THE FUTURE OF RADIOECOLOGY AT AECL? BACK TO BASICS

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Abstract

In order to develop a research program in radioecology at AECL, I examined the history of radioecology in general and at AECL in particular. Radioecology has been preoccupied with providing parameters to industry and regulators and has lost sight of its link to ecology. High impact research at AECL has involved the novel use of radiotracers to quantify ecological processes, syntheses of radionuclide or contaminant bioaccumulation or partitioning, and studies of atmospheric or sediment transport. Ongoing research at AECL will focus on areas with potential for high impact in radioecology, while providing industry and regulators with useful models and parameters.

1. Introduction

Radioecology is an interdisciplinary field that lies between the basic fields of ecology, geochemistry and radiation biology and the applied fields of nuclear technology, environmental engineering, health physics and radiation protection [1, 2].

In planning and developing a new research program in radioecology at Atomic Energy of Canada Limited (AECL), I began to organize my thoughts in relation to a few overall objectives. Some of these objectives are relevant to any good research program, while others are specific to the goals of AECL. These objectives include:

- The research should be state of the art, and focussed on new and emerging issues.
- The research should have the potential for high impact in radioecology, environmental science and/or ecology.
- The research should build off of strengths, capabilities and unique characteristics of AECL and the Chalk River site.
- The research should meet the specific current and anticipated needs of AECL and the CANDU Owners Group (COG).
- The research should serve to improve public understanding regarding the environmental risk of nuclear energy through public outreach.

In order to meet these objectives, I conducted two literature reviews. One involved a review of recent literature, primarily editorials, on the state of radioecology. The second review involved compiling the publications of radioecologists at AECL from the 1950's to the present, including the number of publications by each author and the number of citations each publication received.

In this paper, I use the former literature review to answer two questions:

1) What is the state of radioecology?
2) What are the major gaps in knowledge?

I then use the latter literature review to address the following questions:

1) What were the past successes in radioecology at AECL?
2) What kinds of research at AECL had high impact in radioecology, environmental science and/or ecology?

Finally, I use these results to provide context for identifying promising research areas and outline proposed research for the coming year.

2. What is the state of radioecology?

Funding for radioecology has historically been dependent on either widespread contamination or the demand for new nuclear power reactors. Funding and interest were high in the 1940's to mid-1960's due to global fallout from atmospheric nuclear weapon tests and nuclear reactor construction, and again in the late 1980's through 1990's due to the accident at Chernobyl [2, 3, 4, 5]. Interest in radioecology has been in a period of decline due to the poor market for nuclear reactors and the winding down of Chernobyl related efforts, leading many to question the relevance of radioecology and its future [6]. With an interest in reducing greenhouse emissions, nuclear power may experience a renaissance, but this has not as of yet led to another phase of renewed interest in radioecology.

By the mid 1960's, E.P. Odum recognized that radioecology needed to shift its preoccupation from techniques and description, to application of the new techniques to solving basic environmental problems and to making major contributions to the theory of ecosystems [1]. Odum believed that radionuclides were powerful tools for investigating energy and material flow and for understanding how physical and biological factors interact to control ecosystem function. Vigorous feedback between ecology and radioecology was regarded as essential [1]. However, Odum's vision for radioecology appears to have lost momentum by the early 1970's, and radioecology has not returned to its perceived role in quantifying ecosystem structure and function. In fact, of the eighteen editorials evaluated for this paper [2-19], only one cites Odum [7], despite his prominence in ecology and radioecology.

I believe there are two primary reasons for the decline of radioecology:

1) A preoccupation with serving the nuclear industry in meeting regulatory compliance.
2) The proliferation of the transfer factor or bioaccumulation factor approach.

Of the editorials reviewed here, only Hunter [8] directly challenges the notion that radioecology must serve the nuclear industry. Hunter correctly identifies the trap of industrial sponsorship on defining approaches, and suggests that the science should drive regulation [8]. The problem with industrial funding, with its focus on meeting regulatory compliance, is that any research that is funded will be forced to fit into the proscribed regulatory model [8]. Unfortunately, commendable efforts to synthesize certain aspects of radioecology by the International Union of Radioecology (PROTECT) [20] or the International Atomic Energy Agency (EMRAS I & II) [21] fall into this trap. This is not to say that that these efforts have no value or should be reconsidered at this point in time, but simply that these activities should be largely irrelevant to research efforts. When possible, research efforts by radioecologists should be designed to provide industry with needed models and parameters while providing data for new approaches.

Take for example the radioecological approach of starting with concentrations in water and/or sediment, predicting a concentration in biota and then either using the predictions to assess risk to biota or to human health through consumption of biota [22, 23]. Or take the EPA screening approach of comparing concentrations in water and sediment to toxicity benchmarks for biota [24]. Both approaches completely remove ecology from the equation. Ecology occurs between the environmental concentration and the biota, in terms of both bioaccumulation and toxicity. Thus, the feedback that Odum envisioned between ecology and radioecology, or more generally between ecology and environmental science has been removed by the regulatory framework. And when ecology remains, it is usually present in a proscribed generic form, non-specific to the ecosystem in question [25, 26] and largely devoid of ecological insight.

Indeed, one of the major knowledge gaps in radioecology and environmental science is what has been termed "bioavailability". Sometimes extraordinary lengths are taken in trying to "adjust" the sediment or water concentration such that a concentration factor or bioaccumulation factor or toxicity benchmark are in agreement with effects observed in the field, or more routinely, in the laboratory (see e.g. equilibrium partitioning approaches such as the biotic ligand model (BLM) [27, 28] or fugacity [29]). These approaches are largely chemical in nature, framed to fit into a proscribed regulatory framework and continue to remove ecology from the equation. In fact, one could argue that bioavailability has replaced ecology. With knowledge on the structure and function of ecosystems and the interaction of the biotic and abiotic components, bioavailability becomes a meaningless concept.

The BLM and fugacity approaches are of little use to radionuclides, as direct toxicity is generally not an issue, and radioactive substances are usually not present as hydrophobic organic compounds. A more general criticism of these approaches is that the assumptions of equilibrium partitioning may not be appropriate in most situations. Open systems include those usually considered in aquatic biogeochemistry and ecotoxicology (whether in the lake, the ocean or the gut of a living organism), and require kinetic models with rate constants describing their approach to steady state [30].

Single compartment, first-order kinetic, mass balance models have been used to predict concentrations or burdens of organics [31], metals [32, 33] and radionuclides [34] in aquatic food webs. These models share a basic structure that accounts for important uptake and elimination processes through first order rate constants. Central to the single compartment model is the assumption that contaminant uptake and elimination occurs to and from one compartment, i.e. tissues of the whole organism, even though the contaminant may preferentially reside in one or more tissue types (Figure 1).

Figure 1 Schematic of a single compartment contaminant mass balance model with multiple inputs and outputs from a single compartment.

The 1st order linear ordinary differential equation (ODE) that describes this model is:

$$\frac{dQ}{dt} = R - kQ \qquad (1)$$

where Q is the contaminant burden (g), t is time (d), R is the uptake rate (g d^{-1}) and k is the specific elimination rate (d^{-1}). R can include terms for water and/or food uptake and k can include terms for elimination through different processes. Integrating (Equation 1) yields:

$$Q_t = \frac{R}{k}\left(1 - e^{-kt}\right) + Q_0 e^{-kt} \qquad (2)$$

As long as elimination can be modeled as a first order process affecting the entire burden, then this approach is valid. Multi-compartment models such as physiologically based pharmacokinetic (PBPK) models can be utilized where these assumptions are not met. The strength of these models lies in their mechanistic structure, their ability to produce dynamic or steady state results, and their flexibility with regard to modification for other contaminants. Radioecologists have used this approach extensively in the past and I believe must turn to it again to improve our understanding of radionuclide bioaccumulation. This approach is presently being advocated for evaluating metal toxicity [33].

Not all the blame for this predicament lies at the feet of radioecologists and environmental scientists. Ecologists have also been negligent when it comes to feedback between these related disciplines. Contaminants are generally excluded from ecological research. One of the unfortunate outcomes of this lack of feedback is the paucity of hypotheses in radioecological publication (and research?). Hinton recognized this problem in an evaluation of a series of papers published in the *Journal of Environmental Radioactivity* [9]. He found that only 5% of papers used the term hypothesis and many initial submissions were simply lists of data or surveys, without any link to processes. Thus, 36 years after Odum's plea to move beyond description and technique [1], radioecologists may still be mired in that trap. The cyclical nature of the discipline, may also play a role, by removing continuity (memory) and leading to "reinventing the wheel" [3], or even worse, bringing in the proscribed approach to radioecology.

3. What are the gaps in knowledge?

There is general consensus among radioecologists regarding gaps in knowledge. These gaps include:

1) Bioavailability/speciation [2, 7, 10, 11, 13].
2) Radionuclides associated with long-term waste disposal [3, 5, 10].
3) Fate and transport modelling [2, 7, 12, 13].
4) Use of radionuclides as tracers [3-5, 7, 11, 12].
5) Radionuclide/contaminant mixtures [2, 5, 13, 14].
6) Dose and its effects on populations [2, 4, 5, 11-18].
7) Hot particles [10, 19].

I have already commented on the problems and possible solutions regarding bioavailability. Radioecologists need to progress on this issue from either of the two approaches currently used for metals (BLM or kinetics), modifying as necessary. There is a wealth of data available that needs to be synthesized.

Several authors have noted the paucity of research on some of the radionuclides associated with long-term waste disposal, including ^{14}C, ^{36}Cl, ^{99}Tc and ^{129}I. Although there is a need for more research on these radionuclides, publications regarding these radionuclides gather few citations (see discussion in next section). Radioecologists will need to generate more general interest in the fate of these radionuclides.

Many radioecologists call for the increased use of radionuclides as tracers of ecological processes. There seems to be a startling lack of recognition that ecologists have continued to use radiotracers, particularly with regard to nutrient uptake and cycling. For example, in discussing the past use of radiotracers as tools for ecosystem studies, Shaw provides a list of radionuclides of interest from a pollution perspective [7], but misses the widespread and continuing use of ^{32}P and ^{14}C in studies of plant and fungal ecology. Indeed, the widespread and growing literature on stable C and N isotopes speaks to the continuing interest in tracers by ecologists. Ecologists, rather than radioecologists, are leading efforts in tracer applications. If radioecologists are interested in resuming their use of radiotracers, then they will have to turn to ecology for context and theory.

Contaminant mixtures remain a difficult and at present, intractable problem. Within groups of contaminants that share a common mode of toxicity (metals, dioxin-like compounds and radionuclides), effects of mixtures can be assessed, but complex mixtures of contaminants from these groups will likely require an integrative measure of effect. I believe that bioenergetic or physiological endpoints are promising areas for research.

Many radioecologists express concern about dose and endpoints, primarily from a regulatory perspective. The relationship between dose and effect at the population level is a complicated issue that has not been satisfactorily resolved in any environmental science. Unlike other environmental sciences, radioecologists face the challenge of finding sites contaminated enough to expect population level effects [13]. Concerted laboratory and field studies in collaboration with radiobiologists will be required to resolve this issue.

Several authors mention hot particles as an emerging issue. The fate of radionuclides contained in these rather refractory particles remains largely unknown, even though large proportions of activity may be contained within them [19]. Hot particles are a concern for AECL, with localized accumulation in Ottawa River sediments at CRL.

4. What were the successes in radioecology at AECL?

In order to identify what kinds of research at AECL had high impact in radioecology, environmental science and/or ecology, I compiled the publications of radioecologists at AECL from the 1950’s to the present, including the number of publications by each author and the number of citations each publication received (Table 1). I defined a high impact paper as one that received 30 or more citations. This analysis does not include all papers and authors, but contains most of those from authors that have made significant contributions to radioecology at

AECL. In total, 198 publications were identified that received 2519 citations (Table 1). Of these, only 17 (8.5%) meet the high impact criteria of 30 or more citations and these papers received 954 citations (38%).

These papers fall evenly into three categories:

1) The novel use of radiotracers to quantify ecological processes [34-39].
2) Syntheses of radionuclide or contaminant bioaccumulation or partitioning [40-45].
3) Studies of atmospheric or sediment transport relevant to a broad suite of contaminants [46-50].

Table 1 Number of papers published by radioecologists at AECL organized according to the number of citations received.

		Citations per paper							
Author	**Era**	**<10**	**10 to 19**	**20 to 29**	**30 to 39**	**40 to 49**	**50 to 99**	**>100**	**Total Citations**
		(number of papers)							**(number)**
Amiro, B.D.	1980's-90's	13	2	3	1	0	3	0	369
Bird, G.A.	1990's	5	4	1	0	0	0	0	117
Cornett, R.J.	1980's-90's	29	8	3	0	0	1	0	339
Ophel, I.L.	1960's-70's	17	0	0	0	0	0	0	50
Rigler, F.H.	1950's-60's	0	0	0	1	0	1	1	244
Rowan, D.J.	1990's	2	6	2	2	2	1	0	347
Sheppard, M.I.	1980's-90's	21	13	2	0	0	2	0	493
Sheppard, S.C.	1980's-90's	19	16	10	1	1	0	0	558
Yankovich, T.	2000's	5	0	0	0	0	0	0	2
Totals		**111**	**49**	**21**	**5**	**3**	**8**	**1**	**2519**

The novel use of radiotracers includes one of the first whole lake tracer studies of phosphorus dynamics, through the addition of ^{32}P to Toussaint Lake [35]. This study by F.H. Rigler, is not only the first of the high impact papers, but also has received the highest number of citations (113). Rigler subsequently published two other papers using ^{32}P to trace food uptake by Daphnia [36, 37]. The remaining three papers involve the use of ^{137}Cs as a tracer of fish bioenergetics [34, 38, 39]. These papers share two key characteristics: 1) the use of radiotracers to quantify ecological processes of general interest that would otherwise be difficult to obtain; 2) they provide the nuclear industry with dynamic models and parameters that could be used to model the bioaccumulation of radionuclides.

The synthesis group of papers is more diverse and includes two papers on the partitioning of radionuclides/metals in soil [40, 43], a paper on soil remediation [41], a paper on arsenic phytotoxicity [42], another on ^{137}Cs bioaccumulation in aquatic food webs [44] and one on dose conversion factors for non-human biota [45]. This group of papers share the key characteristic of providing models and data that address general concepts of partitioning and bioaccumulation, as well as providing industry and regulators with models and parameters.

The final group of high impact papers consists of two papers on atmospheric turbulence [46, 47], one on sediment transport and deposition [48], one on evapotranspiration [49] and another on long-range atmospheric transport of nitrogen [50]. Although these studies provide models and parameters that could be used in modelling the fate and transport of radionuclides (or other contaminants), none of them explicitly address radionuclides.

There are two additional high impact papers from AECL radioecologists worth noting. The first published just prior to joining AECL, involved the demonstration of biomagnification of PCBs by fish and has received 123 citations [51]. The other published just after leaving AECL, involved quantifying carbon emissions from Canadian forest fires, and received 118 citations [52]. Both of these papers provided important results of broad interest.

In looking at the publications in radioecology at AECL (and having written some of them), it appears that the cost, quality and novelty of the research are often unrelated to the impact of the results. Papers that received fewer citations suffer from several problems:

1) The topic (often radionuclide) is of little general interest to radioecologists, environmental scientists or ecologists.
2) The scope of the paper was limited to one site, one species, one radionuclide, etc.
3) The results did not provide models or results of general use to radioecologists, environmental scientists, ecologists or regulators.

This suggests that for greatest value (cost/citation), research efforts should be directed at producing generality or synthesis. This analysis also suggests (unfortunately) that novel research should be approached cautiously unless the results address an issue of general concern. In addition, research should when possible, provide results that serve several purposes (e.g. general interest and regulatory applicability).

5. Research initiatives in radioecology at AECL

Research initiatives in radioecology at AECL for the next few years will include:

1) An evaluation of Ottawa River benthos in relation to radionuclide and metal accumulation at the Chalk River Laboratories outfall (NRCAN).
2) Speciation of radionuclides at CANDU generating stations and its effect on radionuclide concentrations in aquatic biota (COG).
3) A bioenergetics approach to evaluating the effect of thermal effluent on fish at CANDU generating stations (COG).
4) The fate of ^{14}C, organically bound tritium (OBT) and ^{137}Cs in the Duke Swamp ecosystem (AECL).

The first two projects involve bioavailability, bioaccumulation, toxicity and for the Ottawa River, hot particles. I intend to approach these issues from either the BLM [28] or kinetics approach [33]. As radionuclides have not been addressed with either of these approaches, modifications to existing models or the development of new models will be necessary. This research has the potential for high impact through synthesis of existing knowledge on radionuclide kinetics in invertebrates and radionuclide partitioning in sediments, and application of these data to the development of a general model of radionuclide bioaccumulation for benthic invertebrates.

The third initiative involves the use Cs isotopes as tracers to quantify fish bioenergetics related to exposure to thermal effluent. The quantification of fish bioenergetics in wild fish continues to be problematic, and this approach has the potential to resolve population level effects that are extremely difficult to identify. The Cs bioenergetics approach has already yielded a number of high impact papers [34, 38, 39].

The last initiative is directed at resolving the mechanisms involved in the accumulation of high levels of ^{137}Cs found in mushrooms. Over a thousand papers have been published on this topic, but most are descriptions of concentrations or concentrations in mushrooms as compared to concentrations in soils. Few hypotheses have been put forward to explain this phenomenon, yet it is likely that an understanding of the processes and fluxes of radionuclide and nutrient uptake by fungi are important not only from a radioecological perspective, but also from a terrestrial ecosystem perspective.

Although I stated that research efforts in radioecology should not be pre-occupied with regulatory issues or made to fit into a proscribed approach, I do believe that research efforts should provide new and improved models and parameters for industry and regulators. All of the above efforts will include both a basic applied aspect. In this respect, I will be looking back to radioecology of the 1950's and 1960's, when the distinction between basic (ecology) and applied (radioecology) science was much less distinct.

I also believe that radioecologists should conduct research that at least in part, provides material for communication with the public about the risks and effects of nuclear releases to the environment. In particular, these risks need to be put into the context of risks from other contaminants, municipal sewage, industrial activities and development. The Ottawa River work will be oriented towards this end.

6. References

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