosphere research in support of HLRWM in Canada has been closely linked to meeting the needs of risk assessment. The program was closely monitored over a decade by an independent Technical Advisory Committee (TAC 1993), and this group was especially adamant that the biosphere research be narrowly focussed and at an 'appropriate' level of scientific detail. 'Appropriate' was a judgement by the TAC, in general it meant that the most favored studies addressed clear and immediate needs to close information gaps in the risk assessment (the EIS). As a result, studies on theoretical ecology or biology were less common. In the assessments, the biosphere information served 1) to estimate doses to humans and other biota resulting from potential radionuclide releases and, 2) to estimate whatever dilution and dispersion might occur. Although dilution is expected, the biosphere is not usually conceived to be a protective barrier. However, certain parts of the environment, and especially soil, can accumulate contamination over time. The Seaborn Panel (1998) had few comments about the biosphere or the way the underlying biosphere research was reflected in the assessment (described in detail in the Related Areas section of this background paper).

KEY ELEMENTS

The biosphere is remarkably diverse, and so is biosphere research that is relevant to HLRWM. To present a concise overview, six key elements are described here in some detail. This is not to diminish other excellent research initiatives that are also relevant to HLRWM. The key elements include:

- Biosphere research and the risk assessment paradigm – detailing where the research emphasis is in the context of the overall assessment problem;
- How biosphere research is done – illustrating the typical level of detail;
- The dualities of biosphere research for HLRWM – describing several ways the research directions are changing;
- Implicit protection of the environment – showing how the intent is to fully protect all aspects of the environment;
- Humans versus non-human biota – demonstrating the largest new research initiative; and
- Continued advances related to humans – showing the continued research activity in the traditional research directions.

Biosphere Research and the Risk Assessment Paradigm

The research topics to support risk assessment are: source, exposure, effects and risk.

Biosphere research for HLRWM has been strongly oriented to risk assessment. Risk assessment has evolved a specific methodology, and that brings specific information requirements. Theoretical biological and ecological research is often not directly required: the research needs for risk assessment are quite practical. Very often the required information relates to quantification rather than hypothesis testing. In other words, the scientific questions are more like ‘how much of this will happen’ as opposed to ‘will this happen or not’. To understand these practical research needs, it is important to relate them to the underlying risk assessment paradigm. The paradigm includes four elements: source, exposure, effects and risk.

The source is obviously the waste, but where it gets to the environment is important.

Risk from exposure to contamination is quantified from information about source, exposure, effects and risk. In HLRWM, the source to the biosphere is either the engineered facility or the intervening rock mass (geosphere). In either case, the important characteristics of the source are the rate, timing and location of the contaminant release. It is also important to know the physical and chemical form of the contaminants. Releases from surface storage facilities can be very effectively controlled, provided there is ongoing monitoring and surveillance, but from closed underground disposal facilities, they are more problematic. This is where much of the corresponding biosphere research has been directed, and where some conceptual differences emerge. Many agencies assume the biosphere source or entry point from geological disposal will be solely into the aquatic environment, with some of the contamination then making its way to the terrestrial human **food chain** by processes such as irrigation. Others, including AECL/OPG (Davis et al. 1993; Sheppard et al. 1995) assume that at least some of the contamination will directly enter terrestrial wetlands. There has been some very interesting research on this, and it is an example of the use of analog information. The underlying question is whether a deep source of radioactive material can be detected at the surface, and this is exactly the same problem faced by prospectors looking for uranium deposits. There has been a cross-fertilization of research methods, including the use of ping-pong balls to sample helium as an indicator of buried, decayed natural uranium (Gascoyne and Sheppard

1993).

Most biosphere research is directed to estimation of exposure from contamination.

Exposure describes the transfer of contaminants (or radiation) from the environment to human or non-human receptors. This is where the food-chain models are used. The basis is simple: how much contaminated food, water or air does a receptor consume? Information on ingestion of food and water and on inhalation of air for humans and other biota is relatively abundant from the literature, and so little research specific to HLRWM is required. Estimates of expected concentrations in the food, water and air are much less certain, and this has been and continues to be the major emphasis in biosphere research for HLRWM. To illustrate, over 80% of the papers at the last ECORAD conference were related to exposure (Bréchnignac and Howard 2001).

Keeping it simple is a hallmark ... most of the required data are measured ratios.

Research dealing with environmental concentrations ranges from largely physical/chemical processes such as **sorption** and dispersion, through to the biological processes such as uptake and excretion. In all of these, there is considerable scope for varying levels of detail. At the simplest level, these processes can be investigated and characterized with empirical (i.e., measured) ratios, and indeed this is the level of detail used in assessment models. To illustrate, the transfer from soils to plants is modeled almost exclusively as an empirical concentration ratio (CR) that is different for each radionuclide and location. Research at this level seeks to obtain more CR values for more settings, to statistically relate CR to environmental parameters, and to understand the uncertainty (variation) associated with these empirical values. The underlying theoretical research on soil-to-plant transfer of elements (usually nutrient elements or some heavy metals) is much more sophisticated. Just to illustrate, the underlying research on plant uptake of iron deals with, among other aspects:

- the release into the soil of iron-specific chelating and acidifying agents by plant roots,
- iron diffusion gradients in the root microenvironment,
- microbial populations specific to the root surface,
- symbiotic fungi that invade the root and simultaneously extract iron from soil,
- the diffusion of oxygen in soil, its consumption by plant and microbial respiration and its effect on iron oxidation and solubility,
- chemical reactions of iron with root cell walls, and
- the ability of the plant to transport iron through the root

to the shoot.

Despite knowing about all of these processes, the international consensus is that this level of detail is far beyond the needs for assessment of HLRWM. Indeed, given that assessments are inhibited by large uncertainties related to time (thousands of years), HLRWM research on such uptake details could convey a false degree of certainty.

Despite considerable recent research on other types of effects, radiation damage remains the key.

The effects dealt with in assessment of HLRWM are almost exclusively related to radiological dose. Physical disturbances such as thermal effects (nuclear fuel waste generates some heat) and the presence of HLRWM structures are considered relatively minor. Chemical toxicity (as opposed to radiological toxicity) is a possible consequence from some non-radioactive constituents of high-level waste, such as boron from borosilicate glass, and from some very-long-lived radionuclides such as ^{99}Tc , ^{129}I and ^{238}U . These are dealt with in assessments, and there has been research effort on chemically toxic impacts of HLRWM (Bird et al. 1997b).

Interestingly, even though the effects of concern in HLRWM are radiological, there was almost no research on radiation effects funded directly by agencies involved with nuclear waste prior to about 2000. In part, this is because the ecological data from the 1970's were considered sufficiently valid, and in part, because radiological dose to humans is intensively studied in relation to health and safety. The very recent interest in radiological effects on non-human biota has spawned some new research on radiation effects, and there is a need for more data on effects to aquatic organisms because they were not often included in the nuclear weapons related research in the 1970's.

Is a very low dose harmful, benign, or beneficial?

There remains debate about the significance of low-level radiation. One argument is that radiation damage has no lower limit: the 'linear-effect-no-threshold' hypothesis says that there is some level of effect (and risk) at even the lowest exposure, because there is a statistical possibility that a single radioactive emission could damage DNA and result in cancer or genetic damage. Another hypothesis (and there are several intermediate to these extremes) is that all life evolved in a higher radiation environment than at present and has adapted to repair genetic or other damage resulting from radiation. There is also compelling evidence of stimulated growth (**hormesis**) as a result of radiation

(Luckey 1980). As academic as this debate may be, it has profound implications for HLWNM because one side could lead to a 'no dose increase is acceptable' position, whereas the other would lead to a 'any dose within the range of normal background is acceptable' position.

In biosphere research, risk translates to a need to characterize natural variation.

Research on **risk** is seldom seen as a component of biosphere research, and there are separate scientific journals devoted to the examination of the concept of risk. However, risk entails probability, and there has been biosphere research to understand the probabilities and uncertainties of the environment. All biosphere data (also true of any data) have associated uncertainty, some related to natural variation (e.g., the average man weighs 70 kg, plus or minus 20 kg), some to uncertainty in measurement (e.g., the rate of loss of gas from a whole lake is difficult to measure), and some to uncertainty in the underlying science (e.g., it is essentially impossible to have a perfect model of a natural system). Historically, uncertainty was dealt with by selecting data values that did not underestimate, and probably overestimated, the effects. This was a purposeful '**conservative**' bias ... a judgment call based on knowledge about the system. Now, HLRWM programs commonly emphasize '**probabilistic assessment**', where best-estimate values and expected uncertainties are used. In adopting this approach, it was discovered there is a shortage of information about the other statistical attributes of biosphere data. In addition to knowing the average or best-estimate value, it is now important to measure statistical dispersion (variation), truncations (impossible upper or lower values) and correlations to other parameters. In some respects, these are more important than the averages, because the extreme values are most important to understand in order to ensure protection of the environment.

Summary

To summarize, the biosphere research related to HLRWM is strongly focussed on issues related to assessment. The risk assessment paradigm divides the process into aspects of source, exposure, effects and risk. By far the greatest emphasis has been on research related to exposure, with some recent effort on effects for non-human biota.

How Biosphere Research is Done

Realism is important,

As with any research, there are probably as many ways to

because no one knows all the interactions that may be important.



do biosphere research as there are researchers. It is beyond the scope of this paper to attempt to describe how biosphere research is done in general, but there are some attributes of biosphere research related to HLRWM that are notable.

- A key one is realism. The research objectives are generally very practical – will this event (the one being studied) have an effect on the environment? Such questions are often difficult to answer with highly controlled laboratory studies, simply because the real environment is not highly controlled. Accordingly, there is considerable effort to conduct research in as realistic a manner as possible. Outdoor experimental settings (photo opposite), long-term observations (weeks not seconds) and locally-relevant organisms are often preferred.
- Similarly, the data collected tend to be relatively gross quantities, such as concentration and mass, as opposed to subtle quantities such as enzymatic activity and membrane function.
- Statistical analysis is a key component, because as in most biosphere research, the requirement is to differentiate an effect (a signal, to use an electronics analogy) from a great deal of background variation (noise).
- Because of this large amount of variation and interaction in the environment, results of research must be qualified: ‘in this setting with this organism we observed this, and it may be relevant to that setting and that organism because ...’. This ambiguity sometimes frustrates specialists in other more exact disciplines, but is the reality of natural systems.
- A distinct attribute is that radioactive substances are used, so the analytical methods are quite different than for other contaminants, and sometimes substantially more sensitive.

Models are an integral part.

Apart from experimental research, there is a substantial component of model development as part of biosphere research. The models range from detailed models designed solely to learn about processes, through to assessment models designed to predict unknown situations based on previous knowledge. In many ways, models have become part of the **scientific method**: the model is our hypothesis of how a system works, and experimental results prove or disprove that hypothesis.

Biosphere research is strongly 'mission oriented'.

What research is undertaken is almost entirely a function of who is paying. Even at universities, curiosity oriented research has been only rarely possible in the past several decades. The opposite is 'mission oriented' research, where the use of the information is clearly established before the research begins. There is competition among researchers for financial support, so those with the funds direct the research. The research is to answer specific questions, and the questions usually derive from issues raised in the assessment of possible effects. Today, this underlies almost all research on biosphere issues, everywhere in the world.

The Dualities of Biosphere Research for HLRWM

The research to assess potential effects to non-human biota is quite different from that for humans.

In a number of aspects, biosphere research is split, usually between the traditional approach and a new approach designed to address a recent topic. These splits probably do not change the effectiveness of the research, but may appear as inconsistencies. For example, potential chemical toxicity is a new topic and is handled differently than the traditional approach to radiological effects. More notably, the research on human versus non-human effects is quite different at present, and this has an interesting and important implication. As outlined by Sheppard (2001), in order to deal with the new topic of effects on non-human biota, a convergence has begun between the rather entrenched disciplines of radioecology and ecotoxicology. Society is more familiar with the results of ecotoxicology, because it leads to the guidelines that control common pollutants such as household products, sewage, pesticides and heavy metals (e.g., from the Canadian Council of Ministers of the Environment). There have been marked advances in ecotoxicology, such as definitions of what must be protected in an ecosystem, how to deal with simultaneous multiple contaminants, and how to interpret the ecological significance of sensitive biochemical-level responses to contaminants (Suter et al. 2000). Radioecology will once again gain significant capability as it adopts methods from another discipline.

Canada has been a leader in the research on effects to non-human biota.

Canada has done some of the ground-breaking research on the various effects of exposure to radiation of non-human biota. In addition to the important contribution of the FIG experiment described earlier, papers from the Canadian HLRWM program (Amiro 1997; 1995; Zach and Amiro

1996a;1996b) became cornerstones in the assessment of effects on non-human biota, especially for their generic approach to dose calculation for the myriad sizes and types of organisms. More advances came from the Environment Canada initiative (under the Canadian Environmental Protection Act, Priority Substances List) that specifically used ecotoxicological methods to assess radiological impacts from nuclear facilities (Bird et al. 2002). A controversial development here was the challenge to previous applications of human-focused treatment of the relative biological effects from **alpha** emissions (and beta emissions from tritium). The position taken was that alpha particles were about twofold more damaging to survival-based, non-human **endpoints** than to cancer-based, human endpoints, and this seems untenable to some researchers who insist that humans are the most sensitive to radiation effects. Ironically, much of the information for effects to humans was derived from non-human surrogate-animal studies. The data from these studies, such as with rodents, are often more valid for assessing effects on similar wild animals than they are for assessing effects on humans.

Summary

The biosphere research related to HLRWM is changing, with one direction being towards the more commonly accepted methods of ecotoxicology. Canada played a prominent role in the early developments in this direction.

Implicit Protection of the Environment

Is estimation of dose and risk sufficient to ensure full protection of the environment?

To generalize the expectations of the public, it might be stated that they want to know that soil, water and air will be protected, now and in the future. The public expects the preservation of biological diversity and the sustainable management of terrestrial, aquatic, and atmospheric resources. Unfortunately, the messages provided by assessments to date have been more convoluted. The results are summarized as an abstract ‘dose rate’, and then this is compared to an even more abstract ‘risk’, and risk can never be zero. The question becomes: does this convoluted process ensure the sustainability and complete protection of the environment?

Biosphere issues for waste storage are better

To begin, it is important to establish what we mean by “sustainability and complete protection of the environment”,

understood than the far-future effects from disposal, but research needs to address both phases.

why dose and risk are described, instead of the many other environmental insults (e.g., contamination, dust, noise, physical disruption) considered in most environmental assessments. In general, the environmental effects can result from two different phases of HLRWM. In the storage phase, it is assumed that the waste is managed for decades by a **competent agency** that can and will detect and fix any problems that occur. This implies the waste is easily monitored and can be retrieved. The disposal phase is when the waste is put in a final permanent location. Both phases must be assessed for environmental effects, but the difference is that during storage it will be possible to detect and mitigate effects before they are serious, whereas in disposal this cannot be assured. Storage has been underway for many years, there is an excellent track record of environmental safety, and so there is little perceived need for biosphere research. In contrast, disposal of high-level waste is unproven, so research is more obviously required. In fact, the information needs for both phases are similar, the assessment capabilities for both must be consistent, and so there is need for biosphere research for both storage and disposal.

Only the most mobile contaminants could escape successful waste disposal ... this helps set priorities.

The very definition of a successful high-level disposal facility is that it must isolate the waste from the environment for centuries or millennia. Even then, only minor failures and very small leakages would be considered acceptable. As a result, only the most soluble and most mobile contaminants could escape, and only in small amounts, from a successful facility. This places the biosphere research emphasis squarely on the mobile radioactive contaminants.

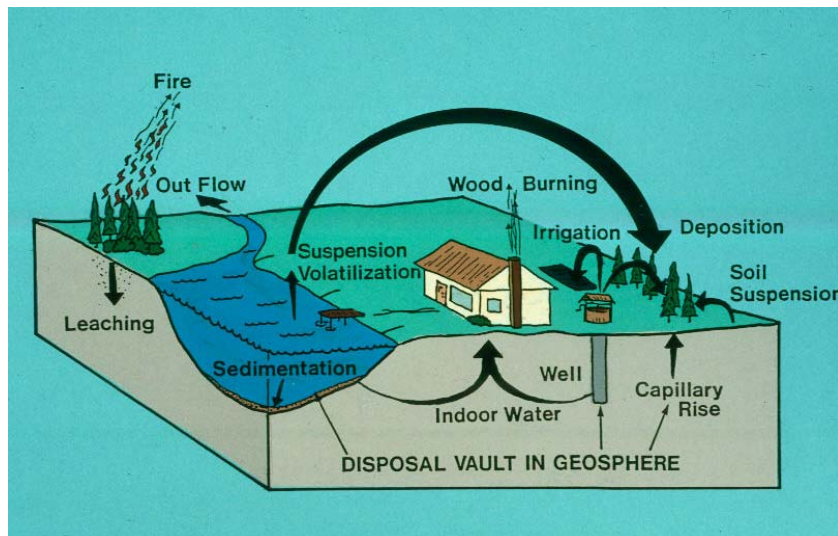
In an effort to ensure all possible contaminant dispersal processes are understood, there has been research into even rather obscure processes.

Mobile contaminants have the potential to spread to all parts of the environment (see schematic). This is the basic assumption in the models used to predict effects related to HLRWM. Indeed, this assumption is so strongly established that there is a portion of biosphere research devoted to finding and evaluating the ‘new’, more obscure **pathways**. These are new in the sense that they are seldom considered as contamination pathways, they are otherwise common events. In the Canadian program, as an example, there were experiments and models to quantify obscure pathways such as:

- contaminated water dispersed into indoor air by humidifiers and showers (Johnston and Amiro 1994);

- contaminants from vegetation dispersed into air by biomass combustion, including fuel, agricultural and wild fires (Amiro et al. 1996);
- contaminants in soil inadvertently ingested from soiled hands or as soil retained on vegetable foods even after washing (Sheppard 1994);
- contaminated aquatic sediments converted to vegetable-garden soil (Bird et al. 1997a); and
- meat products contaminated because livestock animals inhaled contaminated air (Zach et al. 1996a).

In general, there has been considerable research on the extent to which radioactive contaminants disperse in the environment. As a result, the **tools** and some data are available to evaluate the protection of water, air and soil quality; the preservation of biological diversity; and the sustainable management of water bodies, shoreline resources, atmospheric resources, and terrestrial resources. However, by the nature of the problem, the standards to be met will relate to radiological dose and risk, despite those being abstract concepts to the lay public.



Many pathways must be well researched to reliably assess possible effects.

The number of pathways that can be modeled in an assessment has progressively been expanded, but very often the new pathways do not add significantly to the assessment results. Typically, one or two pathways completely dominate an assessment, and all others are insignificant additions. However, this does not necessarily simplify the assessment, because different pathways dominate for different radionuclides, different time periods and different receptors, even if the source remains unchanged. As a result, biosphere research must continue to address a broad

spectrum of possible pathways. As an example, the dominant pathway for ^{14}C is often the water-fish-human pathway and for ^{36}Cl it is often the soil-plant-human pathway, and ^{14}C will tend to be more important earlier in the assessment time than ^{36}Cl . Clearly, many pathways must be well researched to reliably assess possible effects.

Summary

The HLRWM biosphere research to protect the environment is directed toward the most mobile radioactive contaminants, because the waste storage and disposal facilities will be required to have exceptional integrity and will retain anything less mobile. Radiological dose and risk are the state-of-the-art quantities to consider for radioactive contaminants. There has been a long-standing assumption that radioactive contaminants will disperse to all parts of the environment. There has been research not only into the obvious processes (e.g., irrigation of garden plants with contaminated water), but also into some rather obscure processes (e.g., release of contaminants to air from water used in household humidifiers). It would seem reasonable to assume, certainly it was the intent of the researchers involved, that the methodology is in place to ensure protection of all aspects of the environment. This is not to preclude the need for improvements in accuracy and the need for more data to better characterize the variation to be expected.

Humans Versus Non-Human Biota

The former assumption was: protect humans and all else will be protected.

Prior to the early 1990s, the mantra of the nuclear industry for protection of the environment was people-oriented and simple: humans are the species most sensitive to radiation - protect humans and all other species will be protected. This position was promulgated by the highest authorities among the international nuclear agencies (ICRP 1977). Since then, this assumption is no longer blithely accepted, perhaps for three reasons: 1) scientists do not like absolute statements and are more willing to believe that there are always exceptions, 2) it is easy to conceive of a contaminated environment where humans are not present (such as a lake bottom) but where other biota will be exposed, and, perhaps cynically, 3) radioecology as a discipline needed a new topic because human-related issues seemed to be solved.

The assumption had some

There was reasonable basis for the assumption that

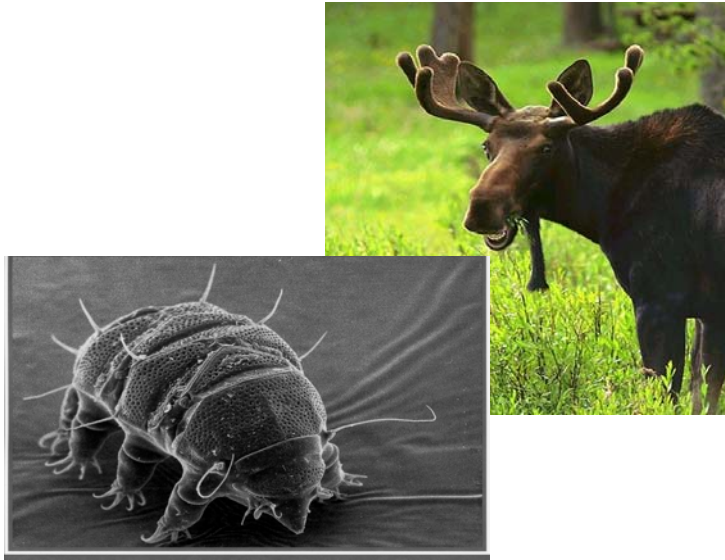
merit, but the present consensus is that it must be examined in detail.

- protection of humans ensured protection of everything else.
- Humans live long enough that cancer is a more common occurrence in humans than in other biota. The link between radiation and cancer is well established.
 - In general, as one considers increasingly complex organisms, there is a greater sensitivity to radiation (Whicker and Schultz 1982). Certainly micro-organisms and insects can be remarkably resistant. It was easy to accept that humans might be inherently most sensitive.
 - Society is concerned about the protection of each individual human, but is more willing to accept that most non-human biota need only be protected at the level of population. Thus for example, cancer in a few older fish may not be an issue as long as there are enough other mature fish in the population to ensure sustainable reproduction. An obvious exception would be endangered species where each individual has exceptional value.
 - The food-chain models to assess effects on humans could be extended to assume that people are exposed to almost all possible environments. To further the previous example, people could be exposed to contaminated lake-bed sediments because of fishing and dredging.
 - There is such diversity among non-human biota that a thorough investigation, at least to the level of detail that was the norm for the assessment of humans, is clearly impossible.

Although these are reasonable arguments, after ten years of debate, they are no longer considered adequate without proof. There is a very large international effort underway now to evaluate the potential effects of all nuclear facilities on non-human biota (Bréchignac et al. 2003; Egan et al. 2001).

The diversity of non-human biota pushes radioecology well beyond the previous norms.

A major challenge is presented by the diversity of non-human biota: the size range among legged animals alone spans 10 trillion-fold (from **tardigrade** to moose, see photos). The previous methods in radioecology required one to know the size, food habits and ingestion rates of the organisms, and it is not a reasonable expectation to carry that methodology forward to all biota. Radioecology must adapt the methodologies of ecotoxicology (Sheppard 2001), where protection of all biota has always been the nominal goal. In doing this, information from many other biological, and especially ecological, disciplines will be needed.



At present, dose thresholds for non-human biota are about 200-fold higher than comparable thresholds for humans.

Radiological dose continues to be the quantity studied, and the effects of interest are those related to sustainability of the population, such as growth, reproduction and genomic stability. Estimation of dose is potentially complicated, although the simplifications proposed by Amiro (1997) seem adequate given the other uncertainties that are part of the whole assessment process. Some dose response information is available, and as in ecotoxicology, it will be a continued research need to systematically quantify the effects of radiation on different biota in different settings. To illustrate the state-of-the-art, Environment Canada (Bird et al. 2002) has recently established that dose rates in the range of 0.2 Gy a^{-1} (for fish) up to 2 Gy a^{-1} (for invertebrates and birds) are the thresholds below which ecological effects are unlikely and above which effects may occur. The dose limit used in Canada for members of the public is, in equivalent units, 0.001 Gy a^{-1} , 200-fold lower than the threshold for fish. Based on this, effects on non-human biota may only be important if they are at least 200-fold more exposed than are humans. This is entirely feasible, as illustrated in Appendix B. Note that the average natural background dose for humans, estimated by Health Canada and including radon, is 0.002 Gy a^{-1} , and that the 0.001 Gy a^{-1} dose limit is in addition to any background dose.

An important underlying fact that markedly simplifies the assessment of the effect of radionuclides on all biota is that

almost none of the radionuclides **biomagnify**. That is, in contrast to organic hazardous materials such as the insecticide DDT, radionuclide concentrations in the body seldom increase as one moves up the trophic levels of the food chain. This has an important implication, as it means that a top predator is not necessarily at greater risk than an herbivore, and that the details of the number of trophic levels between the source and the organism of interest is not a priority.

Summary

There has been a major paradigm shift, from a grand statement that to protect humans was sufficient, to a more detailed investigation of exceptions to that assumption. This topic is the subject of a massive international effort, and rapid advances can be expected. At present, it would appear that non-human biota are more important in settings where humans are not specifically exposed, but if humans are present then protection of humans is probably sufficient to protect the whole environment.

Continued Advances Related to Humans

The key HLRWM radionuclides include some that are isotopes of biologically essential nutrients.

Although the science related to the possible effects of present-day nuclear facilities on humans is fairly mature, the assessment of HLRWM is somewhat different and has led to specific advancements. One of the key areas has been a shift in emphasis among radionuclides. The dose from present-day releases are dominated by ^3H , ^{131}I , ^{137}Cs and U- and Th-decay series (the emphasis on these is illustrated in Table 1). In HLRWM, the emphasis has shifted to very-long-lived and very mobile radionuclides, so that ^{14}C , ^{36}Cl , ^{99}Tc and ^{129}I are prominent. Three of these (^{14}C , ^{36}Cl and ^{129}I) are isotopes of common, stable, life-essential elements. This implies **biological regulation** in the uptake of these three radionuclides, and significant modification of uptake because of differences in the stable element concentrations⁴. The older biosphere models do not fully account for these additional influences. Canada was a leader in deploying models that account for the ratio of radioactive/stable-element concentrations, and other HLRWM agencies such as ANDRA in France and Nirex in the UK are just beginning to follow this lead. The necessary underlying assumption is that the radioactive and stable isotopes behave in the same way, and there is strong evidence that this is a reasonable assumption for the more massive elements (^{14}C and heavier).

Table 1. Numbers of papers in the Journal of Environmental Radioactivity from 1995 to 2002, in decreasing order, that cited the following elements and associated radionuclides in the title, keywords or abstract (from Sheppard 2003).

Element	#	Element	#	Element	#
cesium	345	plutonium	71	iodine	22
uranium	134	thorium	49	technetium	20
strontium	119	tritium	28	carbon (^{14}C only)	12
radon	109	cobalt	26	neptunium	7
lead	74	manganese	24	chlorine (^{36}Cl only)	1

Biochemical processes cannot effectively tell the difference between stable and radioactive isotopes (heavier than ^{14}C) so, for example, deficiency in stable iodine (^{127}I) in the environment could well result in enhanced uptake of iodine in general, which could include enhanced uptake of the radioactive ^{129}I .

The nearly universal focus on the human critical group as a self-sufficient agrarian community lacks realism.

Virtually all HLRWM assessments to date have dealt with a human receptor described as the ‘critical group’ or alternatively the ‘potentially exposed human groups’. This concept is intended to define a group of people in the worst place at the worst time, with habits that tend to maximize their exposure to radionuclides. Typically, the critical group resembles a small rural community with a higher degree of self-sufficiency than is common today. One problem with this is that the interested public does not easily identify with such abstract life-styles, and research has been done to make the critical group less abstract (Zach et al. 1996b). Another is that the critical group concept tends to focus the research efforts away from what might be more plausible exposure scenarios. As an example, if the HLRWM facility is located in a relatively remote area, then the roads and infrastructure built to service the facility may attract a community that with time evolves into a town or urban setting. Although it is argued that exposure in an urban setting is less than for a self-sufficient agrarian setting, this fairly plausible evolution of the environment toward urbanization is not often considered. There is biosphere research on urban radionuclide behaviour, most of it related to Chernobyl and present-day nuclear facilities (Betti, 2000; Nicholson and Hedgecock 1991), but this is seldom applied to HLRWM.

If the assessment emphasis moves to include collective dose (the sum of dose to all people), then several aspects of the problem will change.

Related very closely to the assessment of urban settings, assessments to date expend most effort on the dose to the **individual**. This may be reasonable if the individual is truly a member of the critical group who are maximally exposed. However, such an approach would favor HLRWM concepts where dilution and dispersion are maximized. Such an outcome is certainly not intended nor conceived as being helpful. An assessment alternative is to consider the **collective dose**, i.e., the sum of doses for all individuals in the affected area, or even all individuals in the world. The idea is attractive because it sums the dose from all contamination released by a facility, regardless of how much it was diluted or how far it went. The major problem is that there is no consensus on how high a collective dose is too high. Additionally, collective dose tends to increase as the size of the area considered increases, because it encompasses more individuals. For example, if ^{14}C from a waste facility spread all around the world in the natural

carbon cycle (as it will eventually), there would be a very small, but finite (quantifiable), dose to all people. Even a very small dose to 600 million people⁵ would add up to a seemingly large collective dose. This somewhat open-ended definition of the number of affected people (or other biota) increases uncertainty in the interpretation of the value. If collective doses were considered, then an urban centre may well be more critical than the agrarian critical group. The research needed in this case is more philosophical than biological ... how does one decide how many 'person-sieverts' (the unit of measure for collective dose) is too many?

Assessing the spatial distribution of contamination in the biosphere is not yet a priority in HLRWM programs ... this is expected to change.

There is also research to improve spatial analysis of HLRWM, and this is related to the concept of collective dose. In recent years, geographical information systems (GIS) and a number of related technologies have provided tools to more effectively evaluate the spatial extent of contamination (both along the surface and with depth). Although progress has not been rapid in applying this to prediction of future spread of contamination, there is a trend in that direction (Nirex 1999). To put the issue into context in the Canadian setting, one of the criticisms from the HLRWM hearings in the mid-1990's was that the assessment did not consider the potential for contamination of a downstream delta, but only considered the immediate area around the source. The counter-argument was that the downstream setting would necessarily be more dilute, so less critical than the source setting. Regardless of the validity of this argument, there is an expectation that further assessments will deal more explicitly with spatial contamination, either for varied critical groups or for estimation of collective dose. Research on this is not a priority at present in most HLRWM programs.

It is difficult to make believable estimates of radiological effects over time periods long enough to include future glaciation.

Another dimension that is difficult to deal with in HLRWM is the change in the environment with time. This was cited as a specific shortcoming of the Canadian program in the Seaborn Panel (1998) report. The environment can change in many ways, and climate has received the most attention. Although the public is now aware of global warming, the future onset of glaciation is the change dealt with in more detail by most HLRWM programs. Glaciation has obvious implications on the environment. The radiological dose during full glaciation, when ice would cover most of what is

⁵ 600 million people is one estimate of the world population in 2002.

now Canada, is not assessed because it is not considered the dominant stress compared to kilometer-thick ice sheets. However, in the cold climates before and after full glaciation, radiological dose is potentially important, and this has been assessed. No one knows what the composition of the environment or the role of humans will be in these environments. However, there is evidence that the uptake and transfer of radionuclides may change in cold versus contemporary, warm climates. For example, ANDRA (2001) concluded that, for cesium at least, there are 20-fold higher concentrations in arctic and boreal plant species than in temperate species, and there was a similar trend for animals. For both plants and animals, this effect may be more related to the fact that different species thrive in colder climates, rather than an effect of temperature or climate itself. There is a significant challenge to make such estimates believable to the public, who are aware that climate is now changing and climate prediction is very unreliable.

Summary

Progress continues on the improvement of the safety assessment methodology for humans in the biosphere. Among other aspects, new models have been developed that account for the fact that key HLRWM radionuclides are also common and biologically essential elements, the concept of the critical group has been revisited, and changes in the environment in space and time are being addressed.

GLOSSARY

Alpha emissions are one of three major types of radioactive emissions. The others are photon (gamma and x ray) and beta (electrons). Alpha particles are massive in comparison to the others, and cause much more biological damage per emission than either photon or beta.

Biological regulation implies that the biochemistry of the organism is genetically organized so that the organisms can specifically absorb or excrete a substance based on physiological needs. It often implies the use of metabolic energy by the organism to activate regulation mechanisms such as specific enzymes. For example, iodine can be deficient in the environment and organisms will very effectively concentrate it in the thyroid where it is an essential nutrient.

Biomagnify is the situation where the concentration of a contaminant increases from prey to predator, with the result that top predators are most at risk (e.g., eagles from DDT in their food chain). This is not the case with most radionuclides.

Biota refers to anything living, including micro-organisms, plants and animals.

Collective dose is a summation of the doses received by all individuals in a group. For example, if the radiological dose to each individual in a group is 10 □ Sieverts, and there are 100 individuals in the group, the collective dose is 1000 □ Sieverts.

Competent agency is intended to mean an organization with the financial, technical and social capabilities to manage, in this case a waste facility, in a manner that meets high standards for human and environmental protection.

Conservative is a word that reflects a simple concept but is very difficult to use accurately in a risk assessment. The concept is that, given some uncertainty, one makes decisions in the assessment that should lead to an overestimate, as opposed to an underestimate, of dose or deleterious effect. The difficulty in application is that it is not always obvious which decision will be conservative in all cases.

Developmental instability in the ecological sense is an attribute of populations of individual organisms that have the same genetic background, but that show enhanced variation among the individuals resulting from differences in their rates and modes of development. Developmental instability results from stress, and may arguably lead to genetic changes that allow adaptation to the stress.

Effects is a term used very frequently related to environmental issues, and it is intended to be as general as its common meaning. During the assessment of any project with environmental connections, the 'effects' discussed can be any change since the project began, including the results of stressors such as toxicity, radiation, noise, temperature and dust. Effects do include changes that appear to enhance the environment, such as stimulated growth, because inevitably there will be accompanying negative effects. Impact is a synonym in this context, because even apparently positive effects will always have a negative component.

Endpoints in ecotoxicology refer to the biological process that is specifically affected by a contaminant. Lethality is an endpoint, but preferred endpoints deal with growth rate or reproductive capacity.

Food chain describes in simple words, who eats whom. Food chains usually start with plants that capture energy from the sun, the next link in the food chain are herbivores that eat plants, followed by carnivores that eat herbivores. The human food chain has the same structure, with agricultural production of foods playing the dominant role.

Genomic stability is the degree to which subsequent generations have the same DNA as the previous generations, evolution is based on there being some genomic instability (change), but too much instability is considered evidence of stress.

Half life is the rate of decay of a radionuclide, the time it takes for half of the radionuclide present to decay to another radionuclide or stable element.

Hormesis is where an organism or ecosystem will have an apparently positive response to a low dose of something that is normally considered a stressor. Many pharmaceuticals work this way: a low dose is beneficial a high dose is toxic. Radiation hormesis is reported to occur, although this is controversial.

Impact is a synonym for ‘effects’ in this context (see ‘effects’ above), because even apparently positive effects will always have a negative component or impact.

Individual as used for biota in the assessment context has exactly the same meaning as in common use: one individual is one organism (including human), without regard to the population to which it belongs.

Pathway in this context is the route contaminants might follow as they move from a source (the waste storage or disposal facility) to a susceptible receptor such as a human or other organism.

Population is a number of individuals of the same species within a specified location that is large enough that it can successfully reproduce and be sustainable, assuming the environment remains unchanged with time.

Probabilistic assessment is a technique where instead of making one estimate of an environmental outcome (called a deterministic assessment), one makes thousands of estimates, each one a different but reasonable reflection of a possible outcome. There are various ways to do probabilistic assessments, but the intended result is a indication of the probability associated with each level of outcome. A typical result might be stated in the form: the dose will be lower than 0.002 Sievert per year in 95% of the possible cases.

Radionuclides are radioactive forms of elements from the periodic table, the nucleus of each radionuclide atom will at some (one) time disintegrate (decay) causing an emission of photon energy and/or particles that can inflict biological damage.

Research is not as easily defined as it may seem. The Webster’s definition is ‘studious inquiry or examination aimed at the discovery and interpretation of facts, revision of accepted theories in the light of new facts, or practical application of such new or revised theories’. The emphasis is on ‘new’ and ‘theory’, which implies information that is broadly useful. Another definition might be: development of information that

could be published in peer-reviewed scientific journal. The implication is that, although many people measure things in the environment, only those measurements that provide new information about specific theories and that are of interest beyond the site where they were measured might be called research.

Risk is a common term, but in the assessment paradigm it is a specific meaning that combines consequence (such as cancer death) and the probability that the consequence will occur.

Scientific method is the basic approach of science: to develop a hypothesis about a natural system, followed by experimental or other kinds of tests to prove or disprove the hypothesis.

Sievert is the unit of measure of dose used for humans (1 joule per kg flesh).

Sorption is taken to imply a range of meanings, from very specific chemical exchange reactions on surfaces through to any net effect of a variety of chemical and physical processes whereby a contaminant in solution becomes associated with insoluble solids such as soils or sediments.

SWOT (strengths, weaknesses, opportunities and threats) analysis is a management tool used periodically to assess and redirect activities, largely by causing these attributes to be listed and recognized.

Tardigrade is a very small, soil-dwelling invertebrate, as small as 50 μm (10^{-6} m) long.

Tools in the assessment context refers to models or ways to compute the effects resulting from specific processes.

Trophic levels refer to, in simple words, who eats whom. A higher trophic level feeds on a lower trophic level, and collectively the trophic levels make up a '**food chain**' (or 'food web' in situations where the trophic levels are not necessarily one after another).

Uptake is a general term used to describe the processes by which a living organisms absorbs materials and contaminants from the environment.

RELATED AREAS

Developments in Canada since the Seaborn Report

The Canadian HLRWM program managed by AECL completed an assessment and submitted it to public hearings in 1993/94, which culminated in the Seaborn Panel (1998) report. Several follow-up research opportunities were undertaken during this four-year period, on very specific issues. These included ^{36}Cl (a radionuclide discovered to be present in greater amounts than previously thought), loss of iodine and carbon as gases from soil, and effects of climate change. Similarly, some international collaboration work was still ongoing. The specific reports are listed in Appendix A, under the following categories:

- Biosphere evolution, onset of glaciation and climate change;
- Understanding of underlying processes;
- Ecological effects assessment and non-human biota;
- Improvements to risk assessment approaches with respect to the biosphere;
- Special risk assessment models for ^{14}C , ^{36}Cl and ^{129}I ;
- Updates to parameter values – iodine, chlorine, carbon; and
- Supporting research for biological and biosphere connections with the geosphere.

Since 1998, there has been continued effort on specific biosphere aspects of the models used for assessment, most quite recently (2001-2003). These more recent developments include:

- a thorough review of the biosphere model;
- a new soil model;
- new parameter values for ^{129}I , ^{36}Cl and ^{237}Np ; and
- recommendations for non-human biota indicator species.

International Developments in the Last Decade

The HLRWM programs around the world are in varying stages, and each has a unique approach to the process of establishing a facility. The United States has chosen a location at Yucca Mountain, so that the corresponding biosphere effort can be fairly specific to the expected discharge location in the Amargosa Valley. For example, they have surveyed the habits of people in the Valley. France has focussed on an underground laboratory site near Bure that may evolve into a storage or disposal facility, and so they are similarly quite specific and have funded research on soils in the region. Many others do not have specific sites on which to focus and so remain, as in the Canadian program, fairly generic. As an example, Nirex in the United Kingdom have continued their emphasis on landscape evolution, using 2D and 3D models and detailing the expected effects of glaciation. Although not necessarily comprehensive, the following table lists some of the biosphere-related activities of the past decade.

Program - Agency	Model emphasis	R&D and Experimental emphasis
UK – Nirex	Climate change, ice sheet modelling Soil transport, including 3D modeling and uncertainty analysis Landscape modelling	Soil leaching and plant uptake lysimeter study for model validation Climate analogue locations Potential Exposed Groups
France - ANDRA	Improved models for Cl-36 and C-14 Biosphere and soil evolution and climate change Migration through natural redox interfaces (Se)	Radionuclide mobility and plant uptake, update of parameter values (Tc, U, I, Pa, Se, Cs, Cl) Site-specific soil characterization and Kd studies Speciation and phytoavailability of Ni, Zr Role of microbes (Se, Tc) Update of cold biosphere parameter values U toxicity literature review Role of soil organic matter on fate of Tc, I and Cl
Sweden – SKI or SKB	Modelling deep groundwater Transport of Chernobyl nuclides More holistic approach to biosphere evolution through modeling of various landscapes – coastal, bog and agricultural, well, lake and running water Model validation through BIOMOVS, VAMP and PSAC code comparisons Attention to model validation for C-14 More attention given to the biosphere model in the last three safety assessments	Soil transport of Chernobyl nuclides Studies on redox and radionuclide movement down from the biosphere in vertical fractures Inclusion of non-human biota Natural analogue study of a peat bog Compilation of site-specific values Investigation of the geosphere-biosphere interface Studies on sea-level changes and glaciation impacts
USA – USDOE/ MOE	Development of GENIIS, evaluation of FEPS	Identification of the critical group and receptors of interest, groundwater usage and diet studies, Compilation of extensive baseline data for the Yucca Mountain site, Transfer parameter values, Climate change, erosion and leaching under desert conditions
Switzerland - Nagra	Development of TAME – Terrestrial-Aquatic Model of the Environment Participation in BIOMOVS and BIOMASS Consideration of climate change	Development of an improved database, especially for sorption. Diet definition based on present and historical data, and with an energy balance limit.

Convergence with Research Related to Other Hazardous Wastes

The objective for both HLRWM and management of other hazardous wastes such as heavy metals and man-made organic compounds is much the same: to protect the environment. The same risk assessment paradigm of source/exposure/effect/risk is used for both. There is a historical difference in approach. Sheppard (2001) described the radioecology approach as top-down, and the ecotoxicology approach as bottom-up. Starting from a strong position in the protection of humans from radionuclides, the radioecological top-down approach led to publication of international consensus dose-limits for all non-human biota, and then for classes of non-human biota. These remain a preferred benchmark in many programs worldwide. There continues to be research effort to define, for example, the ‘reference organism’ comparable to the ‘reference man’ used to date in radioecology (Bréchignac et al. 2003). In contrast, the basic approach in ecotoxicological assessment tends to be bottom-up (Suter et al. 2000).

After defining a very specific environmental feature to protect, an ecotoxicology ‘assessment endpoint’ is defined. Almost inevitably, there are no data for the effects of the contaminant of concern on the chosen assessment endpoint. This gap is bridged, for assessment purposes, by defining a ‘measurement endpoint’ which is an organism, endpoint and exposure characteristic that can be used as a surrogate for the assessment endpoint. Surrogates are not perfect, so adjustment factors are applied to ensure that the measured effects data will not underestimate the toxicity to the assessment endpoint in the field. Clearly, the top-down and bottom-up approaches can yield the same results. They can be based on the same data. Perhaps the key difference is in how they are perceived by the regulators, the public and the environmental non-government organizations. The top-down approach carries the perception that details may be overlooked to achieve a sweeping recommendation. It has aspects of an opaque ‘trust us, we are experts’ position. The bottom-up approach can convey the perception that details and site-specific issues are considered. The assumptions may be more transparent. The bottom-up approach appeals to an ecologically democratic perspective, where humans are considered only part of the ecosystem. It may be the only useful approach when it becomes important to protect valued non-human individuals, such as individuals of endangered species and domestic pets. It is significant to note that the bottom-up approach has been used for nuclear facilities by Canadian Nuclear Safety Commission staff seconded to Environment Canada (Bird et al. 2002), and thus it is the present norm in Canada.

There are other reasons why convergence may be beneficial. In terms of size of research effort, other hazardous materials are studied much more extensively than are HLRWM radionuclides. The resulting advancements in ecotoxicology will be beneficial to radioecology. Examples include:

- use of body-size to extrapolate exposure and effects data from one organism to another (discussed for ^{129}I by Macdonald 1996),
- attention to the roles of chemical speciation and natural complexing agents on exposure (discussed for ^{129}I by Sheppard 1996), and

- how to deal with reported effects on biochemical endpoints (biomarkers) that do not have a clear relationship to ecological sustainability.

The United States Environmental Protection Agency (EPA) is a leader in dealing with hazardous waste, and has a policy to broadly share its technology. Many agencies in Canada and throughout the world use EPA models because, even when they are not state-of-the-art, there is precedent in their use and they are freely available. For example some toxicity databases, risk calculators and ecological benchmark data exist for use on national scales (http://risk.lsd.ornl.gov/rap_hp.shtml; http://www.epa.gov/enviro/index_java.html; <http://star.eea.eu.int/asp/default.asp>; <http://www.tera.org/iter/>). In addition, the U.S. Department of Agriculture, the U.S. Department of Commerce and its subagencies, such as the National Oceanic and Atmospheric Administration, the U.S. Department of Defence, the Department of Energy, Department of Health and Human Services, including its National Institute of Environmental Health Sciences all contribute to the Committee on Environment and Natural Resources Interagency Research and Development (<http://www.ostp.gov/NSTC/html/enr/enr-apb.html>) Other countries offer similar resources, and it is logical that, to the extent possible these be adopted for HLRWM.

How could the impact of HLRWM biosphere research be enhanced?

The biosphere research for HLRWM and other nuclear activities has strengths, weaknesses, opportunities and threats, the ingredients of a SWOT analysis and an indication of where enhancements are possible. The following SWOT analysis is simplified to a few points, and capsulizes much of what was discussed in this position paper.

- | | |
|---------------|---|
| Strengths | <ul style="list-style-type: none"> - large body of scientific literature from over 50 years of research specific to radionuclides and radiation in the environment; - generally good history of environmental protection in the nuclear industry (there are few cases of effects where none were predicted); and - international consensus for protection of humans, and a developing consensus for the protection of non-human biota. |
| Weaknesses | <ul style="list-style-type: none"> - HLRWM issues are not as well researched as are other issues in the nuclear environmental area; - radioecology, the study of radionuclides and radiation in the environment, is a declining discipline especially in North America, so there is loss of capacity; and - there some resistance internationally to convergence with ecotoxicology methods, despite the fact that radioecology has always adopted information from other disciplines. |
| Opportunities | <ul style="list-style-type: none"> - to better integrate basic climatology, geography and ecology into models of the evolution of the environment as it affects radionuclides; - to engage the public by making the assessment outputs more tangible and identifiable; and - to develop analogues and large-scale biosphere demonstration experiments to test and illustrate the assessment capabilities |
| Threats | <ul style="list-style-type: none"> - nuclear waste disposal is postponed past when there remains a viable and competent nuclear environmental skill capacity, or in some other way essential information is lost. |

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APPENDIX A PAPERS, REPORTS AND CONFERENCE TALKS ON VARIOUS BIOSPHERE TOPICS FROM THE CANADIAN PROGRAM SINCE 1992

Biosphere Evolution, Onset Of Glaciation And Climate Change

Papers in this section deal with aspects of climate change as it could affect a waste disposal facility. The emphasis is on long-term change, specifically the onset of the next glaciation, which is anticipated in another 10,000 years.

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Sheppard, M.I., B.D. Amiro, P.A. Davis and R. Zach. 1995. **Continental glaciation** and nuclear fuel waste disposal: Canada's approach and assessment of the impact on nuclide transport through the biosphere. *Ecological Modelling*, 78: 249-265.

Understanding of Underlying Processes

Underlying processes is a rather general term, and the following papers are classed as that because they tend to explore issues that were not directly used in an assessment, or that support an assessment in an indirect way.

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Ecological Effects Assessment and Non-Human Biota

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Supporting Research for Biological and Biosphere Connections with the Geosphere

The connection of the geosphere and biosphere, although a very obvious and ubiquitous natural occurrence, is difficult to model and this has not been done in a consistent way among the many agencies interested. The transition seems to represent not only a change in media, but more importantly a change in scientific and assessment approach. The following publications reflect the assessment done in Canada, where the geosphere/biosphere interface was also the bridge from a site-specific geosphere to a generic biosphere.

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APPENDIX B EXAMPLE OF DOSE ESTIMATES FOR HUMANS VERSUS NON-HUMAN BIOTA

Purpose

In the assessment of impacts of radionuclides in the environment, there is a recent emphasis on calculating dose to non-human biota. This is in contrast to a few years ago when it was assumed that if humans were protected, all biota were protected. This Appendix is an example for a present-day situation where it could be argued that there is greater risk to non-human biota than to humans. The example is for contaminated river-bed sediments, which is relevant to HLRWM in that the source to the biosphere of contamination in several HLRWM disposal options would be groundwater discharge into a surface water body.

Description of the Example

The contaminated river sediments were downstream of the outfall of a nuclear facility, and the assessment of these has been fully documented. The suite of radionuclides found or expected in the sediment reflected an establishment where spent fuel was handled, and included Cs-137, Sr-90, Y-90, Co-60, Zn-65, Ru-106, Cs-134, Ce-144, Eu-154, Pb-210, Bi-210m, Po-210, Ra-226, Rn-222, Th-232 and Am-241. The contamination was not uniform. The mean concentration of the key contaminant, Cs-137, was 2.6 Bq kg^{-1} dry weight, the highest observed concentration was 117 Bq kg^{-1} , and the 99th percentile concentration (which was never actually observed) was estimated to be 210 Bq kg^{-1} . It was observed that there were pockets of high concentrations adjacent to boulders and in other places protected from the current. The sediments were found to support a substantial population of clams, of several species, and these were considered to be the non-human biota most at risk because they are long-lived, relatively sessile, and in intimate contact with the sediment. The river is sparsely inhabited by humans, although there are occasional visits along the shore and in boats by sport fishermen.

Exposure Assumptions

It was assumed for this Appendix that the clams may opt to inhabit the same protected places where the contamination was especially high. Thus, they were assumed to be perpetually exposed to the 99th percentile sediment concentration. They received radiation exposure from both external radiation (because they absorb radiation emitted in the sediment in which they live) and internal radiation (because they have radionuclides in their tissues as a result of their diet and uptake from the water).

There is no present direct exposure of humans to these sediments. Concentrations in fish tissue were observed to be very low, so that ingestion was not an important exposure route. Clams are not harvested and consumed. There is a low probability that sediments along the shore may become contaminated, or that someone may contact contaminated

sediment on a boat anchor. The exposure assumption was envisioned as a sport fisherman standing for 10 hours per year on shoreline at the average concentration of the deep sediment. This is considered quite unlikely, and to overestimate the probable exposure.

Dose Estimates

The dose estimates reported here are modified to fit the above exposure assumptions. The dose to clams perpetually exposed to the 99th percentile concentration is estimated to be $1.5 \times 10^{-3} \text{ Gy a}^{-1}$. The dose to humans exposed for 10 hours per year to the average sediment concentration is $1.2 \times 10^{-8} \text{ Sv a}^{-1}$.

Risk Quotient

In order to compare the risks to the clam population and the human individual exposed as described, risk quotients (RQs) were computed. The RQ is the estimated dose divided by the guideline or threshold dose where effects may be possible. For the clam population, the threshold is the Expected No Effect Value (ENEV) used by Environment Canada (Bird et al. 2002) of 2 Gy a^{-1} . For the human individual, the threshold is derived from a risk limit and is $5 \times 10^{-5} \text{ Sv a}^{-1}$. Since Gy and Sv are comparable quantities, it is obvious that the human threshold is 40,000-fold lower, and hence more protective.

The risk quotients are:

clam population	0.0008
human individual	0.0002

Conclusion

The risk quotient in this case was fourfold higher for the clam population than for the human individual, although in both cases the doses are far below levels one might consider problematic. One could argue about the exposure assumptions. However, this is a simple and real example, where the kind of environmental contamination that might result from a HLRWM facility could have a greater impact on non-human biota than on humans. The reason here is simple: the non-human biota is more directly exposed because it inhabits the most-exposed position in the environment. It is not a case of the non-human biota being more sensitive to radiation.

References

Bird, G.A., P.A. Thompson, C.R. Macdonald and S.C. Sheppard. 2002. Ecological risk assessment approach for the regulatory assessment of the effects of radionuclides released from nuclear facilities. IAEA Third International Symposium on the Protection of the Environment from Ionising Radiation, Darwin, Australia, July 22-26.