Adopted levels and derived limits for Ra-226 and the decision making processes concerning TENORM releases

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Abstract. A fraction of a primary dose limit can be, in general, agreed upon as a dose related level to be adopted in decision-making processes. In the case of TENORM releases, fractions of primary dose levels for ^{226}Ra, ^{228}Ra, and ^{210}Po may be of particular importance to establish adopted levels and derived limits to guide decision making processes. Thus, for example, a registration level for ^{226}Ra could be adopted at the highest portion of the natural background variation. Above such level, intervention and remedial action levels could also be adopted. All those levels would be fractions of the primary level, but translated in terms of derived limits expressed in practical units. Derived limits would then be calculated by using environmental models. In such approach "critical groups" would have to be carefully defined and identified. In addition, the size of a critical group would be chosen to be used in environmental modeling. Site specific environmental models and parameters are desirable, though unavailable, or very difficult to obtain, in most cases. Thus, mathematical models and parameters of more generic nature are often used. A sensitive parametric analysis can make a ranking of the parameters used in a model, allowing one to choose how important each parameter will be for the model output. The paper will point out that when using the adopted levels and derived limits, as suggested above, the uncertainties and importance of the parameters entering an environmental model can make the difference for decision makers to take the right or wrong decision, as far as radiological protection is concerned.

1. INTRODUCTION

The International Commission on Radiological Protection (ICRP) was created in 1928 by independent scientists to gather the most updated scientific information at any given time in order to publish sets of recommendations concerning radiation protection. Such sets of recommendations end up being followed, to a large extent, by national and international bodies whose objectives and responsibilities were to protect workers and the general public from potential deleterious effects of ionizing radiation. As time passed, the ICRP underwent several transformations in both, structure and composition. After the World War II, the ICRP received worldwide recognition as an important international independent organization, much needed as the world was entering into the nuclear age. As a consequence, the ICRP published a large number of technical documents that became respected guidelines for radiation protection throughout the world. In the United States of America, the field of radiation protection developed somewhat differently because of the experience accumulated in the Manhattan Project [1–2]. However, many American investigators in radiation protection have been giving their contribution to ICRP development since its inception.

The National Committee on Radiological Protection (NCRP) was formed in the United States with the objective of developing recommendations on radiation protection. The NCRP succeeded in 1946 the National Committee on Radiation Protection and Measurements, which had been created in 1929 as the Advisory Committee on X ray and Radium Protection. The NCRP is na advisory independent organization without authority to establish or enforce any requirements for radiation protection. However, the NCRP recommendations are highly influential in the development and guidances for radiation protection in the United States, and even in other countries. As far as NORM and TENORM are concerned, the NCRP has published a number of reports [3–9].

Recently the National Academy of Sciences – National Research Council (NAS-NRC) of the United States published an authoritative report which examined the guidelines for exposures to TENORM [10]. The relationships among risk, dose, exposure, and concentration of radionuclides in environmental media were discussed in this NAS-NRC report. Figure 1 illustrates such relationships [10]. A concept underline in Figure 1 is taht a measure of risk due to exposure to radiation may be cancer mortality, or in some cases cancer incidence (morbidity), however, in many environmental-radiation assessments the end point of the calculations is dose rather than cancer risk. When such is the case an assessment of risk corresponding to given concentrations of radionuclides in the environment can be used, or vice versa.

This paper deals with adopted levels and derived limits, expressed in practical units, as surrogates for risks and doses used in the standards used for radiation protection.

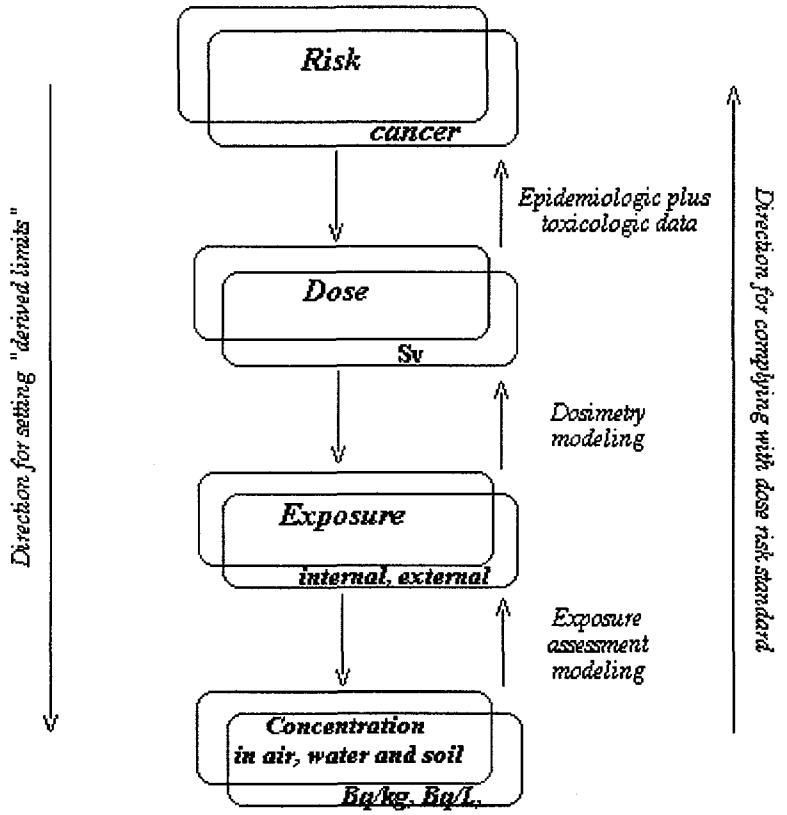

Figure 1. Relationships among risk, dose, exposure, and concentration of radionuclides in environmental media. Adapted from ref. [10].

2. RISK ASSESSMENT

The subject of *risk assessment* has been part of an intense debate following the publication, in 1977, of the recommendations made by the International Commission on Radiological Protection (ICRP) in its Publication 26 [11].

Here it is worth mentioning that many investigators in the field of radiation protection, as well as a large number of officials from national authorities throughout the world failed to perceive promptly that the intense debate on *risk assessment* that followed the set of recommendations published by the ICRP in 1977 was in reality a consequence of an evolution of concepts. At that time the ICRP recognized that, for purposes of regulation and monitoring,

the quantity called radiation dose was difficult to determine directly; accordingly, it suggested simplified models establishing interrelationships for radiation doses, environmental quantities and parameters, and planned releases of radionuclides into the environment [12]. The ICRP recommended also derived and secondary limits, explained in detail in ICRP Publication 30 Part 1 [13]. The metabolic data and models used in the ICRP Publication 30 were essentially those of an adult person with anatomical and physiological characteristics of the Reference Man [14].

The system of *risk assessment* and dose limitation devised by the ICRP Publication 26 is to be used within the framework of *risks* versus benefit and cost-effectiveness. This is essentially a system of dose reductions. The key phrase was already written in paragraph 52 of ICRP Publication 9 [15]: "*As any exposure may involve some degree of risk, the Commission recommends that any unnecessary exposure be avoided, and that all dose be kept as low as is readily achievable, economic and social considerations being taken into account.*"

Not withstanding, the concepts associated with *risk* had already been used for many years in the previous ICRP recommendations. As early as 1959, the ICRP Publication 2 introduced a dose limitation system based on a fraction of the maximum permissible concentration (MPC); this system contrasted the concept of acceptable *risk* to the individual and society with the benefits which might be derived from activities involving exposure to radiation [16]. ICRP Publication 9 explicated that any exposure to radiation[1] might carry *risks* of somatic and genetic effects [15]. Paragraph 34 of ICRP Publication 9 explains that the permissible radiation dose must limit *risk* to an acceptable level, and suggests that such a dose might also be called an **acceptable dose** [15]. In addition, Paragraph 74 of Publication 9 states that at very low levels of *risk*, such as those associated with the dose limits for members of the public, only minor consequences to the health of those exposed (or their progeny) may occur if the dose limits are exceeded [15]. The concept of maximum permissible dose (MPD) was introduced to quantify a degree of risk associated with a limit of radiation dose at which the assumed risk could be considered acceptable to the individual and to society in relation to the benefit derived from activities involving exposure to radiation. These earlier concepts associated with *risk* were somewhat related with the United Nations Scientific Committee on the Effects of the Atomic Radiation (UNSCEAR) Reports [17–18].

The Publication 8 of the ICRP had already moved closer to UNSCEAR position by considering useful to estimate *risks* for radiation protection purposes [19]. Three types of *risks* were considered in the ICRP Publication 8 [19]: somatic *risks* to the exposed generation, genetic *risks* to the first generation offspring of exposed persons, and genetic *risks* to later generations. Absolute *risks* were expressed as [19]: "*the number of disabilities expected per unit dose of radiation in the lifetime of a million members of a population or as the number of disabilities per year in such population.*" Orders of risk were also used in such a way that a *risk* of death or injury would be defined as a *fifth order risk* if in a total population of 10^6 persons, 10 to 100 deaths (or injuries) would be expected. Relative *risks* were considered when the *risk* associated with an effect supposedly caused by 1 rad could be compared with the *risk* of a similar effect caused by natural causes [19]. Tentative estimates of genetic *risks* proved to contain too high uncertainties to be taken quantitatively into account. The genetic *risks* which might be associated with low level ^{226}Ra releases from the front end of the nuclear fuel cycle, for example, could not be estimated with any degree of certainty based on the concepts of *risk* used in the ICRP Publication 8.

The ICRP Publication 9 established that the MPD for occupational exposure should be regarded as upper limits and the annual dose limits for members of the public should be one-

[1] The word **radiation** as used in the ICRP Publication 9 and in the context of this work refers only to **ionizing radiation**, and is used interchangeably.

tenth of the corresponding MPD for workers. The MPD concept gave rise to the maximum permissible concentrations in air $(MPC)_a$ and in water $(MPC)_w$. The dose limitation system introduced by the ICRP in 1959 was based on a 5 rem (50 mSv) 30 years genetic dose limit, which through models and calculations led to MPCs in air and water [16]. Both, the $(MPC)_a$ and $(MPC)_w$ can be derived from a power function or an exponention model. The $(MPC)_w$ values for ^{226}Ra, for example, were derived based on the assumption that the maximum permissible burden to bone (the critical organ for ^{226}Ra) was 0.1 μCi (3.7×10^3 Bq), which could be obtained by consuming 1.1 L of water in working day periods of 8 hours, corresponding to one half of the water consumed in 24 hours. Such maximum permissible body burden to bone supposedly would carry "*no effect*" as far as bone tumors were concerned. It was observed that there was a built in risk factor in recommendations made on the basis of comparisons with ^{226}Ra body burdens, because $(MPC)_w$ values for ^{226}Ra concealed a degree of *risk* assumed to be acceptable [20].

3. RADIATION PROTECTION GUIDE (RPG) AND NORM/TENORM

The cumulative wastes from surface uranium mining in the United States from 1950 to 1977 amounted to about 1.7×10^3 Gt [21]. This fact was one of the main reasons why the Public Law 95-604 was enacted. As a practical consequence to this law the U. S. Department of Energy (USDOE) established the uranium mill tailings remedial actions [22]. Later on, in 1983, the United States Environmental Protection Agency (USEPA) issued a report to the United States Congress that presented a generic assessment of the general impacts of the uranium industry in the United States [23]. However, at that time *risk* assessments for the ^{226}Ra releases were not available. The USEPA position became clearer with the final decisions on the "National Emission Standards for Hazards Air Pollutants (NESHAPs) under section 112 of the Clean Air Act (CAA) for emissions of radionuclides from the following sources category: DOE facilities, Licensees of the Nuclear Regulatory Commission and Non-DOE Federal Facilities, Uranium Fuel Cycle Facilities, Elemental Phosphorous Plant, Coal Fired Boilers, High level Nuclear Waste Disposal Facilities, Phosphogypsum Stacks, Underground and Surface Uranium Mines, and the operation and disposal of Uranium Mill Tailings Piles" [24]. In this USEPA document, the *safe or acceptable level of risk* is tentatively explained taking into account the Natural Resources Defense Council, Inc.(NRDC)v.EPA decision 824 F.2d at 1146 (1987) - better known as the *Vinyl Chloride Decision* - at the District of Columbia Circuit [24]. In a later publication the USEPA specifies that the non-threshold model (for the dose-response curve) is used to assume "*an estimated risk to an average member of the U.S. population of* $5x10^{-2}$ *fatal cancers per sievert* ($5x10^{-4}$ *fatal cancers per rem) delivered at low dose rates*" [25]. The same document also says that the *risk per sievert* of severe mental retardation from doses to a fetus is estimated to be at least one order of magnitude greater than that of fatal cancer to the general population. The risk of inducing severe hereditary effects is of the order of 10^{-2} *per sievert* (10^{-4} *per rem*) [24]. USEPA tried, to the extent possible, to harmonize its guidance with the knowledge of the effects of ionizing radiation on humans, taking into proper account the scientific data gathered throughout many years by the BEIR Committee of the National Academy of Science–National Research Council on health risks of low levels of ionizing radiation [26–28]. In addition, the USEPA document considered the UNSCEAR reports published from 1977 to 1988 [29–31]. This USEPA's radiation protection guidance constituted a review of the of earlier guidances to Federal agencies on the protection of workers and the general public from radiation (25 FR 4402 and 25 FR 9057).

Table I. Recommendations proposed in the USEPA radiation protection guidance. Adapted from ref. [25].

NUMBER	PROPOSED RECOMMENDATION
1	There should be no exposure of the general public to ionizing radiation unless it is justified by the expectation of an overall benefit from the activity causing the exposure.
2	A sustainable effort should be made to ensure that doses to individuals and to populations are maintained as low as reasonably achievable. This includes consideration of economic and societal factors, and apply to radiation exposure that may occur now or in the foreseeable future.
3	The combined radiation doses incurred in any single year from all sources of exposure should not normally exceed 1mSv (100mrem) effective dose equivalent to an individual.
4	Authorized limits for sources should be established to ensure that individual and collective doses in current and future populations satisfy the objectives of the Radiation Protection Guide.
5	Risks associated with exposure of the general public to radiation that may occur due to Federal agency decisions and the policies upon which these actions are based should be made public as part of the decision process.
6	Assessments and records appropriate to the origin and magnitude of expected doses and the exposed population be performed and maintained to demonstrate conformance with requirements which implement these recommendations.
7	Exceptions to Recommendation 3 for planned exposure to radiation should be made only for highly unusual circumstances, and only when requirements which implement these recommendations.

The ICRP recommendations of 1977, in Publication 26 [11], and 1990, in Publication 60 [32], as well as NCRP Report No. 116 [9] were also considered relevant to the USEPA guidance. The USEPA guideline proposed to change the "*Radiation Protection Guide (RPG) limiting the average genetic dose to members of the U.S. population to 5 rems (50 mSv) in 30 years and the annual whole body dose to 500 mrem (5 mSv) dose equivalent be replaced by a single RPG of 1 mSv (100 mrem) effective dose equivalent received by or committed in a single year to any individual from all sources combined; doses from individual sources normally be limited to a fraction of the RPG; and increased emphasis be given to the principle that all exposure should be maintained as low as reasonably achievable, within the RPG*" [24]. USEPA's 1994 recommendations are summarized in Table I.

The application of the USEPA's RPGs to NORM/TENORM, however, pose a number of problems. The natural radiation background presents significant spatial and temporal variations. There is not a well defined baseline of exposures from natural sources of radiation against which exposure due to TENORM can be compared. The latter has been addressed recently by UNSCEAR [33].

4. UNSCEAR, IAEA AND THE NORM ISSUE

Although there is a concealed degree of *risk* assumed to be acceptable in the $(MPC)_w$ values for ^{226}Ra, the last UNSCEAR Report does not address the risk issue. However, the 1997 UNSCEAR Report calculated the effective doses resulting from intake of natural radionuclides in air, food and water from measured concentrations in the body or estimated from concentrations in intake materials. The worldwide average committed dose from annual intakes was estimated to be 0.23 mSv, being 0.17 mSv due to ^{40}K and 0.06 mSv from radionuclides of the ^{238}U and ^{232}Th series, excluding radon and its decay products. The UNSCEAR estimations of the average annual effective dose to adults from natural sources are reproduced in Table II.

Table II. UNSCEAR estimations on the average annual effective dose to adults from natural sources of ionizing radiation. Taken from ref. [33].

Component of exposure	Annual effective dose (mSv)	
	Normal	Elevated
Cosmic rays	0.38	2.0
Cosmogenic radionuclides	0.01	0.01
Terrestrial radiation: external	0.46	4.3
Terrestrial radiation: internal*	0.23	0.6
Terrestrial radiation: internal**		
Inhalation of Rn-222	1.2	10
Inhalation of Rn-220	0.07	0.1
Ingestion of Rn-222	0.005	0.1
Total	2.4	----

* Exposure excluding radon
** Exposure from radon and its decay products

It is interesting to notice that, taking into account the data presented in Table II, the average annual effective dose from external exposure to terrestrial radionuclides is double than that due to internal exposure. These two modes of exposure represent about 29% of the total exposure, radon inhalation is responsible for 50%, cosmic radiation accounts for 16%, while all other modes of exposure contribute with less than 5% of the total annual effective dose. When one does not consider high exposure to cosmic rays, in areas of high natural background the main doses are due to inhalation of radon, and external and internal exposures

to terrestrial radiation. These latter modes of exposures are the most likely way that NORM/TENORM will incur doses to humans.

The UNSCEAR evaluated the internal doses from ingestion of uranium and thorium-series radionuclides, taking into account a fractional population distribution of 0.05, 0.3 and 0.65, respectively for infants, children and adults. The UNSCEAR annual effective doses form ingestion of uranium and thorium-series radionuclides are summarized in Table III.

Table III. Annual effective doses from ingestion of uranium and thorium-series radionuclides. Taken from ref. [33].

Radionuclide	Annual effective dose (μSv)			
	Infants	Children	Adults	Age-weighted
^{238}U	0.23	0.26	0.25	0.25
^{234}U	0.25	0.28	0.28	0.28
^{230}Th	0.42	0.50	0.64	0.59
^{226}Ra	7.6	12	6.3	8.0
^{210}Pb	54	49	25	34
^{210}Po	227	114	75	95
^{232}Th	0.26	0.32	0.38	0.36
^{228}Ra	33	42	10	21
^{228}Th	0.38	0.28	0.22	0.24
^{235}U	0.011	0.012	0.012	0.011
TOTAL	320	220	120	160

The age-weighted total value of 160 μSv reported in Table III is more than three times higher than the 52 μSv derived in the earlier UNSCEAR Report [34]. The total annual effective dose from inhalation (≈ 10 μSv) and ingestion of terrestrial radionuclides is about 340 μSv, of which 170 μSv is from ^{40}K [33]. It is not clear, however, whether those effective doses from natural radionuclides can be used as representatives or not. Further data are necessary to establish a dose baseline due to the intake of natural radionuclides. Such baseline becomes more important as TENORM may reach the foodchains.

The ICRP Publication 26 reviewed critically the former concept of genetic dose limit of 5 rem (50 mSv) in 30 years from all sources of radiation additional to the dose from natural radiation background and from medical procedures [11]. The revision made in the ICRP Publication 26 was made under the following assuption [11]: "*continuance of the former genetic dose limit could be regarded as suggesting that acceptability of a higher population exposure than is either necessary or probable, and a higher risk than is justified by any present or easily envisaged future development.*"

The International Atomic Energy Agency (IAEA) adopted principles based on the system of dose limitations recommended by the ICRP Publication 26, stressing that cost-benefit analysis, quantitative assessment, and value judgements should support decision making processes [35–37]. However, the IAEA recommendations did not address the issue of naturally occurring radioactive materials (NORM).

5. CURRENT BASIC SAFETY STANDARDS (BSS) AND NORM

A number of well respected international organizations — the Food and Agriculture Organization (FAO), the International Atomic Energy Agency (IAEA), the International Labour Organization (ILO), the Nuclear Energy Agency of the Organization for Economic Co-operation and Development (OECD/NEA), the Pan American Health Organization (PAHO) and the World Health Organization (WHO) — recently sponsored the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) [38]. The BSS was approved by the IAEA's Board of Governors in September 1994. The NORM issue was not specifically contemplated in the BSS, however, exempt activity concentrations and exempt activities of radionuclides were established based on the following general principles [38–39]:

> "(a) the *radiation risks* to individuals caused by the *exempted practice* or *source* be sufficiently low as to be of no regulatory concern;
> (b) the collective radiological impact of the *exempted practice* or *source* be sufficiently low as not to warrant regulatory control under the prevailing circumstances; and
> (c) the *exempted practices* and *sources* be inherently safe, with no appreciable likelihood of scenarios that could lead to a failure to meet the criteria in (a) and (b)."

Table IV lists the exempt activitiy concentrations established in the BSS for ^{222}Rn (plus ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po), ^{224}Ra (plus ^{220}Rn, ^{216}Po, ^{212}Pb, ^{208}Tl -36%-, ^{212}Po -64%), ^{226}Ra (plus ^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi, ^{214}Po, ^{210}Pb, ^{210}Po, ^{210}Pb), ^{228}Ra (plus ^{228}Ac), ^{228}Th (plus ^{224}Ra, ^{220}Rn, ^{216}Po, ^{212}Pb, ^{208}Tl -36%-, ^{212}Po -64%), Th-nat (including ^{232}Th and progeny), ^{230}U (plus ^{226}Ra, ^{222}Rn, ^{218}Po, ^{214}Po), and U-nat (including the ^{238}U progeny), which are the most relevant radionuclides in the case of NORM releases, and activity concentrations found in some selected extractive industries [38].

It would be helpful to be able to establish easy to measure limits, so industries that deal with NORM or have TENORM as byproducts could benefit from these practical limits. Derived limits for ^{226}Ra releases will be presented here for illustration purposes only.

6. SECONDARY AND DERIVED LIMITS FOR RA-226 RELEASES

One must bear in mind that a primary dose limit is established based on an amount of effective dose which is not supposed to be exceeded. The ICRP defined, for practical purposes, secondary, derived and authorized limits which were since then adopted by the IAEA and EU [37;46–48].

Metabolic and environmental modeling are necessary to make possible inter-comparison involving measurable quantities instead of effective dose. Thus, for example, the use of metabolic and environmental models in association with a derived limit (DL) for ^{226}Ra releases allows a direct comparison with measurable and/or estimated ^{226}Ra concentrations in environmental and biological media due to actual or potential releases of this radionuclide into the environment.

Derived limits for ^{226}Ra, as well as for any other radionuclide, should be based on the annual limit of intake (ALI). The ALI for ^{226}Ra is 7×10^4 Bq/yr (1.9 μCi/yr). This ALI shall not be exceeded ever, and is to be used for the control of occupational exposure. However, for adult members of the public a ^{226}Ra ALI of 7×10^3 Bq/yr (0.19 μCi/yr) has been suggested as

appropriate, and was actually adopted by the EU to be used by the Member States in theirs radiation protection programs [47]. It is interesting to notice here that this EU ALI is about twice the maximum permissible body burden adopted by the ICRP much earlier [16].

Table IV. Exempt activity concentrations for the most relevant radionuclides (plus their progeny) in the case of NORM releases, as established in the Basic Safety Standards and activity concentrations found in selected extractive industries.

RADIONUCLIDE	ACTIVITY CONCENTRATION (kBq/kg)	
	Exempt [39]*	Extractive industries
Rn-222	10	
Ra-224	10	
Ra-226	10	2.7 [40] – 658 [41]
Ra-228	10	368 [42]
Th-228	1	1.1 [40] – 200 [41]
Th-natural	1	0.7 [43–45] – 111 [40]
U-230	10	
U-natural	1	3 [43–45] – 30 [40]

* The reference numbers are indicated between brackets.

A ^{226}Ra DL has been suggested for a manioc growing Brazilian region where thorium and uranium rich pyrochlore and apatite [49]. However, practical applications of DLs for ^{226}Ra releases in more general terms can also be used, as well as for other radionuclides.

DLs for ^{226}Ra releases can be linked to primary or secondary limits, like an ALI, with an accuracy which will depend on the realism and adequacy of the environmental model used in the derivation. Thus, environmental modeling is essential for calculating DLs for ^{226}Ra releases.

Generic models and parameters can be used in the preliminary assessment of environmental transfer of radionuclides from routine releases. Thus, a generic derived limit (GDL) either for ^{226}Ra releases from a specific source or for ^{226}Ra concentrations in environmental or biological media can be easily calculated based on generic models and parameters for this radionuclide.

Potential *critical groups* must be defined or identified for the application of a GDL for ^{226}Ra or any other radionuclide. The concept of *critical group* was introduced to circumvent the lack of precision in the definition of the expression "*members of the public*," frequently used in the ICRP publications. On the one hand, "*members of the public*" imply large differences in age, size, metabolism, customs, and environmental variations in the places of working and living. On the other hand, *critical groups* must be small enough to be relatively homogeneous with respect to those characteristics that can affect the doses received; like age, diet, and behavior [11;35;37]. An homogeneity requirement establishes that, in general, the maximum to minimum ratio within a critical group do not exceed an order of magnitude. *Critical groups* may be either identified among existing members of the general population, or

defined as a group of persons; in either case a critical group is expected to be exposed to a higher dose level than that received by the general population. A typical size of a *critical group* is up to a few tens of persons, mostly to restrict habit surveys. However, when large populations are uniformly exposed, the size of the *critical group* can be considerably larger. The size, as well as the identification or definition of *critical groups* are relevant aspects to be considered in environmental modeling concerning ^{226}Ra or any other radionuclide releases into the environment.

In addition to *critical groups*, environmental modeling requires the use of *critical pathways* for a critical radionuclide. In the case of ^{226}Ra releases into the environment, the relative importance of ^{226}Ra vis-a-vis ^{210}Po as the critical radionuclide should be considered in some pathways, because the latter may be also an important contributor to internal dose levels under certain circumstances [50].

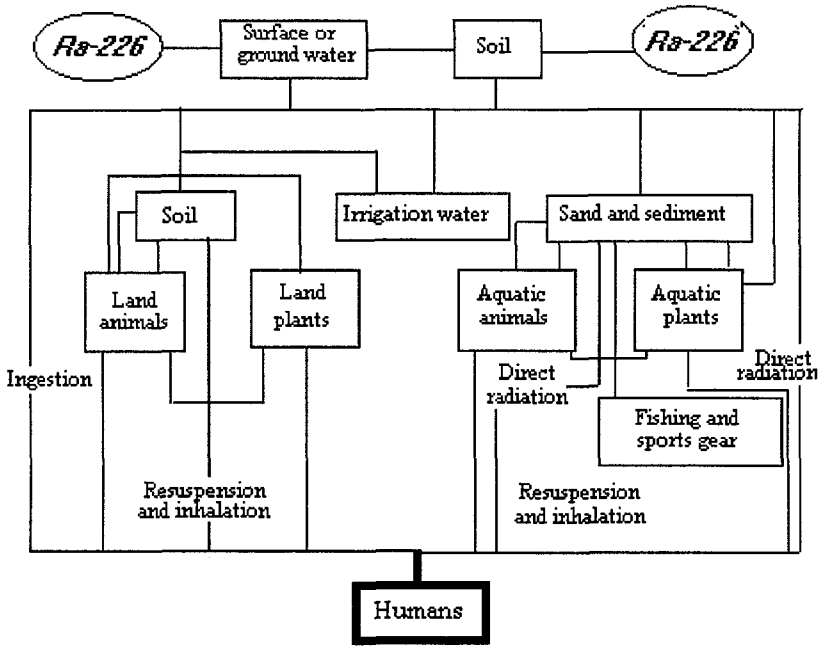

Figure 2. Selected pathways for ^{226}Ra through soil and surface or ground water. Adapted from ref. [12].

Critical pathways to be considered for ^{226}Ra releases will be essentially terrestrial or aquatic, because air is usually an unimportant pathway for ^{226}Ra intake. Simplified pathways for ^{226}Ra released into ground and surface waters, and in soils are presented in Figure 2. One must observe, however, that the direct radiation exposure pathway is only important when the *critical group* is located near the site of ^{226}Ra releases or is living near surface soils or sediments that accumulated high ^{226}Ra concentrations. Direct radiation might be considered a *critical pathway* when, for example, TENORM bearing tailings are inadvertently used as construction material or are not isolated from a *critical group*. In such cases, however, radon rather than ^{226}Ra should be considered the critical radionuclide.

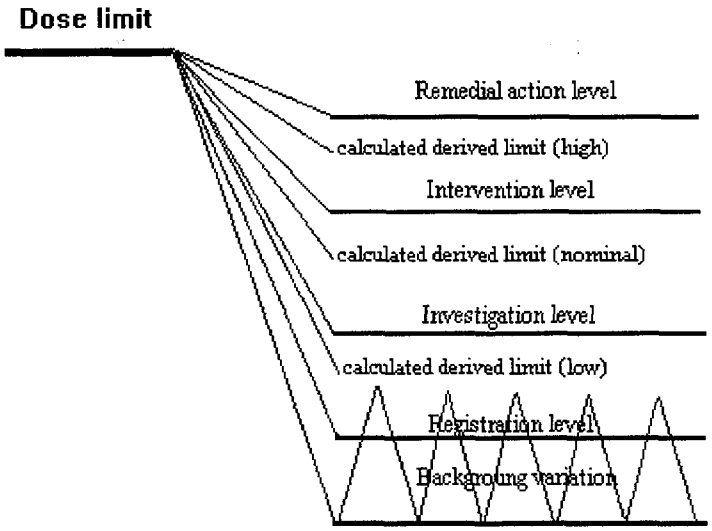

Figure 3. Schematic representation of calculated derived limits (low, nominal and high) — in accordance with parameters used — plus registration, investigation, and remedial action levels in comparison with the natural radiation background variation.

Table V. Selected derived limits (DLs) for ^{226}Ra

DERIVED LIMIT FOR	PRACTICAL UNITS*
Water	Bq/L
Pasture or soils	Bq/kg
Rate of discharge	Bq/year
Air	Bq/m^3

* Not necessarily SI units.

The basic conditions for an useful DL are the following:

1. be comparable with measurable quantities. Thus, for ^{226}Ra one can expect, for example, to determine DLs with units in accordance with Table V.
2. be related with the ALI for ^{226}Ra. That means 7 x 10^3 Bq/yr (0.19 μCi/yr) for adult members of the public;
3. be chosen in such a way that once not exceeded, the dose limit will not be exceeded also.

It is well recognized that the physical descriptions of the critical pathways followed by ^{226}Ra from the source of release until will reach humans, and the appropriate values for parameters used in generic environmental models may differ considerably of site specific environmental models and parameters.

Site specific models and parameters are desirable in most cases, but by and large, they are unavailable and are very difficult to obtain. As a consequence, mathematical models and parameters of more generic nature are often used.

Concerning the uncertainties of radio-ecological assessment models it has been observed the following [51]:

"*(i) there is a need to distinguish between research and assessment models, mainly regarding the objectives for developing and applying such models;*
(ii) limits specifying the applicability of the results of modeling should be clearly indicated when using deterministic models for decision making; and
(iii) the introduction of further complexities in a model does not necessarily assure any improvement in the predictions."

When the calculated doses approach dose limits, that means, whenever doses predicted by models are less than about one order of magnitude below the relevant dose limit, the model structure, its parameters and all associated values should be re-evaluated. The criterion to decide to re-evaluate a model is a matter to debate.

Figure 3 suggests a sequence of dose related levels that can be useful in decision making processes. Once a primary dose limit is established, fractions of this primary limit can be agreed upon. Thus, for example, a registration level would be established at the highest portion of the background variation. Above this registration level investigation, intervention and remedial action levels would also be established. All those levels could be established in terms of fractions of the primary dose, but translated in terms of derived limits expressed in practical units, as in Table V. The derived limits would be calculated by using environmental models. A sensitive parametric analysis can make a ranking of the parameters used in the model, allowing one to choose how important each parameter can be in the model output.

A detailed discussion on the uncertainties involved in radiological models, as well as an application of ranking parameters, based on sensitive analysis of an environmental model can be found in the literature [51–52]. When using adopted levels and derived limits as those suggested in Figure 3, the uncertainties and importance of the parameters entering an environmental model can make the difference for decision makers to adopt a right or wrong decision concerning radiological protection.

7. CONCLUDING REMARKS

1. A brief review of the concept of *risk* as used in radiation protection was presented, taking into consideration its evolution since the earlier uses.
2. The adoption of secondary levels of dose and derived limits for ^{226}Ra releases have been proposed and illustrated.
3. Attention has been called in regarding the need of parametric analysis to rank parameters entering the models used to obtain the derived limits.

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