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THE ICRP

JP Samain,ir.
Counsellor ABR/BVS

Abstract
This paper intends to give a short presentation of the International Commission on Radiological Protection (ICRP).

On the website of the Commission the task of the ICRP is given as to help to prevent cancer and other diseases and effects associated with exposure to ionising radiation, and to protect the environment.

Founded in 1928 in the framework of the International Congress of Radiology, it has developed, maintained, and elaborated the International System of Radiological Protection used world-wide as the common basis for radiological protection standards, legislation, guidelines, programmes, and practice.

ICRP is an independent, international organisation with more than two hundred volunteer members from approximately thirty countries across six continents. These members represent the leading scientists and policy makers in the field of radiological protection. The Commission had very soon elaborated rules to establish a full control over its membership: nowadays, the members are elected after a public appeal to candidature.

ICRP has published more than one hundred reports on all aspects of radiological protection. Most address a particular area within radiological protection, but a handful of publications, the so-called fundamental recommendations, each describes the overall system of radiological protection.

The International System of Radiological Protection has been developed by ICRP based on:

i) The current understanding of the science of radiation exposures and effects

and

ii) Value judgements.

These value judgements take into account societal expectations, ethics and experience gained in application of the system.

The ICRP is organised with a **Main Commission** and four **committees**.

- The Main Commission organizes the work of the Committees and approves the documents for publication.

- **The Committee 1 is dedicated to Radiation Effects.**

Committee 1 considers the risk of induction of cancer and heritable disease (stochastic effects) together with the underlying mechanisms of radiation action and also, the risks, severity, and mechanisms of induction of tissue/organ damage and developmental defects (deterministic effects).

- **Committee 2 devotes its efforts to the assessment of doses from radiation exposure.**

Committee 2 is concerned with the development of dose coefficients for the assessment of internal and external radiation exposure and with the development of reference biokinetic and dosimetric models as with the establishment of reference data for workers and members of the public.

- **Committee 3 is related to the Protection in Medicine.**

Committee 3 is concerned with protection of persons and unborn children when ionising radiation is used for medical diagnosis, therapy, or for biomedical research; also, assessment of the medical consequences of accidental exposures.

- **Committee 4 is specially active on the application of the Commission's Recommendations**

Committee 4 is concerned with providing advice on the application of the recommended system of protection in all its facets for occupational and public exposure. It also acts as the major point of contact with other international organisations and professional societies concerned with protection against ionising radiation.

On behalf of the Committees a lot of Task groups elaborate draft documents; for the time being about 20 groups are active. For instance , some of them are preparing reports for the next months : TG97 on the application of the Commission's recommendations for surface and near-surface disposal of solid radioactive waste, TG 98 on application of the Commission's recommendations to exposures resulting from contaminated sites from past industrial, military and nuclear activities, TG 99 on Reference Animals and Plants (RAPs) monographs, TG 101 on radiological protection in therapy with radiopharmaceuticals, TG 102 on detriment calculation methodology , TG 103 on Mesh-type reference computational phantoms, TG 104 Integration of protection of people and the environment in the system of radiological protection . New TG have been established during the last meeting of the Commission : TG107 on Advice on Radiological Protection of the Patient in Veterinary Medicine, TG108 on Optimisation of Radiological Protection in Digital Radiography, Fluoroscopy, and CT, TG109 on Ethics in Radiological Protection for Medical Diagnosis and Treatment and TG110 on Radiological Protection for Workers and the Public in Veterinary Practice.

It is noticeable that the Main Commission, in 2001, had established a fifth committee dedicated to the protection of the environment. This committee aims to ensure that the development and application of approaches to environmental protection are compatible with those for protection of man, and with those for protection of the environment from other potential hazards. Last year, the ICRP decided to suppress this committee with the aim to promote a better integration of the radiological protection of the environment in the general work of the other committees. Each committee has to manage the environmental dimension within its own field to reach a global approach of the protection of the human being and the other species. For instance, it is the reason why the committee 3, in charge with the protection in the medical applications will cover the veterinary uses of radiation.

The Main Commission gather each six month: the last meeting occurs last April in Canada. The summary of this meeting can be found on the website of the Commission. A focus of this meeting was a thorough review of the current programme of work, and discussion of the future programme of work in relation to areas of the system of radiological protection that may require further consideration. More than twenty topics have been listed : amongst them individual radio sensibility, other detrimental effects than cancer and hereditary effects, clarification of the environmental protection, social and economical parameters related to optimization, protection of the children, etc. The Commission intend to share the same large vision of health as the WHO including all relevant topics.

One of the goals of the Commission is to free the Annals; as the sale of the Annals is one the source of financing for the ICRP, the commission has begun to collect funds.

To finish this presentation, ICRP, and ICRU as well, will celebrate its 90th anniversary in Stockholm next October.

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INTEGRATING THE ENVIRONMENT INTO A UNIQUE SYSTEM OF RADIATION PROTECTION
THE ICRP APPROACH - STRUCTURE, PRINCIPLES, DATA, AND APPLICATIONS IN DIFFERENT EXPOSURE SITUATIONS

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Abstract

ICRP started the development of a framework for environmental protection based on an evaluation of the ethical and philosophical basis established in ICRP Publication 91. This was first described in 2008, when the ICRP published a document (Publication 108) which outlined the concept and use of twelve Reference Animals and Plants (RAPs). The RAPs are intended to span terrestrial, freshwater and marine ecosystems through selection of as few organisms as necessary to enable collection and development of datasets on radiation effects and radionuclide transfers and associated dosimetry. Other ICRP reports and task group outputs have expanded on different aspects of the system of radiological protection which now incorporates the environment. Most recently, the way to apply the system of radiological protection to demonstrate environmental protection has been described in the ICRP's Publication 124. In this publication, the Commission's objectives for environmental protection (Publication 103) and how the Derived Consideration Reference Levels (DCRLs) apply within different exposure situations (planned, existing and emergency) were laid out. The

DCRLs are defined as the reference range of dose rates, above the natural background, within which deleterious effects of ionising radiation may occur in individuals of a given RAP type. This article describes the ICRP approach to environmental protection and demonstrates how the system for radiological protection protects both humans and wildlife. It highlights where there are differences between aspects of human and environmental radiological protection. For example, in the protection goal. Put simply, the environmental goal (to protect populations and biodiversity) differs from the goal of protecting individual humans. Furthermore, there are differences in the application of the system of radiological protection where for humans we have dose limits but for wildlife we do not. This is based on the fact that, for there to be a limit, there must be some benefit to the potential increased exposure which is being limited but for wildlife it is difficult to see how there may be such a benefit for a population of a potentially impacted wildlife population. However, the use of limits and constraints is not dissimilar to the intent behind DCRLs which are numeric benchmarks of importance in risk assessment. While the system has been established, there are still areas where further development/thinking is required. For example, we are exploring how simplified numeric criteria may be used in planned exposure situations that are protective of both the public and non-human species. For existing exposure situations, we need to better understand the potential impacts on animals and plants especially when considering the remediation options that may be applied. Understanding both the radiological and non-radiological consequences may be important in making decisions. In emergency situations, understanding the potential impacts on non-human species may be important for communication, although in practice little may be done to mitigate their exposure.

1. Introduction

1.1. Setting the scene for an integrated system for radiological protection of humans and the environment

Human and ecosystem health are now recognised as strongly interconnected as evidenced for example, by several principles and goals for sustainable development recently agreed in the 2030 development agenda of the United Nations [[1]]. In Europe and worldwide, many examples of regulations directed to protection of the environment as a whole (*e.g.,* nature conservation, uses of environmental resources, air, soil, water quality) exist and try to answer the growing awareness by the public of the importance of the global quality of environmental resources and biodiversity.

Faced with exposure situations where various environmental and human-population related factors strongly interact, holistic approaches to risk assessment seem more and more justified to ensure sustainable and safe use of chemical and radioactive substances and to protect both human and ecosystem health. Integrated chemical risk assessment (IRA), defined as "*the mutual exploitation of environmental risk assessment (ERA) for human health risk assessment (HHRA) and vice versa*", has emerged over the last two decades within the European chemical regulatory framework; the goal being to coherently and more efficiently characterise the overall risk to humans and the environment [2]. This concept could logically expand to radioactive substances bearing in mind that differences both in risk assessment methodologies and regulatory framework exist.

Actually, radiological risk assessments have followed a similar but delayed evolution, as reflected in the latest rearrangement of the ICRP committees for the term 2017-2021. The remit of the former committee 5 (dedicated to environment) has been allocated to four committees with an extension of their respective terms of reference to integrate issues dealing with non-human species in addition to humans (e.g. biological effects for C1, dosimetry for C2, medicine with "veterinary patients" for C3 and applications of the integrated system for C4). This also results from the ICRP willingness for such an approach very early, stating that "*...it will be essential to consider how protection of both people and the environment can be achieved within a broad philosophical framework, using complementary approaches, based on the same underlying scientific knowledge*" [3]. Now, ICRP has established a dedicated Task Group (TG104) to ensure the effectiveness of the integration of Protection of People and of the Environment in the System of Radiological Protection by developing an overarching structure for a system that protects both people and the environment from the harmful effects of radiation. The TG aims to promote a coherent forward-looking programme to integrate protection of people and of the environment within the ICRP work in each Committee, and provide ongoing review and advice for the programme prepared by each Committee" [4].

1.2. The key elements of the system of radiation protection

ICRP recommendations on the framework for radiation protection recognise three exposure situations and apply the fundamental principles of justification[1], optimisation[2] and limitation[3] of protection to them [5]. The three exposure situations are:

- Planned exposure situations are exposure situations resulting from the operation of deliberately introduced sources. Planned exposure situations may give rise to exposures that are anticipated to occur (normal exposures) and to exposures that are not anticipated to occur.
- Emergency exposure situations are exposure situations resulting from a loss of control of a planned source, or from any unexpected situation (such as a malevolent event), that requires urgent action in order to avoid or reduce undesirable exposures.
- Existing exposure situations are exposure situations resulting from sources that already exist when a decision to control them is taken.

These recommendations have been followed, to the extent possible, in the International Basic Safety Standards [6]. This includes recognition of the same three exposure situations, though with some differences in definitions and their description. For example, an existing exposure situation is defined in [5] as one "*… that already exist when a decision on control has to be taken*." IAEA defined this as one that "*that already exists when a decision on the need for control needs to be taken*" [6].

In Publication 103 [5], ICRP also set out that the "*primary aim for the Commission's Recommendations is to contribute to an appropriate level of protection for people and the environment against the detrimental effects of radiation exposure without unduly limiting the desirable human actions that may be associated with such exposure*." It goes on to state that the

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[1] Justification means that any decision that alters the radiation exposure situation should do more good than harm.

[2] Optimisation of protection means that all doses should be kept as low as reasonably achievable, economic, societal and environmental factors being taken into account.

[3] Limitation means that the total dose to any individual human should not exceed the appropriate limits. Note that such principle does not apply to non-human species.

aim for environmental protection is to prevent or reduce “the frequency of deleterious radiation effects to a level where they would have negligible impact on the maintenance of biological diversity, the conservation of species or the health and status of natural habitats, communities and ecosystems.

An integrated system of radiological protection has been developed starting from two parallel approaches (Figure 1). The use of a Reference Male and Female concept has been well established within human radiological protection and has been used to derive numeric criteria that can be used to establish the appropriate level of protection (*e.g.,* dose limits, constraints and reference levels).

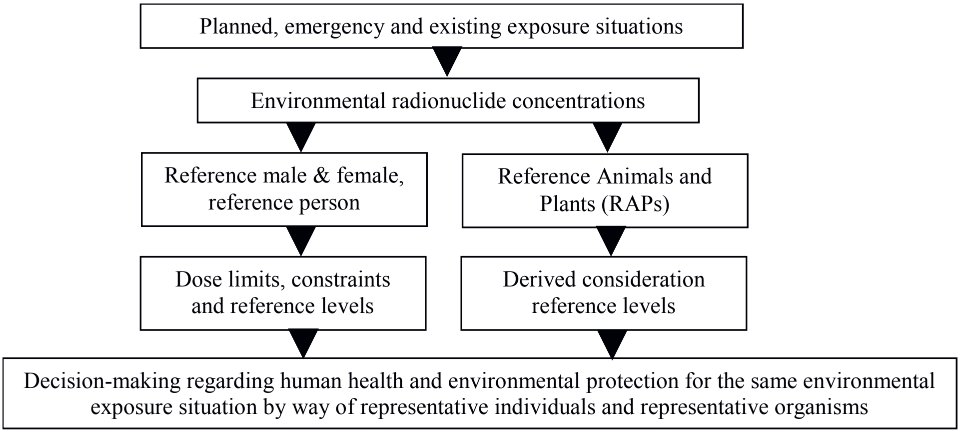
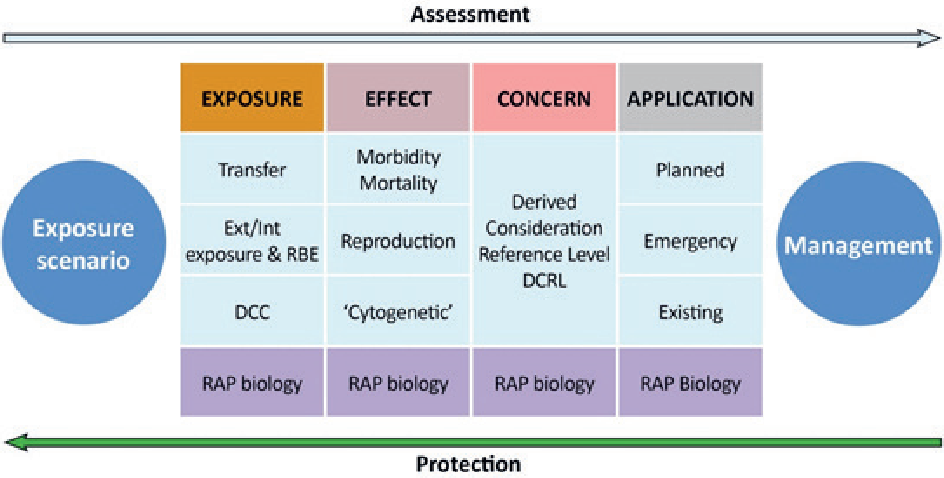


Figure 1: Schematic approach to the protection of both the public and the environment in relation to any exposure situation [7].

In parallel for the environment, twelve Reference Animals and Plants (RAPs) have been identified and used to collate information on transfer of radionuclides (Publication 114 [8]), dosimetry (see Publications 108 and 136 [7,9] respectively) and used to determine Derived Consideration Reference Levels (DCRLs) based on the effects literature for the twelve RAPs (see Table 1). DCRLs are defined as *“a band of dose rate within which there is likely to be some chance of deleterious effects of ionising radiation occurring to individuals of that type of Reference Animal or Plant, derived from a knowledge of defined expected biological effects for that type of organism that, when considered together with other relevant* *information, can be used as a point of reference to optimise the level of effort expended on environmental protection, dependent upon the overall management objectives and the exposure situation*." Figure 2 shows the elements of the ICRP approach that enable assessment of the consequences of a specific exposure scenario, and the management of the exposure scenario based on a system for protection, either this occurs in planned, emergency or existing exposure situations.

Figure 2: The elements of the ICRP approach for assessment of the consequences to ecosystems



of a specific exposure scenario, and for the management of such exposure scenario based on a system for protection. Abbreviations: DC, dose coefficient; Ext/Int, external/internal; RAP, reference animal and plant; RBE, relative biological effectiveness [4].

In Publication 124 [10], the ICRP described its objectives in relation to protection of the environment through the protection of animals and plants (wildlife) using the Derived Consideration Reference Levels (DCRLs) which were first described in Publication 108 [7]. The DCRLs relate radiation effects on a selected set of twelve Reference Animals and Plants (RAPs) to different potential pathways of exposure over and above the normal background natural radiation levels. Publication 124 goes on to explain how the DCRLs may be used in the three different types of exposure situations to which its recommendations apply while considering the key principles that are relevant to protection of the environment. Importantly, the approach described indicates the appropriate level of effort relevant to different exposure situations.

Table 1: The twelve RAPs and their associated DCRL.

Wildlife group	Ecosystem[1]	RAP	DCRL, mGy d^{-1} (shaded) *µGy/h (rounded down, 1 digit)*		
			0.1-1 *4-40*	1-10 *40-400*	10-100 *400-4000*
Large terrestrial mammals	T	Deer	🟩		
Small terrestrial mammals	T	Rat	🟩		
Aquatic birds	F, M	Duck	🟩		
Large terrestrial plants	T	Pine tree	🟩		
Amphibians	F, T	Frog		🟩	
Pelagic fish	F, M	Trout		🟩	
Benthic fish	F, M	Flatfish		🟩	
Small terrestrial plant	T	Grass		🟩	
Seaweeds	M	Brown seaweed		🟩	
Terrestrial insects	T	Bee			🟩
Crustacean	F, M	Crab			🟩
Terrestrial annelids	T	Earthworm			🟩

Starting from the two approaches as shown on Figure 1, the present ICRP goal is to go from a parallel approach to an integrated one. The feasibility of such integration effort can be done:

1. for the exposure analysis, by using consistently similar environmental dispersion models and radioecological databases where relevant;
2. for the effect analysis, by respecting the types of endpoints of interest and benchmarks but using the same underlying principles to *ad hoc* define dose criteria;
3. for risk characterisation, by comparing in a similar way the estimated dose or dose rates to the dose criteria.

Table 2 reports the main elements for integration and Figure 3 summarises the concepts and principles shared between human and non-human risk assessment and protection in a unique system of radiation protection.

Protection endpoint		**Effect category**	**Dosimetric quantity**	**Risk**	**Dose criteria**
Human health (gender, ages, individual sensitivity…)	Individuals	Tissue reactions; Stochastic effects	Absorbed dose (weighted for RBE); Effective dose		Limits (public - planned) or reference levels (public – existing or emergency)
	Populations			Nominal risk coefficients	
Ecosystem health (RAPs)	Populations	Mortality; morbidity; reproductive success; ‘mutations’	Absorbed dose (weighted for RBE)	Risk quotient relative DCRL?	DCRLs

Table 2: Elements needed for the effect analysis and risk characterisation demonstrating the consistency between human and non-human radiological risk assessment and protection.

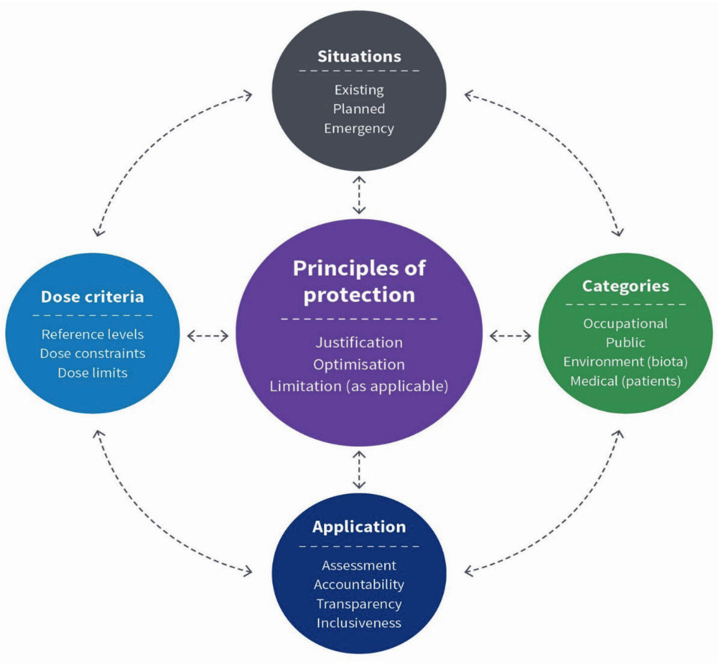


Figure 3: Concepts, elements and principles constituting the integrated radiation protection system that applies for humans and environment [4].

2. Application of the DCRLs in Planned Exposure Situations

In planned exposure situations, the lower boundary of the relevant DRL band is recommended for use as an appropriate reference point for the protection of different types of biota (Figure 4) taking into account factors such as the area over which the radioactive releases are to be considered (and the relevant biota home range size). Furthermore, where there are multiple sources of exposure, the combined potential exposure from these sources should be taken into consideration for the relevant DCRL when assessing protection options. Additional factors may need to be taken into consideration depending upon the exact nature of the exposure situation. For example, for the management of long-lived wastes, there may need to be consideration of how the biosphere may change over time. Knowing the key properties of the radionuclides involved in the exposure situation and how their chemical and physical characteristics may influence the transfer to biota of interest is also important. Furthermore, there may be additional factors such as public opinion, the legal and political situation, the population size affected etc. may all need to be considered.

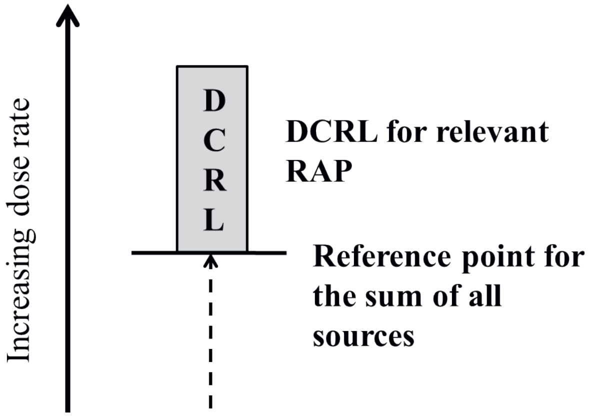


Figure 4: Relationship between Derived Consideration Reference Levels (DCRLs) and ambition to avoid deleterious exposures in planned exposure situations [10].

In practice there should be few, if any, occasions where planned exposure situations are likely to lead to situations where the protection of the environment/non-human biota is potentially compromised and additional protective measures are warranted. The emphasis here instead is usually on demonstrating that the environment can be considered protected.

Furthermore, the exposure pathways for non-human biota and humans in the environment are likely to be similar, e.g. inhalation of (re)suspended contaminated particles or gaseous radionuclides, contamination of external layers such as skin, fur or hair, ingestion of contaminated food/prey/plant material/water, external exposure from contaminated surfaces (e.g. soil) or immersion in a plume of radioactive materials. However, to be able to show in a simplified and consistent manner that both humans and the environment are protected, it should be possible to back-calculate environmental media activity concentrations based on human dose criteria (e.g. the 1 mSv dose limit or a suitable dose constraint for a site or source) and the appropriate reference criteria for the RAPs using the DCRLs as suggested above. Selecting the most restrictive of these environmental criteria, whether from the human or RAP calculations, would then demonstrate protection of both humans and the environment. This approach has been carried out already by the International Atomic Energy Agency (IAEA) for the [11] and the OSPAR Commission [12].

The back-calculated values are termed Environmental Assessment Criteria and their generation is an example of an integrated assessment [12]. It should be noted, however, that it is assumed the source of the human food stuffs (e.g. fish) coexist in the same locations as the non-human biota being used to estimate the environmental doses.

The above approaches are also consistent with the IAEA Safety Standards [6] which set out that the protection of humans and the environment (in terms of non-human biota and resources) for the present and in the future, should be protected in an integrated manner.

3. Application of the DCRLs in Emergency Exposure Situations

In emergency exposure situations, communication of possible radiological effects is key and, while priority needs to be focused on the protection and safety of humans in the event of an emergency, experience has shown that in such situations, questions regarding the state of the environment may also arise. Therefore, being able to say something on the implications of an emergency on the environment more generally could be useful. Figure 5 shows the approach of using severe-effect reference levels that was described in Publication 124 [10]. The concept of a severe-effect reference level is often used in the chemical industry and ICRP defined this as "*approximately equivalent to a band of doses two orders of magnitude above the DCRL band*" [10]. These severe-effect reference levels may be used during the initial phase of the emergency to predict effects on non-human biota. Over time, as the radioactivity levels decline through radioactive decay, particularly of short lived radionuclides, or through management action, it is also possible to predict the changing impact on non-human biota. However, improved and more detailed communication is not the only possible outcome of integrating the environment into the system of radiological protection for emergency exposure situations.

Better integration of the environmental considerations into protective-action decisions may lead to early consideration of the environment in, for example, better planning in the longer term regarding where to place new facilities from the point of view of potential radiological impacts on non-human biota or incorporating radiological considerations in the emergency preparedness planning and in the potential longer-term recovery options that might be applied. This approach should integrate and embed thinking about environmental protection issues as part of the optimisation for protection under all circumstances from the start of planning new facilities and uses of radioactive materials.

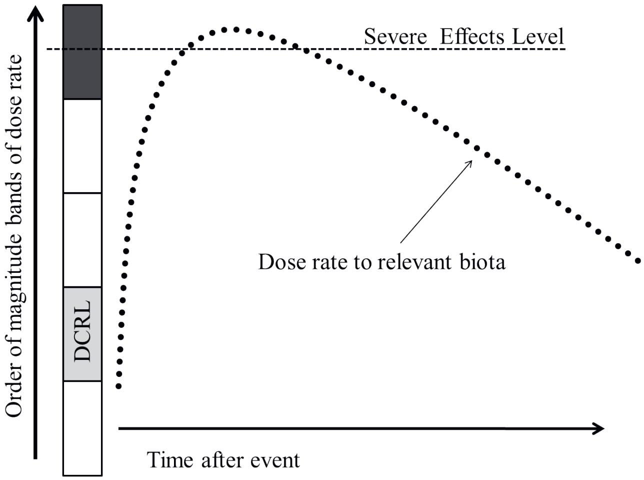


Figure 5: Potential use of severe-effects bands, relative to Derived Consideration Reference Levels, to relate exposure of non-human biota following an accidental or emergency release of radionuclides into the environment [10].

4. Application of the DCRLs in Existing Exposure Situations

For existing exposure situations, ICRP recommends that the aim should be to reduce exposures to levels that are within the DCRL bands for the relevant populations (see Figure 6), with full consideration of the radiological and non-radiological consequences of so doing [10]. If dose rates are within the bands, the ICRP believes that consideration should be given to reduce exposures, assuming the costs and benefits are such that further efforts are warranted. However, there are a range of protective actions for existing exposure situations that will optimise radiological protection. In the past, these options have primarily focused on optimising protection for humans and there are examples where, in doing this, the ethical principle of doing more good than harm has not been adhered to with respect to demonstration of protection of the environment and non-human biota. Therefore, integrating environmental protection into the decision-making process should therefore help to ensure that consideration will be given to the impacts on non-human biota It should be noted that there are several aspects that should be considered for example:

- the radiological assessments (before and after remediation) of the exposure of humans and non-human biota (bearing in mind that the non-human biota may be present at the site for longer periods of time than humans);
- the area being impacted (and therefore the size of the potentially affected populations of non-human biota that may be of interest at the site);
- the presence of non-radiological hazards that might need to be addressed;
- the consequences and impacts of the current situation and after the potential controls are put in place.

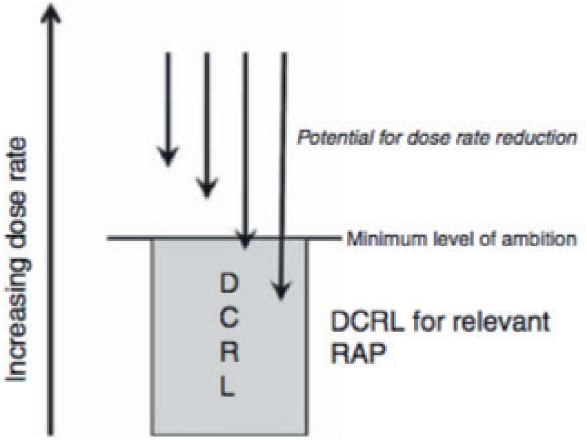


Figure 6: Relationship between Derived Consideration Reference Levels (DCRLs) and ambition to reduce exposures in existing exposure situations [10].

5. Learning lessons from past management practices

While the application of the system of radiological protection has been advanced by ICRP Publication 124, there are still a number of questions that remain such as:

- What should be done if the assessments suggest impacts above the DCRLs but there is no significant impact on humans?
- How should multiple hazards (e.g. radiological, non-radiological and physical in nature) be considered?

- How can the DCRLs be applied effectively within the optimisation of radiological protection?

The last bullet point is important, bearing in mind that the overall aim is to achieve ALARA (as low as reasonably achievable) with consideration of social and economic costs. The key now is to consider how the environment should be included alongside social and economic costs as indicated Publication 111 [13]. TG105 will use different case studies to evaluate what has happened in the past, to address the 'What if' questions to determine if different decisions might have been made had the environment and non-human biota specifically been considered. These evaluations will be undertaken using a systematic review and through discussions with people who are/were involved in the decision-making processes regarding the case study sites at sites such as Andreeva Bay used for waste management; Winterbeek which is a radium contaminated site; Little Forest burial group for radioactive waste; atomic weapons testing sites such as Maralinga and the Marshall Islands; contaminated sites from around Mayak; Chernobyl and Fukushima nuclear incidents etc. Three cases studies are briefly described before considering the lessons learnt so far.

5.3. Case Study 1: waste storage site remediation

Andreeva Bay is a site for the temporary storage (STS) of spent nuclear fuel and radioactive waste. Despite its current use, it is a major nuclear legacy site, which is also being remediated in the northwest of Russia [14]. As part of a regulatory cooperation program between the Federal Medical and Biological Agency of Russia (FMBA) and the Norwegian Radiation Protection Authority (NRPA), a project has been set up to investigate the possible impact of radioactive contamination on representative animals and plants in the STS area. The objective being to determine whether the criteria set out in Shandala et al [14] for the range of proposed remediation options would be sufficient to meet protection objectives for the environment as represented by ICRP DCRLs.

To facilitate the assessment, the dose rates to representative species of animal and plants were determined. The representative species were identified in line with the recommendations made by ICRP [10] and are a set of locally relevant species of fauna and flora including:

- “Motley grass”
- Squat birch (*Betula humilis*)
- Earthworm (*Lumbricidae* sp.)
- Moor frog (*Rana arvaiis*)
- Norwegian lemming (*Lemmus lemmus*)

These are typical of the region, live directly at the industrial site, and are readily a categorized within the RAPs scheme.

Shandala *et al.* determined the doses to humans and showed that, for a range of remediation options of different parts of the contaminated sites, the doses for people varied from 0.1 to 3 mSv y^{-1} [14]. The higher doses were for the workers while the public received doses in the region of 0.1 mSv per year except for the most heavily contaminated area where the dose rate was the same as the public dose limit of 1 mSv y^{-1}. The ERICA assessment tool [15] was used to convert these activity concentrations in soil to wildlife dose rates. These are presented in Table 3 alongside the corresponding DCRLs. In some cases the dose rates corresponding to the dose constraints exceed the DCRLs (highlighted bold). In addition, actual measurements in limited areas of the site also suggest that DCRLs are exceeded locally, although it should also be noted that the contamination is patchy.

It should be noted that the populations of potentially affected wildlife are limited to those living on the STS site. These on-site individuals are likely to be substantially more adversely affected by the building and construction work on-going at the site. If there was an over-riding interest in protecting these individuals of fauna and flora, this impact would be of substantially greater significance. However, it should be noted that the same wildlife species live in extensive areas adjacent to the site that are neither materially affected by contamination nor the industrial works so the impact on the population as a whole is limited. Consequently, the provisional conclusions are that the current protection measures taken at this site and within the existing remediation criteria are sufficient to meet protection objectives for the environment as represented by ICRP DCRLs given the wider population. However, if these species were localised to the STS etc. the situation could be different.

5.4. Case Study 2: consequences of past releases of radioactivity

Research to support the remediation of areas affected by historic releases of radionuclides from the Mayak PA nuclear complex has focused on the status of fish in the Techa River [16]. Within the period from 1949 to 1956 industrial low-level radioactive wastes were released into the Techa River and associated wetland in the Chelyabinsk Oblast, Russia. Over the whole period 76 million m^3 of effluents were discharged with total activity of about 1.1E17 Bq. Fish are most sensitive to the impact of a wide range of adverse environmental factors, including radioactive contamination. Between 2011 – 2013 research into the status of the fish of the Techa River due to long term exposure to radionuclides was conducted. At each sampling point, samples of water, bottom sediments, zooplankton, zoobenthos, algae, and fish (roach, perch, and pike) were collected. Cs-137, Sr-90 and H-3 were determined in all samples and the following parameters measured in each fish caught: weight and size of the body, age, sex, fin colour, sperm motility during spawning, and morphometric parameters. Hematologic, cytogenetic, cytologic investigations of the studied fish specimen were also conducted.

Remediation Option	Site	Representative organisms	Dose rate maxima, mGy d^{-1}	DCRL, mGy d^{-1}
Conversion	STS Industrial Area	Moor frog	67.2	10-100
		Motley grass	**14.6**	1-10
		Lemming	**148.9**	0.1-10
		Earth worm	0.6	10-100
		Birch	**43.9**	1-10
	STS Supervision Area	Moor frog	0.4	1-10
		Motley grass	0.1	1-10
		Lemming	1.0	0,1-1
		Earth worm	0.1	10-100
		Birch	0.3	1-10

Conservation	STS Industrial Area	Moor frog	38.1	10-100
		Motley grass	8.3	1-10
		Lemming	**84.4**	0.1-1
		Earth worm	0.4	10-100
		Birch	**24.9**	1-10
Liquidation	STS Industrial Area	Moor frog	4.3	10-100
		Motley grass	0.9	1-10
		Lemming	**9.6**	0.1-1
		Earth worm	0.1	10-100
		Birch	2.8	1-10
	SA	Moor frog	0.4	10-100
		Motley grass	0.1	1-10
		Lemming	1.0	0.1-1
		Earth worm	0.1	10-100
		Birch	0.3	1-10

Table 3: Assessed Wildlife Dose Rates for the Different Remediation Options compared with the relevant DRCLs

The ERICA Assessment Tool [15] was used to calculate the absorbed dose rate in the fish assuming equilibrium distribution of radionuclides in the organisms and in the surrounding media. The estimated radiation exposure, with a dose rate up to 220 µGy d^{-1} for fish in the spawning period, was correlated with a dose-dependent reduction in the number of cells in the peripheral blood [17]. Such changes were most pronounced in pike and roach. Other biological effects were observed that could be associated with radiation exposure were: decreased sperm cell motility; changes in fin colouration; increases in the frequency of trypanosome invasion, which can indicate a decrease in the immunological reactivity of the fish, and changes in the body shape of perch. The results served as a basis for the development of regulatory measures for radiation protection of natural ecosystems and it should be noted that, for the fish species considered, the dose rates at which effects were seen are below the corresponding DCRLs (1-10 mGy d^{-1}). Consequently, it is necessary to consider the natural and/or confounding factors that may modify the effect of radiation, such as spawning and fish trypanosome invasion in fish.

5.5. Case Study 3: management of legacy radioactive waste

The Little Forest Legacy Site (LFLS) formerly known as the Little Forest Burial Ground, in Australia was originally categorised as a nuclear waste disposal facility. The LFLS contains low level radioactive waste and other waste buried in trenches during the 1960s when Australia was exploring nuclear energy. The site is currently fenced and controlled for access and used for research purposes such as the study of migration of radioactive materials in the environment. Assessments of the potential impacts on people and wildlife have been conducted as recommended by the ICRP and in line with the international Basic Safety Standard requirements for existing exposure situations.

The key findings in these assessments (using monitoring data) were that the exposure to the public was very far below the 1 mSv dose limit. However, there were indications that the wildlife (particularly for amphibians living in a nearby creek where the leachate from the trenches may be going and acacia trees whose roots may grow into the trenches) potentially could lead to exposure issues. For the bulk of the wildlife species the dose rates predicted where below the relevant DCRLs. However for the acacia tree and the larvae of the frog were around the relevant DCRL. In both cases the assessment scenarios are considered to be worst case and the number of individuals potentially impacted were small and when considering the potential impacts on populations in the area are unlikely to be significant.

In this case, it is not possible from the assessments conducted to explore direct comparisons between people and wildlife exposures but here we have an existing exposure situation where the exposure to wildlife, while currently not an issue of concern from the environmental protection point of view, may be a relevant component of strategies for long-term management.

6. Lessons learnt

While the ICRP has produced a number of publications on how environmental protection can be addressed including the derivation of the DCRLs and, in Publication 124 [10], how these DCRLs may be applied to the three potential exposure situations, the advice on remains limited. The general advice that existing and emergency situations need to be examined on a case-by-case basis and that, in both situations, DCRLs can be used as tools to inform decisions with regard to consequence management alternatives. It is critical to note that the DCRLs have been identified as dose rate bands within which, if experienced or expected, one should stop and consider further what best to do in the context of justification and optimisation decisions.

Optimisation and selection of preferred alternatives is largely dependent upon local social and economic factors and to date have focused on the aspects affecting people. DCRLs are an effective tool for determining whether impacts on wildlife should be a factor within such an analysis, e.g. if assessment results indicate dose rates within or above the range of DCRLs as shown in the case studies presented however there are still key issues that need to be considered. For example, a key issue is the ability to define and justify the wildlife population(s) of interest. Without this definition, the relevant environmental concentrations of radionuclides cannot be determined and so no appropriate comparison with DCRLs can be made. This means, by definition, considering whether the individuals in the contaminated area are sufficient to be classed as a viable population and whether there are individuals of the same species that are not impacted by the radioactivity that could maintain a viable population. Additionally, the selection of a population of interest, and how much it is worth protecting, is a value judgement. Such a judgement could be supported by a comprehensive understanding of present and likely future distributions of radionuclides in relevant environmental media and how these may exposure the wildlife of interest. Assessments of what is a viable population for considering the impacts on wildlife, and which addresses temporal and spatial averaging on long time-scales, have been considered for waste disposal facilities [18] and will have application when considering existing exposure situations.

The same sites and areas around them which present existing exposure situations may also be contaminated as a result of planned activities as well as accidents that gave rise, in due course, to existing exposure situations. This has occurred in areas affected by releases from Mayak PA and complicates the application of the advice from ICRP [10] as there are very different aspirations for the DCRLs and their application under planned and existing/emergency exposure situations.

Existing exposure situations typically arise at legacy sites where there are other pollution hazards, or, as in the case of NORM legacies, the uranium simultaneously presents a notable chemical as well as a radiological hazard [19]. Herein, the most recent information available on the chemical toxicity and biokinetics of uranium could be used to propose new standards for limiting intakes of the element to people. The approach adopted by Thorne and Wilson [19] allows coherent standards to be set for ingestion and inhalation of different chemical forms of the element by various age groups of humans. The same approach might also be applied to address assessment of the impacts on wildlife coherently and thus allow the consideration of both chemical and radiological aspects.

For perspective, it might be noted that coherent regulation of multiple or mixed hazards has been recognised as a challenge for a long time. A joint document issued by Nordic regulatory authorities noted over 20 years ago that, "*Threshold levels exist for the detrimental effects of some chemicals, but for others, the only prudent approach is the use of a non-threshold hypothesis, as is also the case with ionising radiation. Universally applicable hazard coefficients for both radioactive and non-radioactive wastes would be very valuable. Further exchange of information between the fields of nuclear and non-radioactive waste management would be desirable to harmonize safety principles and management practices*." Such objectives then as now present significant challenges, such as limited information on the genotoxic properties of various substances to allow such hazard indexes to be defined for each substance. There is also the issue of the impact of multiple stressors as illustrated in work by Aleström [20].

The case studies also highlight a number of aspects that should be considered such as:

- The spatial distribution of the radioactive materials;
- Any temporal issues relating to the radionuclides of potential interest at a given site;
- The presence of chemical hazards sitting alongside radiological hazards;
- The need for comparatively long-term assessments;

- Sometimes it is more likely to be wildlife that is the receptor of interest compared to people;
- The justification of any changes in terms of benefits to both people and wildlife;
- Include in the assessment aspects to explore the consequences and impacts from understanding the current situation and what the potential consequences of controls put into place are.

7. Conclusions

Overall when considering how to effectively manage exposure situations, we need to consider the benefits for, and impacts on, people from a radiological perspective along with any impacts on wildlife present in the area affected. However, some management options (particularly with respect to cost and expediency) may actually lead to significant environmental damage (for example digging up and removing contaminated top soil which may contain a seed bank or by using chemicals to clean up the soil in situation). Wherever possible, including consideration of the aspects of environmental protection in the optimisation and the decision-making process should allow us to "do more good than harm" for both people and wildlife.

Integration of human and ecological risk assessment and management provides consistent results, incorporates the interdependency of human health and environmental and natural resources quality and, finally improves the efficiency and quality of assessments and decision making.

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RADIOLOGICAL SURVEILLANCE OF THE ENVIRONMENT IN BELGIUM

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1. Introduction

The need to assess the radiological state of the Belgian territory and to evaluate the impact of practices on the environment and the population goes back as far as the establishment of the first nuclear activities in the 1950's. However, the scope, scale and organisation of radiological surveillance in Belgium have changed over the years, led by an evolution in the obligations and responsibilities on the matter (see section 2). Currently, the responsibility for radiological surveillance of the Belgian territory and population lies with the Federal Agency for Nuclear Control (FANC).

The main driving forces for change over the years can be found in both a growing insight of radiological impact and a general shift in focus towards environmental protection. Additionally, occasional rapid changes have occurred due to major accidents such as Chernobyl (1986) and Fuskuhima (2011) as well as more localized incidents such as that of Fleurus (2008) which initiated a re-evaluation of the approach.

It has to be emphasized that "Radiological surveillance" encompasses a broader scope than environmental monitoring alone, and can rather be described as the range of activities that aim to evaluate and where necessary limit the impact of all sources of radiation on the environment and the population. This aim can be achieved through actions on several different levels in the surveillance strategy, which will be explored in section 3.

More specifically, surveillance of the environment by FANC is organised along two main systems: a sampling and analysis programme and an online measurement and alert network (TELERAD) which complement each other in the support of the Agency's surveillance strategy. Section 4 will give a short overview of these systems.

Finally, we will look ahead at the possible evolution in obligations, notably those in the protection of the environment itself. Section 5 will explore the implications of the ICRP system for protection of the environment in a Belgian context.

2. The legal foundations of radiological surveillance

The legal obligations which guide the establishment of and approach in radiological surveillance can be found on both the national and international level.

On the national level, the attribution of responsibility in radiological surveillance to FANC is vested in the "FANC-law" of 1994 [1], which regulates the creation of FANC, its competences and its functioning. Article 21 of the law specifies the obligations of the Agency in "radiological surveillance of the Belgian territory in its entirety in routine and emergency situations" which englobe the measurement of radioactivity in the environment and the evaluation of doses to the population as a whole. It also allows for the Agency to make use of public and private organisations to achieve this goal.

The Royal Decree of 20 July 2001 [2] further specifies, under its articles 70 and 71, the scope of radiological surveillance of the environment and the population. It furthermore specifies that scope of surveillance includes both artificial and natural sources of radiation, and that the cost of surveillance must be carried by the Agency.

On the international level, radiological surveillance is addressed on a scientific and regulatory level by the recommendations of the main bodies in radiation protection such as ICRP and IAEA. At the European level, the proposed approach has been translated into several requirements, directives and regulations under the scope of Euratom Articles 35 and 36, such as recommendation 2000/473/Euratom [3], which outlines the minimal requirements for radiological surveillance in member states as well as the need for a representative and independent measurement programme, the results of which have to be reported to the Commission.

Additional obligations come from the 1992 Oslo-Paris convention, OSPAR [4] in short, which aims to protect the marine environment of the North-East Atlantic. One notable obligation in this framework is the sampling of water and sediments offshore within the 12-mile coastal zone.

Finally, bilateral agreements between FANC and neighbouring countries may add goals to the radiological surveillance programme. One such example are the “Franco-Belge agreements” of 1984 on the surveillance of the Chooz nuclear power plant, located a few kilometres south of the border between France and Belgium.

3. Organisation of radiological surveillance in Belgium

In general, radiological surveillance by FANC is organized along several lines, each of which covers a part its obligations :

- *Source monitoring*, which aims to limit and evaluate sources of radiation from nuclear, industrial and medical practices. Surveillance of these practices is obtained on three levels: the authorization, inspections and environmental monitoring;

- Surveillance of *specific types of exposure situations* such as NORM, radon, drinking water, orphan sources, etc. Each of these requires a distinct approach due to their specific subject and differences in stakeholders;

- *General surveillance* of the environment, which aims to evaluate the general radiological state of the environment;

- *Alert monitoring*, which allows, through continuous measurement of radioactivity in air and water, for verification of authorized releases and immediate response to unforeseen radiological events on the Belgian territory.

FANC has developed surveillance programmes to gather the necessary data to support evaluation and decision making in each of these lines, most notably:

- An *environmental monitoring network* based on sampling and analysis.
- *A real-time surveillance and alert network* (TELERAD)

These two systems, which form the core of the radiological surveillance of the environment, will be further described under section 4.

Other sources of data, such as a database of portal monitor incidents and a database for dosimetry data of workers, complement these programmes.

4. Radiological surveillance of the environment

As mentioned above, radiological surveillance of the environment in Belgium is organized in two surveillance networks, both of which are coordinated by the Surveillance of the Territory unit at FANC, which is part of the Environment and Health department.

The *environmental monitoring network*, is an annual programme of sampling and analysis of radioactivity in all compartments of the environment, which combines the goals of environmental surveillance around nuclear installations and the general obligations in environmental monitoring. Additionally, it integrates the necessary sampling for thematic surveillance, e.g. around NORM or legacy sites and samples taken for independent verification.

This duality between reinforced monitoring around nuclear sites and the general aim to monitor radioactivity in the environment largely dictates the optimization of the measurement point distribution in Belgium for each vector. Surface water, soil, sediments, biota and air particles are mainly sampled around the nuclear sites in receiving environmental compartments such as rivers. For others, such as the food chain and drinking water, a more evenly distributed sampling is performed in the Belgian territory.

It is beyond the scope of this paper to give a complete overview of the programme, but the most recent results can be found in the annual report on radiological surveillance of the environment [5]. The sampling and analysis programme is renewed every five years and attributed to two laboratories on the basis of a public call. In 2017, 4350 samples were taken on which approximately 25000 individual analyses were performed.

A *real-time surveillance and alert network*, TELERAD, continuously measures radioactivity in the air and rivers, and generates alerts in case of a significant increase in radioactivity.

Gamma dose rate measurements in air are performed by more than 250 stations, scattered on the Belgian territory according to the same dual goal as the environmental sampling: reinforced surveillance around nuclear sites, and a more scattered grid between sites. A ring of stations on and around each nuclear site is capable of performing gamma spectrometry, allowing for a nuclide-specific detection of atmospheric releases. Each station has a 10 minute measurement cycle.

Measurements in water are performed by 8 measurement stations which can measure global dose rate and the gamma spectrum, either directly or by continuous sampling of water. These stations are located in the main rivers which receive discharges from nuclear sites, such as the Molse Nete, the Scheldt and the Meuse rivers. Additionally, measurement stations have been placed directly in the discharge canals of the Doel and Tihange NPPs.

Alerts from the network are automatically generated and sent to a pool of FANC experts, which have to evaluate the cause of the alert and take the necessary measures. The results of all measurement stations can be consulted on the TELERAD website [6], where hourly values are reported and, if a significant increase in radioactivity levels has been detected, commented by a FANC expert to explain the cause of the alert.

5. The ICRP system for protection of the environment in a Belgian context

The ICRP system for protection of the environment, as outlined by its publications 103,108 and 124, requires a specific set of data on the radiological state of the environment to allow for assessment. The main question in a Belgian context is therefore whether the data we have allow for such a radioecological assessment.

In general, this is not the case. The current environmental monitoring programme has not optimized for such a goal, neither in its choice of sampling points for the environmental compartments nor in its choice of sampled biota. The choice of the latter is currently guided by their use as bioindicators and their availability for sampling. Optimization of the sampling programme for an assessment of impact to non-human biota would require a more strategic choice of environmental vectors and species as well as nuclide libraries.

For some specific Belgian sites however, such an assessment has already been performed, either by the ICRP methodology or by the comparable ERICA integrated approach. Most notably, an environmental impact assessment for the nuclear power plants has been performed in the past, based upon the release limits of the authorization, which did not identify any risk to non-human biota [7]. A similar assessment has been made as part of the impact study of the future low-level waste facility in Dessel [8], also based on expected releases. A notable study for an existing exposure site is that for the radium contamination of the Winterbeek and Grote Laak rivers by phosphate industry [9]. For this case-study, a NORM site, it could be shown that screening levels for some species are exceeded and a more detailed study is therefore justified.

At this moment, there is no formal obligation to integrate the ICRP approach for non-human biota into national legislation on radiation protection. However, FANC is actively involved in discussions on the subject at the international level and keeps track of insights and evolutions on the scientific as well as the regulatory level. Furthermore, a large volume of environmental data are already available at FANC for a number of sites which could be exploited and used to perform a screening assessment. In the short term, such a screening of Belgian sites would be beneficial for further optimisation of future priorities.

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METHODOLOGY FOR THE RADIOLOGICAL ASSESSMENT OF NOBLE GASES IN NON-HUMAN BIOTA

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Abstract

A practical methodology is presented for the assessment of radon (^{222}Rn) and thoron (^{220}Rn) radiation dose rates to non-human biota, including animals and plants. This methodology is based on an allometric approach that scales allometrically the breathing rate and dimensions of the respiratory system as a function of whole body mass, and can calculate the dose rate to sensitive tissues and the whole body of terrestrial wildlife. We explain the derivation of the dose coefficients with all the underlying assumptions and we discuss the degree of conservatism associated with the method. A more complex, physiologically based model was developed for the plants, and we show here how it was used to demonstrate that the more simplified allometric methodology is reasonably accurate and conservative in terms of predicting internal and external dose rates to plant leaves.

From the method’s application to a test case it is concluded that radon levels in some natural environments (such as mammals burrowing in soil) exceed background levels and no-effects dose benchmarks for non-human biota. This suggests that advised benchmark dose rates such as ICRP derived consideration reference levels for wildlife need to be better put into context with background dose rates, including exposure to radon, depending on the purpose of the benchmark and the assessment level. It is also clear that the contributions that radon and thoron make to radiological impact in wildlife need to be evaluated in line with emerging radiation effects data.

Introduction

In recent years, a general consensus has emerged that radiation protection must extend not only to humans but also to the environment itself. This has led to a drive towards integration of human and wildlife radiological assessments [1]. Despite this, exposure to radon isotopes and their radioactive progeny has been disregarded as a general rule, probably due to the inherent complexity of radon/thoron dosimetry. However, radon and thoron are relevant in an impact assessment to wildlife given the NORM releases in the biosphere [2]. Dose rates to wildlife in high background soil, such as burrowing mammals, can exceed the lower end of the ICRP derived consideration reference levels (DCRLs), the set of dose rate bands used in wildlife protection for each of the reference animals and plants defined by ICRP [3] within which there is likely to be some chance of the occurrence of deleterious effects. For radon/thoron daughters, the most significant contribution to the received exposure is the internal dose by the daughter products. Radon gas itself gives a very small contribution by comparison.

Radon (^{222}Rn) belongs to the ^{238}U decay chain, and has a half-life of 3.8 d. Its four first products are very short-lived. Thoron (^{220}Rn) belongs to the ^{232}Th chain, and has a half-life of 56 s. Its decay products are also very short-lived except for the longer-living ^{212}Pb (10.6 h). Since thoron has a shorter half-life (56 s), and the progeny emits less alpha energy, the dose from thoron and its progeny is lower than that of radon. For this reason there are fewer studies related to the measurements of thoron in the outdoor environment in comparison with radon and its progeny [4]. However, thoron progeny, like that of radon, can also be hazardous and therefore it should be included in wildlife dose rate estimations.

Due to its complexity, radon and thoron (Rn/Tn) dosimetry for biota poses a scientific challenge. Only a few rodent studies model explicitly lung deposition [5-8]. A simplified method for radon respiration in burrowing mammals was developed [9]. Following this, we developed a more advanced method which covers a wider range of animals and plants. More recently, as part of ICRP Committee 5 on radiological protection of the environment [10], task groups were set-up to provide more realistic dosimetry for non-human species including dose coefficients for non-human biota, and one of the additional activities performed was to expand the above method into a more advanced allometric approach for radon and thoron in mammals [2]. Additional modelling of the transfer of radon and its daughters to plant surfaces was carried out to verify the allometric approach [11].

The above methodologies have been applied in a practical way, firstly in a practical assessment tool that was used to assess ^{222}Rn authorisation limits under the UK Radioactive Substances Act (RSA) 1993 [12, 13] and, following this, to estimate the radon dose rates to burrowing mammals in the field [14].

The present paper summarises the above methodological developments and the implications of some of the radon dose rates observed.

Description of the approach

To ensure that the method is applicable to various species of biota, we provided a way to scale the dimensions of the lung and tracheobronchial tree, as well as the breathing rate. Allometry gives a means to provide simple relationships for these parameters as a function of the whole-body mass. This is because many biological parameters relating to organism structure relate in turn to metabolism, which scales with mass according to the Brody-Kleiber law [15, 16]:

$$Y = A \times M^{b},\ b = 0.75$$

When calibrated for large mammals, this simple expression tends to overestimate somewhat the breathing rate value for smaller animals (and vice versa). We addressed this by using generalised allometric equations, such as the following equation for the breathing rate of terrestrial mammals [2]:

$$B(M) = a^{*} M^{b^{*}} = e^{\beta_0} M^{1+\beta_1+\beta_2 \ln M}$$

Where *B* is the ventilation rate (m^3 h^{-1}) and *M* is the mass of the organism (kg). From the compilation of Bide et al. [17], the following values were adopted: $\beta_0 = -3.562 \pm 0.050$, $\beta_1 = -0.226 \pm 0.019$ and $\beta_2 = (7.26 \pm 4.45) \times 10^{-3}$. We further neglected the log-quadratic term, leading to:

$$B(M) = e^{\beta_0} M^{1+\beta_1}$$

Which corresponds to the ‘Kleiber law’ with an exponent of 0.77 instead of 0.75.

Breathing induces a constant flow of radon atoms into the lung while undergoing continuous decay. We assumed that the influx and the decay are in balance due to the short half-life of the decay products. We also assumed that the gas is exhaled but the decay products are trapped inside the lung. In other words, full absorption of progeny is assumed within the respiratory organs/systems, and no further redistribution of the deposited activity due to biokinetic processes, exhalation or excretion from the organism, is accounted for. In practice, the inhaled aerosol is log-normally distributed, with fractional deposition in the different regions of the respiratory tract varying between 20% and 99% depending on size. We are, therefore, making a conservative assumption in respect to maximising the dose rate, obviating the need for a more detailed respiratory tract clearance model. We avoid this because it would make the method unduly complex and impractical, considering its stated conservative screening purpose.

With the above assumptions, the dose coefficient DC can be calculated as:

$$DC = B \frac{E}{M_T} g$$

Where B is the respiration (breathing) rate ($m^3\ h^{-1}$), E is the total energy absorbed in the target tissues due to radiation emitted by the radon progeny until decay to Pb isotopes ($\mu J\ Bq^{-1}$) as calculated using data from ICRP *Publication* 107 [18], M_T is the mass of the target tissue/organ (kg) and g is a geometrical factor which takes into account (in)homogeneity of activity deposition in airways/respiratory organs (dimensionless).

It was assumed that the target geometry for the delivery of the dose was a tubular section of density ρ_T equal to the density of water, surface area S_T, radius R_{aw} and thickness h_T, the latter being conservatively set at 50 µm to ensure full deposition of α-particle energy in tissue, given their short range in water:

$$M_T = \rho_T \, S_T \, R_{aw} \left(\frac{h_T}{R_{aw}} + \frac{h_T^2}{2R_{aw}^2} \right) \approx \rho_T \, S_T \, h_T$$

With the above information, we calculated dose coefficients in the form of simple power functions for DC's in µGy h^{-1} per Bq m^{-3} for the following target tissues: bronchial epithelium (BE), full tracheobronchial epithelium (TB), lung (L) and whole body (WB). In practice, whole body dose rates are calculated except for the most specialised assessments. This is due to the fact that dose effects data are only available at the level of whole body [19, 20], there not being as of yet effects data for the different lung tissues in wildlife.

The above method is designed for mammals only, because they have the same blueprint mammalian lung system, but the approach is potentially applicable to birds, reptiles and even insects because their breathing system is progressively different from mammals. Our method would likely provide a conservative estimation for birds, reptiles and insects, although this is a conjecture and is still to be verified [13].

For plants, a simple conservative approximation is used, whereby the surface area of the plant is assumed to be exchanging gases with the atmosphere. The allometric formula for respiration rate in plants is calculated based on net CO_2 efflux data. Due to the important role of carbon dioxide in the metabolism of plants, the allometric approximation for the plant respiration rate may be conservative. This is because the plant is likely to be less selective for inert noble gasses like radon and thoron. On the basis of the following allometric respiration formula for plants using CO_2 respiration:

$$BR_{PLANT}(m^3 s^{-1}) = 1.95 \times 10^{-4} M(kg)^{1.02} = a_{PL} M^{b_{PL}}$$

Two simple power functions for DC's in µGy h^{-1} per Bq m^{-3} were obtained for plant tissue and whole plant. They depend on the plant radius (the plant is assumed to be cylindrical) and h_T, the depth of sensitive tissue, again assumed to be 50 µm.

Results

Calculated radon and thoron internal exposure DC's for ICRP Reference Animals and Plants (RAP) are given in Table 1 below. The calculation of internal absorbed dose rate can be carried out simply by multiplying the listed DC's by the parent radon activity concentration in ambient air. A linear correction factor can be applied if an equilibrium factor different from unity is required. Full details on how to make a scale conversion from the mass of the lung epithelium (M_{BE}), bronchial tree (M_{TB}) and whole body are given elsewhere [2, 13].

The DC's for the ICRP RAPs in the terrestrial environment exposed to external sources of radon and thoron isotopes and their progenies in ambient air are shown in Table 2. The calculation of external absorbed dose rate is carried out by assuming that the organism is exposed to radiation arising from (a) radon present in the air-filled soil pores (e.g. in burrows) and (b) direct immersion in the atmosphere with radon and its progeny. Both components of the external dose rate can be represented by the following equations:

$$D_S = DC_{ext}\, C_{Rn}\, CF\, \rho_{air} \left(f_S + 0.5 f_{SS} + r_f f_A \right)$$
$$D_I = DC_{ext}\, C_{Rn} \left(f_A + 0.5 f_{SS} \right)$$

where D_S and D_I (µGy h^{-1}) represent the dose rates from radon in the air-filled soil pores and direct immersion in the atmosphere, respectively; C_{Rn} (Bq m^{-3}) is the concentration of ^{222}Rn in air, CF (m^3 kg^{-1}) is the concentration factor used for converting concentration in air in Bq m^{-3} to soil in Bq kg^{-1} fresh mass (arising from radon present in air-filled soil pores), DC_{ext} (µGy h^{-1} Bq^{-1} m^3) is the dose coefficient for external exposure, ρ_{air} is the density of air and f_S, f_{SS} and f_A (dimensionless) represent the occupancy factors for three exposure situations: below ground in soil, on the soil surface and immersion in air above the ground [2].

The external exposure DC's of Table 2 are much smaller (between one and six orders of magnitude) than their internal exposure counterparts. The data in this table comes from two independent methods. The first method [13] under assumptions of a uniform isotropic model is based on Monte-Carlo-integrated point kernels of various radiation in an infinite medium. The second method [21] uses differential air kerma above infinite terrain due to radioactive sources in ambient air, as calculated by a Monte Carlo method. The first method has been compared with the external DC for in-soil exposure to radon and progeny using a DC calculation facility [22] largely compatible to that available in the ERICA assessment tool [23, 24]. The comparison was satisfactory, with relative differences ranging from 3 to 10% in animals and 3 to 25% in plants.

For animals, our model gives similar predictions for total dose rates to whole body than the more simplified approach derived by MacDonald and Laverock [9] with differences ranging from 30 % for the smallest organism (mole) to 1% for the largest (badger). We believe these differences relate to differences in the lung scaling method, which we believe to be more accurate in our model because it uses the generalised allometric scaling approach described above.

Comparisons with previously-published data for lung deposition of radon products in rodents [5, 6] are difficult because these use a full model of the tracheobronchial tree predicting that (a) a significant fraction of the radon daughters is removed by the nasal passages and (b) lung clearance processes transport and redistribute radon daughters from the alveolar region to the bronchial part of the airways, with associated decay during transit. None of these processes are considered in our allometric method. However, we have estimated that dose rates calculated by a full respiratory model would be lower by a factor of up to 10 difference from the present approach. For example, in two separate studies of lung cancer incidence in rats following exposure to radon progeny [5, 6], DC's 5.6 and 7.4 times lower than calculated by the present allometric method were obtained. Other authors [7] estimated an absorbed dose rate to the whole lung for an integrated unit exposure in mice, again lower than our calculated DC for rat, reinforcing our belief that the present model is adequately conservative.

Given that the assumptions made for plants are simple and there was no prior study with which to effect a comparison, we developed a more advanced model in order to calculate if our dose coefficients for vegetation are sufficiently realistic. This was a physiologically based plant model where the exchange of gasses between plant and atmosphere is modelled in more detail. The model was developed specifically for radon.

The resulting compartment model represents the radon aerosol, with compartments for the free, unattached and attached fractions of ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po in air. Plant uptake is represented as surface interception of unattached and attached daughters, diffusion of radon through stomata and permeation of radon through plant epidermis. Plant turnover was represented as translocation of deposited activity from plant surface to plant interior. A schematic of the model is given in Figure 1.

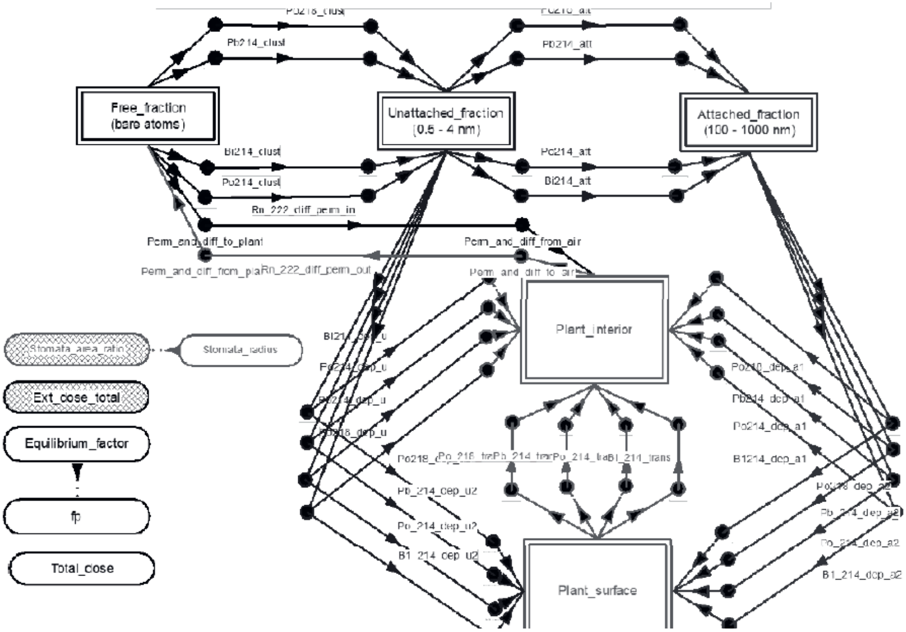

Figure 1: Schematic of advanced radon model for plants. Each sub-model contains the decay chain of radon: $^{222}Rn \Rightarrow {}^{218}Po \Rightarrow {}^{214}Pb \Rightarrow {}^{214}Bi \Rightarrow {}^{214}Po$. Exchange rates link individual compartments across sub-models, with rate constants linked to the parameter set

The model considers the following processes: (a) ^{222}Rn diffusion via stomata and permeation via epidermis (free fraction to plant interior sub-models); (b) ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po interception through stomata (unattached and attached fractions to plant interior sub-models); (c) ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po aerosol deposition (unattached and attached fractions to plant surface sub-models) and (d) translocation of deposited ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po (plant surface to plant interior). The endpoint of the model is the derivation of internal, surface and external exposure DC's as a function of plant surface area and steady-state concentration at ground level.

Full details of the model design and DC's calculated by this model are given elsewhere [11]. The main conclusions of this modelling exercise are as follows. Surface-deposited activity is the most significant contributor to dose, the dominant component being the α-emitting and short-lived ^{214}Po, followed by the α-emitting but longer-lived ^{218}Po (one order of magnitude below). The α-emitting nuclides are the predominant contributors to dose because they have the highest absorbed fractions. Next in importance is the dose rate from external exposure to airborne radionuclides. Here, the non α-emitting radionuclides logically predominate due to their longer range in matter, starting with ^{214}Bi, with the remaining radionuclides being three orders of magnitude or more below.

The sum of internal and surface dose rates for the advanced plant model are consistent with the internal dose rates for the simpler allometric approach. External dose rates for the current model are a factor of two below those for the allometric approach. This is not surprising, given that the allometric model adopted an equilibrium factor of one, whereas the advanced model uses 0.5. Total dose rates given by both methods are wholly comparable. It is concluded that the simpler model's calculations for plants are reasonable, despite the many assumptions made.

Following design and the above validation of the method, an application was made to a real situation involving exposure of burrowing mammals to radon in burrows at an area of 'Rn rich soils' in the United Kingdom [14]. Dose rates were calculated from measured field soil gas concentration at 7 woodland, scrub and pasture sites selected to have a range in potential Rn soil gas concentrations, using the allometric methodology described previously, assuming an equilibrium factor $F = 0.8$ and an α-radiation weighting factor of 10. Artificial burrows were made and passive detectors were installed within them to measure the soil gas ^{222}Rn activity concentration in the sites across the gradient of expected ^{222}Rn concentrations.

Dose rates from ^{222}Rn to burrowing mammals were found likely to be at least ten times higher than previously considered natural exposure sources (^{40}K, Th/U series). In many areas, they considerably exceed the ERICA predicted no-effect dose rate benchmark of 10 µGy h^{-1} [23]. This leads us to reflect on the following point. Absorbed dose rates to burrowing mammals due to exposure to ^{222}Rn are likely to be an order of magnitude higher than those suggested in previous evaluations of natural background exposure rates that had omitted this radionuclide. The resulting dose rates in some areas are considerably in excess of incremental no-effects benchmark dose rates that have been suggested for use in screening levels. Consequently, we call for an examination of the consequences of radon exposure to wildlife and subsequent comparisons with exposure to background (radon) levels, and an analysis of what does the benchmark value mean in this context.

Table 1: Parameters for calculation and values of aggregated unweighted DC's for internal exposure of animals due to progeny of radon isotopes ^{220,222}Rn. Notation for animals: bronchial epithelium (B), tracheobronchial tree (TB), full lung (L) and whole body (WB). Notation for plants: sensitive tissue (ST) and whole body (WB).

Parameter	**Amphibian (ICRP Frog)[a]**	**Reptile (ERICA snake)[a]**	**Mammal smll. (ICRP rat)**	**Mammal big (ICRP deer)**	**Bird (ICRP duck)[a]**	**Lichen & bryophytes (ICRP bryophyte)**	**Grasses and herbs (ICRP wild grass)**	**Trees (ICRP pine tree)**
M (kg)	0.0314	0.744	0.314	245	1.26	1.1×10^{-4}	2.6×10^{-3}	471
a (m)	0.08	1.2	0.2	1.3	0.3	0.04	0.05	10
b (m)	0.03	0.035	0.06	0.6	0.1	2.3×10^{-3}	0.01	0.3
c (m)	0.025	0.035	0.05	0.6	0.08	2.3×10^{-3}	0.01	0.3
B (m^3 h^{-1})	2.1×10^{-3}	0.023	0.012	2.5	0.034	6.5×10^{-5}	1.6×10^{-3}	360
DC's per air concentration of ^{222}Rn (µGy h^{-1} Bq^{-1} m^3)								

DC_B	1.4	1.8	1.7	4.2	1.9	N/A	N/A	N/A
DC_{TB}	0.15	0.20	0.18	0.46	0.21	N/A	N/A	N/A
DC_L	0.032	0.014	0.017	4.1×10^{-3}	0.012	N/A	N/A	N/A
DC_{SS}	N/A	N/A	N/A	N/A	N/A	0.031	0.14	5.5
DC_{WB}	3.8×10^{-4}	1.7×10^{-4}	2.1×10^{-4}	5.8×10^{-5}	1.5×10^{-4}	3.3×10^{-3}	3.5×10^{-3}	4.5×10^{-3}
DC's per air concentration of ^{220}Rn (μGy h^{-1} Bq^{-1} m^3)								
DC_B	22	28	26	65	30	N/A	N/A	N/A
DC_{TB}	2.4	3.0	2.8	7.0	3.2	N/A	N/A	N/A
DC_L	0.49	0.21	0.26	0.062	0.18	N/A	N/A	N/A
DC_{SS}	N/A	N/A	N/A	N/A	N/A	0.48	2.2	85
DC_{WB}	5.9×10^{-3}	2.6×10^{-3}	3.2×10^{-3}	8.9×10^{-4}	2.4×10^{-3}	0.051	0.054	0.069
[a] DC for non-mammals are shown for illustrative purposes only								

Table 2: Comparison of the DC for animals and plants externally exposed to radon and thoron (^{220,222}Rn) and their progeny in ambient air

Organism	DC (μGy h^{-1} Bq^{-1} m^3)			
	in infinite air [a]	in air [b] (h=500 m)	in air [b] (h = 10 m)	on the ground [b]
Radon (^{222}Rn) and progeny				
Amphibian (ICRP frog)	7.8×10^{-4}	7.5×10^{-4}	4.4×10^{-4}	4.1×10^{-4}
Reptile (FASSET snake)	7.6×10^{-4}	7.5×10^{-4}	4.4×10^{-4}	4.1×10^{-4}
Mammal (ICRP rat)	7.3×10^{-4}	7.6×10^{-4}	4.5×10^{-4}	4.1×10^{-4}
Mammal (ICRP deer)	3.8×10^{-4}	5.1×10^{-4}	3.0×10^{-4}	2.8×10^{-4}
Bird (ICRP duck)	6.9×10^{-4}	7.5×10^{-4}	4.4×10^{-4}	4.1×10^{-4}
Lichen and bryophytes (ICRP bryophytes)	9.9×10^{-4}	6.0×10^{-4}	3.5×10^{-4}	3.3×10^{-4}
Grasses and herbs (ICRP wild grass)	8.5×10^{-4}	7.2×10^{-4}	4.2×10^{-4}	3.9×10^{-4}
Tree (ICRP pine tree)	5.1×10^{-4}	4.5×10^{-4}	2.7×10^{-4}	2.5×10^{-4}
Thoron (^{220}Rn) and progeny				
Amphibian (ICRP frog)	N/A	6.7×10^{-4}	4.0×10^{-4}	3.8×10^{-4}
Reptile (FASSET snake)	N/A	6.9×10^{-4}	4.1×10^{-4}	3.9×10^{-4}
Mammal (ICRP rat)	N/A	6.9×10^{-4}	4.2×10^{-4}	3.9×10^{-4}
Mammal (ICRP deer)	N/A	4.9×10^{-4}	3.0×10^{-4}	2.8×10^{-4}
Bird (ICRP duck)	N/A	6.9×10^{-4}	4.1×10^{-4}	3.9×10^{-4}

Lichen and bryophytes (ICRP bryophytes)	N/A	4.5×10^{-4}	2.7×10^{-4}	2.5×10^{-4}
Grasses and herbs (ICRP wild grass)	N/A	6.0×10^{-4}	3.6×10^{-4}	3.5×10^{-4}
Tree (ICRP pine tree)	N/A	4.4×10^{-4}	2.7×10^{-4}	2.5×10^{-4}

[a] Uniform isotropic model method, using absorbed fractions based on Monte Carlo integration of photon and electron point kernels [13]

[b] Absorbed dose rates in tissue-equivalent spheres exposed to photon-only sources in air [21]

Summary and conclusions

A method to calculate radiation dose rates from radon and thoron progenies to ICRP reference animals and plants is now available. This method is relatively simplified in terms of assuming simple geometries, uniform distribution of radionuclides in the biota and the fact that absorbed dose rates are averaged to the whole organism. The most important assumption is that the alpha-emitting progeny of radon and thoron is absorbed 100% in the breathing organ, obviating the need for a more complex model of the respiratory tract whilst maintaining an element of conservatism in the assessment methodology.

A more complex, physiologically based model was developed for the plants, and used to demonstrate that the more simplified allometric methodology described here is reasonably accurate and conservative in terms of predicting internal and external dose rates to plant leaves. Differences with respect to the allometric model were justified as being due to combination of surface and internal dose rate and the equilibrium factor of one conservatively assumed for the radon aerosol in the allometric method.

From the allometric method's application to a test case, it is concluded that radon levels in burrows can exceed no-effects benchmarks for non-human biota. This suggests that advised benchmark dose rates such as ICRP derived consideration reference levels (DCRLs) for wildlife [3] need to be better put into context with background dose rates, including exposure to ^{222}Rn. The context should depend on the purpose of the benchmark and the assessment level. It is also clear that the contribution of ^{220,222}Rn to wildlife exposure needs to be evaluated in terms of the (as yet unavailable) effects data.

This study opens several challenges amongst which we highlight the need to (a) integrate Ar, Kr, Rn assessment into a single tool (or incorporate into the ERICA approach), (b) perform additional investigations of allometric radon/thoron dosimetry for insects, birds and reptiles, (c) seeking evidence for dose rates that would cause stochastic effects in the lung of animals using more detailed lung modelling (if appropriate) and (d) the aforesaid need to review of benchmark values in context of background and radon levels in the natural environment.

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