Keynote Address

MANAGING EXPOSURE TO NORM — CONSENSUS OR CHAOS?

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Abstract. Ten years after the first in this series of international symposia on NORM was held in Amsterdam, exposure to natural sources has continued to have a high profile in most parts of the world and has evoked a considerable degree of controversy. The paper looks at the progress made in identifying and quantifying the radiological risks to exposed individuals and putting in place, at the national level, additional or revised legislative and regulatory measures for the mitigation of these risks. The current direction in which the approach to managing exposure to NORM is moving, especially in the light of the revised recommendations proposed by the ICRP, is also examined. The achievement of a harmonized approach to the management of exposure to NORM is clearly an important goal, especially given that minerals and raw materials are traded internationally on a very large scale. It would appear that shortcomings in the regulatory approach in certain countries may be hampering the achievement of this much-needed internationally harmonized approach and creating a situation in international trade that some might describe as 'chaotic'. The development of standards and regulations continues to depend quite heavily on dose modelling assessments where adequate facility-specific data are not yet available. The paper demonstrates by way of two examples — exposure of workers in mineral processing industries and exposure of members of the public to drinking water contaminated by mine residues — why great caution is required in the dose modelling approach.

1. Introduction

It is now exactly a decade since the first in this series of international symposia on NORM was held in Amsterdam. This event came six years after the publication of the current version of the basic recommendations of the International Commission on Radiological Protection (ICRP) in the form of ICRP Publication 60 [1] and just one year after the publication by the International Atomic Energy Agency (IAEA) of the current version of the *International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources* (the BSS), jointly sponsored by four organizations within the United Nations and by two other international bodies [2]. These two publications marked the first real steps taken at the international level to deal with protection against exposure to natural sources of radiation. They set in motion a series of developments around the world to focus regulatory attention on this area, one notable example being the publication, in 1996, of Directive 96/29/Euratom of the Council of the European Union [3], which placed specific legal requirements on European Member States for the control of work activities involving a significant increase in exposure to natural sources.

Considerable effort has now been devoted worldwide to identifying and quantifying the radiological risks to exposed individuals and putting in place, at the national level, additional or revised legislative and regulatory measures for the control of these risks. Indeed, the whole topic of exposure to natural sources has attained a high profile in most parts of the world and has also evoked a fair degree of controversy. The achievement of a harmonized approach to the management of exposure to NORM is clearly an important goal, especially given that minerals and raw materials are traded internationally on a very large scale. However, there are signs that such a harmonized approach is still proving to be elusive.

All three of the above mentioned international publications — ICRP Publication 60, the BSS and the European Council Directive — are now undergoing revision, so it is particularly opportune at this time to examine the progress made, to determine the direction in which our radiation protection philosophy is moving and to evaluate our success (or lack thereof) in achieving an internationally harmonized approach to protection against exposure to natural sources including, in particular, exposure to naturally occurring radioactive material (NORM).

2. What is NORM?

Opinions differ on what exactly is meant by the term NORM. Reports of the occurrence of significant concentrations of radionuclides of natural origin in the oil and gas industry go back to 1904 [4] and it seems that the term NORM was first coined by this industry in the late 1980s when referring to the radium-rich scales deposited inside well tubulars, surface piping, vessels, pumps and other production and processing equipment. Since then the term has become widely adopted beyond the oil and gas industry and now tends to be associated with almost any type of mineral or mineral processing activity where the presence of radionuclides of natural origin is of interest.

The term NORM has become firmly entrenched in our technical vocabulary, but as an acronym for 'naturally occurring radioactive material' it is actually a misnomer — the descriptor 'naturally occurring' refers to the radionuclides in the material and not necessarily to the material itself, which may well be a product of a physical, chemical or thermal industrial process. Furthermore, because radionuclides of natural origin are ubiquitous in our environment, it could be argued that all materials are effectively NORM — not only minerals (rocks and soil) of all types, but also all vegetable and animal matter including the food we eat, the water we drink and even our own bodies. Clearly, there is a need to single out only those few materials of potential radiological concern.

One attempt to do this has been through the introduction of a new term — TENORM ('technologically enhanced naturally radioactive material'). However, this approach does not solve the problem and, indeed, can be misleading, because it implies that the materials of concern are limited to those in which the radionuclides have become concentrated as a result of an industrial process. This is often the case, but not always. For instance, it is estimated that a smelting plant worker exposed to furnace fume and precipitator dust with a highly *enhanced* ^{210}Pb concentration of, say, 200 Bq/g could receive an annual dose of about 120 μSv, whereas a titanium dioxide production worker exposed to ilmenite feedstock with an *unenhanced* ^{232}Th activity concentration of, say, 2 Bq/g could receive an annual dose of 800 μSv, nearly seven times higher[1]. Materials in their natural state are in principle no less important to consider than materials with activity concentrations enhanced by some form of processing and any distinction between the two for the purposes of radiation protection is artificial and without any scientific foundation.

The approach adopted by the IAEA for the purposes of international radiation protection standards is to use only the term NORM, regardless of the origin of the material, while defining 'radioactive material' more narrowly as "material that is designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity" [6]. NORM is then a particular form of radioactive material (defined in the narrower sense) where the radioactivity in question is associated with radionuclides of natural origin. This approach solves the problem of how to single out only those materials of radiological concern, while avoiding the need for any additional and potentially misleading terms such as TENORM, the use of which is therefore discouraged.

Uranium ore, of course, falls within the definition of NORM, but is a special case because the mining and processing of this material form part of the nuclear fuel cycle and have therefore long been subject to stringent regulatory control. This has led to a situation where the 'nuclear-style' standards applied to these operations are in some respects inconsistent with the standards now being established for other NORM-related activities. Nevertheless, the nature of the radiological hazards associated with uranium mining and processing is such that a significant level of regulatory control will always be required.

3. Perspectives on the five NORM symposia to date

3.1. Topics of major interest

Looking at the subject matter presented at the five NORM symposia spanning the last decade, some interesting observations can be made. While the categorization of presentations into specific topics is rather subjective and complicated by the fact that some presentations covered more than one topic, a general picture does seem to emerge, as shown in Fig. 1. (The mining and processing of uranium ore is

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[1] The basis for the derivation of these doses is given in Ref. [5].

not included in the analysis because it received relatively little coverage, having long been the subject of attention elsewhere). About 20% of the subject matter relates to the establishment of standards and regulations and to the identification of the main types of industrial activities of concern, reflecting the considerable progress made in this area during the ten year period, particularly in Europe. However, a greater proportion of the subject matter — nearly half — has been devoted to studies conducted in particular industrial facilities or types of facility. This is encouraging, because without this detailed facility-specific information, it is difficult to imagine how sensible steps can be taken towards identifying what needs to be controlled and how.

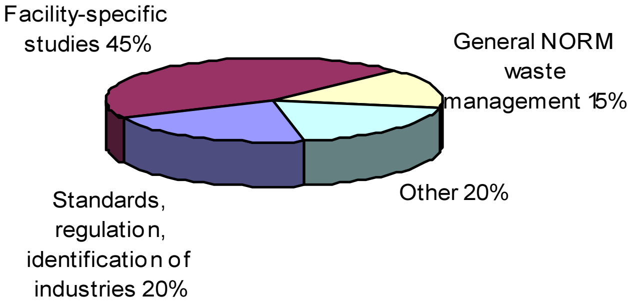

FIG. 1. Subject matter presented at NORM I to NORM V.

3.2. Scope of regulation — the key issue

The question of how to define the scope of regulation of NORM activities (other than the mining and processing of uranium ore) in terms of the concepts of exclusion, exemption and clearance has been the main area of concern from the very beginning — the opening remarks made at the first NORM symposium in Amsterdam [7] were devoted almost entirely to this issue. Despite the fact that significant progress has since been made towards achieving international consensus, as described later in the paper, some issues remain unresolved and the issue of defining the scope of regulatory control continues to dominate discussion. Consequently, the implementation of an internationally harmonized approach to deciding what should be included within the scope of regulation is still far from being achieved.

3.3. Principal NORM industries of interest

The 'facility-specific studies' category shown in Fig. 1 is broken down in Fig. 2 to indicate the principal NORM industries of interest and the relative coverage given to those industries during the five NORM symposia. Analysis of an IAEA database of more than 700 literature sources on exposure to NORM (other than exposures in uranium ore mining and processing), shown in Fig. 3, gives much the same result. Although there has been fairly uniform coverage of the main industries of concern, it seems that the phosphate industry has been the subject of the most attention, as would have been expected given the widespread nature of this industry, the variety of processes involved and the existence of very large quantities of NORM residue in the form of phosphogypsum.

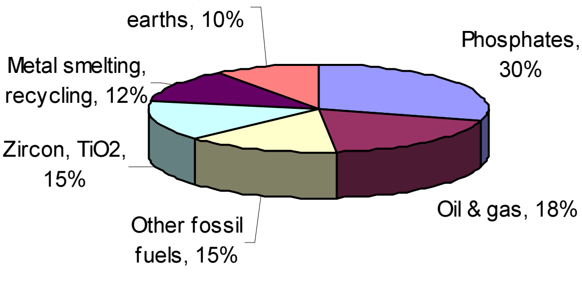

FIG. 2. Facility-specific studies presented at NORM I to NORM V

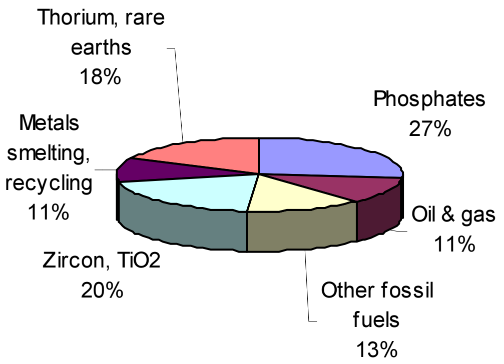

FIG. 3. Breakdown of IAEA literature database on NORM

The industries identified in Figs 2 and 3 have been broken down into more detail in a recent IAEA Safety Report [5] to generate the following list, roughly in descending order of radiological priority:

1. Extraction of rare earth elements;
2. Production and use of thorium and its compounds;
3. Production of niobium and ferro-niobium;
4. Mining of ores other than uranium ore;
5. Production of oil and gas;
6. Manufacture of titanium dioxide pigments;
7. The phosphate industry;
8. The zircon and zirconia industries;
9. Production of tin, copper, aluminium, iron and steel, zinc and lead;
10. Combustion of coal;
11. Water treatment.

The categories ‘mining of ores other than uranium ore’ and ‘water treatment’ are included particularly because of the potential for exposure to high concentrations of radon in underground workplaces, although there may also be concerns about the buildup of radionuclides in effluents and residues.

A working party on NORM established by the European Commission Article 31 Group of Experts to assist in the revision of the Directive 96/29/Euratom has recently proposed an almost identical list of NORM industries that may in future become automatically required to submit notification to the relevant national regulatory body.

The IAEA is currently engaged in the development of a suite of publications in its Safety Reports Series to provide detailed information for regulatory bodies and operators involved in some of the industries listed above. Safety Reports have been completed for the oil and gas and the zircon and zirconia industries [8, 9] and further reports dealing with the phosphate industry, the titanium dioxide pigment industry and the extraction and use of thorium are in preparation [10–12].

4. Progress in the development of regulatory standards

The recommendations in ICRP Publication 60, together with additional guidance on radon in ICRP Publication 65 [13], have provided the basis for the international standards on exposure to natural sources contained in the BSS [2] and supporting Safety Guides. The standards make an important differentiation between exposures subject to the requirements for intervention and those subject to the requirements for practices.

4.1. Exposures subject to the requirements for intervention

4.1.1. General requirements

Paragraph 2.5 of the BSS states that "Exposure to natural sources shall normally be considered as a chronic exposure situation and, if necessary, shall be subject to the requirements for intervention …", meaning that in such circumstances:

- The exposure does not fall within the scope of regulation in terms of the requirements for practices;
- Remedial action has to be undertaken to reduce or avert the exposure whenever such action is *justified* (usually, this means when a specified action level is exceeded); and
- The form, scale and duration of any such remedial action has to be *optimized* so as to produce the maximum net benefit, understood in a broad sense, under the prevailing social and economic circumstances (usually, this entails the selection of an optimized level of remediation for inclusion in the remedial action plan).

4.1.2. Specific requirements for radon[2]

A chronic exposure situation addressed specifically in the BSS [2] is exposure to radon. The requirements for radon are no different from those for any other chronic exposure situation, but more detailed guidance is provided for radon in the BSS in accordance with the recommendations contained in ICRP Publication 65 [10]. For dwellings, the expected range of action levels for remedial action is an annual average of 200–600 Bq/m^3. Fig. 4 illustrates the situation in the context of worldwide indoor radon concentration data from the 1993 UNSCEAR report [14] — these data suggest a population-weighted average radon concentration of 40 Bq/m^3, although national averages may depart significantly from this value. The adoption of a range of action levels therefore reflects the recognition that "… the best choice of an action level may well be that level which defines a significant, but not unmanageable, number of houses in need of remedial work", and that "It is then not expected that the same action level will be appropriate in all countries" [1]. The lower bound of the range of action levels (200 Bq/m^3) corresponds to the 98th percentile of the worldwide radon concentration distribution.

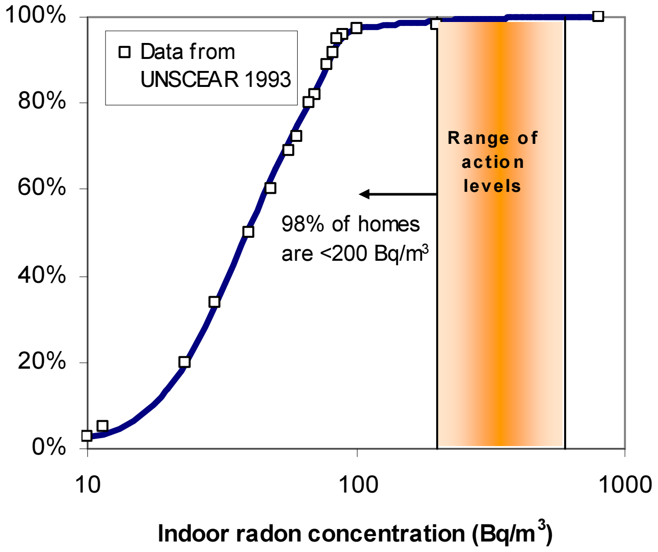

FIG. 4. Action levels for radon concentrations in dwellings in relation to the cumulative worldwide distribution

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[2] In this paper, the use of the term 'radon' is generally taken to include not only the parent radionuclide ^{222}Rn but also its short lived progeny. However, the term 'radon concentration' refers to the concentration in air of the parent radionuclide ^{222}Rn alone.

It is important to note that the choice of radon action level for dwellings is based not only on dose considerations but also on the practicalities of remedial action (i.e. the percentage of homes to be remediated). For a typical exposure situation, conversion from indoor radon concentration to annual effective dose can be made quite readily because the conversion involves relatively few assumptions (mainly assumptions about occupancy and radon progeny equilibrium factor). Assuming an annual occupancy of 7000 h and an equilibrium factor of 0.4, action levels in the range 200–600 Bq/m^3 correspond to annual effective doses in the range 3–10 mSv. This provides a logical basis for the determination of action levels for workplaces because, as stated in ICRP Publication 65 [13], "Workers who are not regarded as being occupationally exposed to radiation are usually treated in the same way as members of the public. It is… logical to adopt an action level for intervention in workplaces at the same level of effective dose as the action level for dwellings." The resulting range (rounded) quoted in Ref. [13], taking into account the occupancy and dose coefficients for workers, is 500–1500 Bq/m^3. In the BSS [2], the mid-point of this range, 1000 Bq/m^3, has been adopted by international consensus as a guideline action level for remedial action in workplaces.

4.2. Exposures subject to the requirements for practices

4.2.1. Which exposures are involved?

Certain human activities giving rise to exposure to natural sources have the characteristics of practices and some form of control in accordance with the requirements for practices, rather than an intervention approach, may be appropriate. The following three situations are addressed in the international standards:

(1) In workplaces where radon is not incidental to the work (e.g. uranium mines) or in other workplaces where a reduction in radon concentrations to below the action level cannot reasonably be achieved, exposure to radon is treated as occupational exposure and subject to the requirements for practices.

(2) Paragraph 2.1 of the BSS states that "The practices to which the Standards apply include… practices involving exposure to natural sources specified by the Regulatory Authority as requiring control …". Paragraph 2.5(a) of the BSS goes on to say that the exposure associated with such practices includes "… public exposure delivered by effluent discharges or the disposal of radioactive waste … unless the exposure is excluded or the practice or the source is exempted…".

(3) The transport of radioactive material, including NORM, is regarded as a practice. However, if the material has not been, or is not intended to be, processed for purposes of extraction and use of the contained radionuclides, the requirements of the *Regulations for the Safe Transport of Radioactive Material* (the Transport Regulations) [15] apply only if the total activity concentration of the material exceeds 10 times the 'activity concentration for exempt material' defined in the Transport Regulations. For a material in which the uranium and thorium decay chains are deemed to be in equilibrium, this condition can be expressed mathematically as:

$$x(^{238}U) + x(^{232}Th) + 0.01\,x(^{40}K) \quad > \quad 10$$

where $x(i)$ is the activity concentration of radionuclide i.

4.2.2. 'Entry' criteria for regulation of materials in accordance with the requirements for practices

In terms of item (2) in Section 4.2.1, it is the responsibility of the regulatory body to specify which exposures to natural sources require control, but no further guidance on this existed at the time of publication of the BSS. Some countries had introduced numerical criteria in one form or another, but there were very large variations between countries, with arguments that some criteria were too strict and others were too permissive. Following many years of international debate, a major step forward was achieved with the publication in 2004 of the IAEA Safety Guide RS-G-1.7 on *Application of the Concepts of Exclusion, Exemption and Clearance* [16]. This Safety Guide advises that "It is usually unnecessary to regulate…" material containing radionuclides of natural origin at activity concentrations below 1 Bq/g for radionuclides in the uranium and thorium decay series and below 10 Bq/g for ^{40}K. The Safety Guide adds, however, that "… there are some situations (such as the use of some building materials containing natural radionuclides) for which exposures from materials due to radionuclides with activity concentrations below [these values] would necessitate consideration by the regulatory body for some types of regulatory control". This is discussed further in Section 8.1.2. Safety Guide RS-G-1.7 states that the aforementioned values may be used:

- In the definition of the scope of national regulations, or
- To define radioactive material for the purpose of such regulations, and
- To determine whether material within a practice can be released from regulatory control.

The values for radionuclides of both natural and artificial origin are expressed as orders of magnitude only, on the basis that the uncertainties in their derivation do not support a greater level of precision. This approach is identical to that adopted for the derivation of exemption values for limited quantities of material in Schedule I of the BSS[3].

In September 2004, the Board of Governors of the IAEA approved the use of these radiological criteria for radionuclides in commodities in the application of the BSS. Shortly thereafter, this decision was reported to the IAEA General Conference at its 48th regular session. The General Conference, in Resolution GC(48)/RES/10, welcomed the decision, encouraged IAEA Member States "…to make use of the criteria, for example to facilitate trade…", and further encouraged the IAEA Secretariat "…to take account of the criteria in the forthcoming review and revision of the BSS".

The approach taken for radionuclides of natural origin in Ref. [16] was based on the realization that the derivation of activity concentration values on the basis of the same radiological criteria as those used for artificial radionuclides[4] would produce values that in many cases would be lower than concentrations occurring in material in the natural environment. Thus many human activities previously unregulated from a radiological standpoint, such as the construction of houses from natural building material or even the use of land in many areas, could become subject to regulation. Establishing levels for radionuclides of natural origin that entailed such widespread regulatory consideration, in circumstances where in many cases it was unlikely to achieve any improvement in protection, was not considered to be an optimum use of regulatory resources. Therefore, the derivation of activity concentration values for radionuclides of natural origin other than radon was not based on a dosimetric approach but on a methodology that placed greater emphasis on optimization of protection, including optimization of regulatory resources.

This methodology followed an approach similar to that used for deriving radon action levels and involved the selection of activity concentration values that took into consideration the worldwide distribution of concentrations of radionuclides of natural origin in soil given in the 2000 UNSCEAR Report [17]. The worldwide distribution for ^{238}U and ^{232}Th series radionuclides is shown in Fig. 5, together with data for various commercially exploited minerals with elevated concentrations of these radionuclides. These data clearly demonstrate the rationale for selecting an activity concentration criterion of 1 Bq/g. The worldwide distribution for ^{40}K in soil extends up to 3.2 Bq/g, which is compatible with the activity concentration criterion of 10 Bq/g for this radionuclide.

4.2.3. Exemption — the first step in the graded approach to regulation

Unlike the situation with radon, in which there is a reasonably identifiable relationship between radon concentration and annual dose, the activity concentrations of radionuclides in NORM do not give a clear indication of the dose that is likely to be received by an exposed worker or member of the public unless there is a reasonable amount of additional information on the exposure scenario involved and the type of NORM giving rise to the exposure. Thus, even if the activity concentration value of 1 Bq/g for uranium and thorium series radionuclides is significantly exceeded, the dose received by an

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[3] These exemption values also appear in Annex I of the European Council Directive 96/29/Euratom [3].

[4] For radionuclides of artificial origin, the resulting activity concentration values were derived on the basis of exposure scenarios as being the lower of the values obtained from (a) the use of realistic parameter values applying an effective dose of 10 μSv/a and (b) the use of low probability parameter values applying an effective dose criterion of 1 mSv/a and a skin equivalent dose limit of 50 mSv/a.

exposed individual may still be such that the optimum regulatory option is not to apply any regulatory requirements, in other words to grant an exemption. This can be regarded as the first step in a 'graded approach to regulation'. In the event that exemption is not the optimum option, the next steps to be considered in the graded approach are, in ascending order of stringency of control, the requirements for notification, registration and licensing. These requirements are in principle no different from those applicable to exposures to artificial sources of radiation. Further information on the application of the graded approach to the regulation of exposures to NORM is provided in Ref. [5].

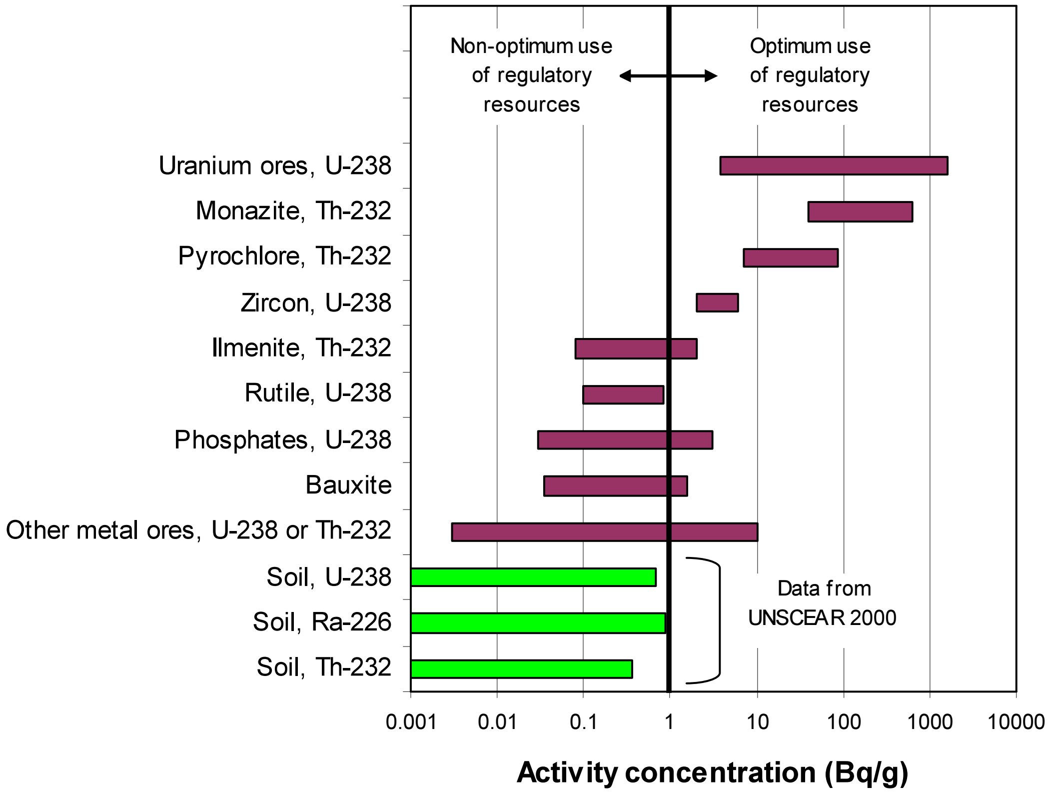

FIG. 5. Concentration ranges of uranium and thorium series radionuclides in minerals

Criteria for exemption, without further consideration, of substances containing radionuclides of *artificial* origin are based on the premise that exemption will be the optimum option when the dose incurred by an individual is of the order of 10 µSv or less in a year [2]. For NORM, the situation is quite different. Owing to the existence of significant and highly variable levels of background exposure to radionuclides of natural origin, exemption is likely to be the optimum option over a much wider range of doses, typically doses of the order of 1 mSv or less in a year. For situations where occupational exposure to gamma radiation and radionuclides in dust is the principal exposure of concern, as is likely to be the case in most NORM industries [5], it is recommended in Refs [18, 19] that "… regulatory agencies choose activity concentrations of parent nuclides within the range 1–10 Bq g^{-1} to determine whether the exposures from these materials should be regarded as occupational" while noting that, on the basis of pessimistic assumptions, activity concentrations in this range "…will lead to an effective dose of about 1–2 mSv in a year", i.e. up to about 10% of the annual dose limit for workers. This is borne out by the results of calculations described in Ref. [5], based on a variety of exposure situations in NORM industries (see Section 5.2).

5. Occupational exposure to NORM

5.1. Dose assessment by modelling and its limitations

Many assessments of doses received by workers have been heavily based on exposure scenario modelling. Caution is required in any modelling assessment, because the extent to which a model simulates the true exposure situation is critically dependent on the assumptions used. A modelling study conducted for the European Commission [20] was intended to provide a basis for the establishment of specific guidance on the regulatory control of workplaces where materials containing naturally occurring radionuclides were of concern. However, because of the very broad range of assumptions considered, this study came up with widely varying predictions of annual worker doses that extended up to hundreds or even thousands of millisieverts. The regulatory and public perception implications of these unrealistic predictions naturally caused consternation among many NORM industries.

The IAEA subsequently conducted modelling assessments for a similar range of exposure situations, but using more realistic assumptions [5]. One major difference from the European study was the assumption that radon in the workplace would be at a concentration below the relevant action level (after remedial action, where necessary) and would not therefore be treated as a source of occupational exposure — evidence suggests that this will generally be the case, especially for above-ground workplaces. The results, expressed in terms of dose per unit activity concentration, are shown in Table 1, noting that the term ‘activity concentration’ here means the highest individual radionuclide activity concentration in the material concerned. The activity concentration values in the last column of Table 1 represent the levels at which the range of effective doses expected to be received by a worker starts to extend beyond about 10% of the 20 mSv occupational dose limit and thus into an area where the need for radiation protection measures becomes more certain. It can easily be deduced from Table 1 that:

- A worker exposed to a large stockpile of material with an activity concentration of 5 Bq/g would be expected to receive an annual dose in the range 0.1–2 mSv (the exact value depends mainly on the type of material involved);
- A worker exposed to a small quantity of material (~1 m^3) with an activity concentration of 50 Bq/g would be expected to receive an annual dose in the range 0.4–2 mSv;
- A worker exposed to furnace fume and precipitator dust with an activity concentration of 500 Bq/g would be expected to receive an annual dose in the range 0.3–1.5 mSv.

TABLE 1. RELATIONSHIP BETWEEN DOSE AND ACTIVITY CONCENTRATION FOR EXPOSURE OF WORKERS TO NORM [5]

Category of material	Broad estimate of annual effective dose per unit activity concentration (mSv/a per Bq/g)		Individual radionuclide activity concentration above which the expected dose may exceed 10% of the dose limit (Bq/g)
	Minimum	Maximum	
Large quantity, e.g. orebody, large stockpile	0.02	0.4	5
Small quantity, e.g. mineral concentrate, scale, sludge	0.008	0.04	50
Volatilized: furnace fume and precipitator dust	0.0006	0.003	500[a]

[a] This value refers to the activity concentration in the precipitator dust, with exposure to fume having been accounted for by assuming an equivalent dust loading of 1 mg/m^3 at the same activity concentration (i.e. a concentration of 0.5 Bq/m^3 in fume) and an activity median aerodynamic diameter of 1 µm.

As pointed out in Ref. [5], these results can be very useful in prioritizing in advance the types of industrial process most likely to need radiation protection measures, since such prioritization only requires knowledge of the activity concentrations of the process materials concerned and assignment of such materials to one of three simple categories.

5.2. Comparison of modelling results with the results of facility-specific assessments

The IAEA is gathering and documenting radiological data on several important NORM industries, including data on worker doses assessed to the extent possible on the basis of facility-specific measurements. This is making it possible to obtain rather more reliable indications of the doses likely to be received by workers. Table 2 shows, for a selection of NORM industries, a comparison of dose information determined from modelling with broad assumptions [20], from modelling with more realistic assumptions [5] and from assessments based to a greater extent on facility-specific measurements. This comparison illustrates how the use of unrealistic modelling assumptions can generate very misleading results, particularly if an attempt is made to include exposure to radon when in most situations this exposure is expected to be moderate and should not be treated as occupational. On the other hand, modelling can give reasonably reliable results provided that realistic assumptions are made.

TABLE 2. ASSESSMENTS OF WORKER DOSES IN A SELECTION OF NORM INDUSTRIES

	Annual effective dose (mSv)			
	Based on modelling using broad assumptions [20]		Based on modelling using realistic assumptions [5]	Based on facility-specific measurements
	Radon included	Radon excluded		
Bulk phosphate ore in a warehouse	0.2–69	0.02–11	0.01–0.8	0.8 (general plant worker)[a] [21]
Thermal phosphorus plant				
Removal of precipitator dust	0.1–10	0.1–10	0.8 (general plant worker)[b]	1 (general plant worker) [22]
Exposure to fume near a furnace	0.02–0.9	0.02–0.9		
Bulk pyrochlore feedstock in a warehouse	132–635	11–121	23	Up to 20[c]
Bulk zircon sand in a warehouse	0.8–583	0.4–286	0.5–0.9	0.25–0.28 [9]
Fabrication of zircon refractory products	0.001–58	—[d]	0.01–0.04	0.05–0.2 [9]
Rare earths extraction				
Bulk monazite sand in a warehouse	13.5–9763	—	10–152	Average 1–8 (general plant worker) [23]
Removal of residue	0.2–184	<0.2–101	0.2–36	
Bulk ilmenite feedstock in a warehouse	0.2–119	0.02–24	0.0004–0.9	0.03–0.08 [11]
Removal of scale, TiO_2 production	50–342	Similar to 'radon included'	<0.01–20	<1–6 [11]
Removal of scale, oil and gas extraction	0.00003–243	Similar to 'radon included'	0.002–33	<1 to a few mSv [5]

[a] Dose from gamma radiation only — dust inhalation was not considered.
[b] It was assumed that the activity concentration of ^{210}Po was 10% of that of ^{210}Pb, in line with observations.
[c] Data not yet available but considered by experts to have the potential for approaching 20 mSv.
[d] —: the contribution of radon could not be established from the data.

5.3. The special case of materials rich in potassium

The natural abundance of ^{40}K in potassium is 0.0117%. The specific activity of ^{40}K, calculated from its 1.265×10^9 year half-life, is 2.617×10^5 Bq/g. Thus, pure potassium contains ^{40}K at an activity concentration of 30.6 Bq/g. Materials rich in potassium, such as some fertilizers, contain ^{40}K at concentrations above background values but, clearly, these concentrations are always less than 30.6 Bq/g. Intakes of ^{40}K are excluded from the international standards because they are controlled homeostatically and not amenable to further control. Therefore, exposure to ^{40}K is an issue only for external exposure. Calculations of the dose per unit activity concentration of ^{40}K likely to be received by a worker exposed to three types of potassium fertilizer — K, PK and NPK — are reported in Ref. [5] and the results are summarized in Table 3. These results show that the total annual effective dose per unit activity concentration is rather insensitive to the type of fertilizer. The annual effective doses derived from these results, shown also in Table 3, are in the range 0.15–0.18 mSv. Even if a ^{40}K activity concentration of 30.6 Bq/g for pure potassium were to be assumed (an extreme worst case assumption), the annual effective dose would still be only 0.6–0.9 mSv. It can be concluded, therefore, that the exposure of a worker to bulk quantities of potassium-rich materials such as fertilizers is most unlikely to warrant regulatory control.

TABLE 3. DOSE RECEIVED BY A WORKER EXPOSED TO A LARGE STOCKPILE OF POTASSIUM-RICH FERTILIZER

	Highest reported ^{40}K activity concentration (Bq/g) [20]	Effective dose per unit ^{40}K activity concentration (mSv/a per Bq/g) [5]			Annual effective dose (mSv)
		Gamma radiation	Dust inhalation[a]	Total	
K fertilizer	9.63	0.016	0.002	0.018	0.17
PK fertilizer	6.16	0.020	0.004	0.024	0.15
NPK fertilizer	5.90	0.024	0.006	0.030	0.18

[a] Dose calculated for ^{238}U and ^{232}Th series radionuclides only.

6. Public exposure to NORM

Public exposure attributable to industrial activities involving NORM is still an area in which dependable information is lacking because the doses are difficult to quantify reliably and their assessment is heavily dependent on modelling with its associated drawbacks. A review of information on doses received by members of the public from NORM industries is given in the 2000 UNSCEAR report [17], which states that “Although exposure rates of the order of 100 µSv a^{-1} could be received by a few local residents, levels of 1–10 µSv a^{-1} would be more common”. Data being gathered by the IAEA on NORM industries is generally in line with the figures quoted by UNSCEAR, although higher doses have been indicated for exposure scenarios involving the uncontrolled use (residential/intrusion) of landfill disposal sites. Examples of the results of dose assessments are given in Table 4.

7. Possible implications of the revised ICRP recommendations and the likely trends in safety standards

On 12 January 2007, the ICRP posted on its website the final draft of its revised recommendations, which are intended to supersede the 1990 Recommendations [1] during the course of 2007. These draft recommendations represent more of an update than a fundamental change, but the ICRP has decided to move away from the previous process-based system of practices and interventions to an approach that emphasizes the similarity of protective actions taken regardless of the exposure situation. Since the current approach to protection against exposure to natural sources differentiates quite explicitly between practices and interventions, the implications of the revised ICRP recommendations need to be examined carefully.

In terms of the revised approach to protection, the ICRP now refers to *exposure situations* rather than types of human activity. Two types of exposure situation are applicable to exposure to natural sources — planned exposure situations and existing exposure situations. It seems that these situations correspond more or less to those that until now have been subject to control in accordance with the requirements for practices and intervention, respectively.

TABLE 4. DOSE RECEIVED BY A MEMBER OF THE PUBLIC: SOME RESULTS OF MODELLING ASSESSMENTS

	Exposed individual	Estimated annual effective dose (μSv)
Zircon and zirconia industries [9]		
Landfill disposal, waste zircon sand	Resident/intruder	0.6–130
Zircon milling	Nearby resident	0.01–32
Zircon milling	Worker, adjacent industrial facility	200–320
Use of glazed tiles containing zircon	Building occupant	9–113
Production of fused zirconia	Nearby resident	37
Landfill disposal, zircon fusion furnace dust	Residential	4.5
Chemical processing of zircon	Nearby resident	Negligible
Landfill disposal, zircon chemical process waste	Resident	750
Landfill disposal, refractory plant waste	Resident	A few μSv
Phosphate industry [10]		
Phosphate mining and beneficiation	Nearby resident	17–21
Thermal phosphorus production	Nearby resident	1
Road construction using phosphorus slag	Road user	1–60
Titanium dioxide pigment industry [11]		
Sulphate production process	Nearby resident	Insignificant

The revised recommendations, as they apply to what are currently referred to as practices, may end up having little impact on international standards. For what has until now been categorized as intervention, it is the opinion of the ICRP that the revised recommendations will lead to an improvement in the level of protection, but quite how this will be reflected in future international standards is presently unclear. The use of the term ‘existing exposure’ in place of ‘chronic exposure’ would seem to be a simple change in terminology, as would the replacement of the term ‘critical group’ by the term ‘representative person’. The principle of justification (of action to reduce doses) still applies as before, but the ICRP no longer uses the concept of an action level to define the level above which remedial action is deemed to be justified (and, conversely, below which such action is not justified). Instead, the ICRP now proposes the concept of a ‘reference level’ that, for existing exposure situations, is a level of individual dose above which one should plan not to stay, and below which one strives to reduce all actual doses, with all exposures above or below this level of individual dose being subject to optimization of protection.

It would appear from the above that, for chronic (existing) exposure situations, the basic principles of justification and optimization remain as the cornerstones of the protection approach but with increased emphasis on optimization. In that sense, there may be no need to make significant changes to the standards. However, the proposed new concept of reference levels would need to be considered carefully — is such a level in effect simply an upper bound on the range of appropriate action levels that may be considered? Judging from the revised recommendations for indoor radon, this would seem to be the case — the recommended upper bounds for reference levels for radon in homes and workplaces are 600 and 1500 Bq/m^3, respectively, identical to the existing *global* upper bounds for action levels, with the reference level in a particular country being set somewhere within this bound by the national authority, taking into account the prevailing economic and societal circumstances. It should be noted also that there are now no values specified as being the equivalents of the existing *lower* bounds of the radon action levels (200 and 500 Bq/m^3 for homes and workplaces, respectively), although the option of such a value being set at a national level for homes is still open, as implied by the statement that "… in addition to reference levels, national authorities may also wish to specify levels at which protection against radon-222 can be considered optimised, i.e. where no further action is needed".

8. In conclusion — what remains to be done?

8.1. Further standards development

8.1.1. Revision of the BSS and other IAEA standards

In 2006, ten years after the publication of the BSS, a review was carried out to determine whether a revision of the BSS was warranted. It was concluded that, while there was no major issue requiring urgent revision, there was a case to be made for a general revision of the BSS in order to take account of the many improvements that had been suggested. The revision process started towards the end of 2006 and will continue over the next few years. This in turn will require a review and revision of at least some of the supporting Safety Guides.

Now that there is some clarity regarding the ICRP's revised recommendations, it is possible to anticipate the way in which international standards are likely to develop over the next few years. IAEA Member States have repeatedly appealed for stability in the standards and, as far as exposure to natural sources is concerned, there is as yet no strong case for significant change. One important task is to take account of the radiological criteria for radionuclides in commodities in the revision of the BSS, in accordance with General Conference Resolution GC(48)/RES/10 (see Section 4.2.2). For exposure to NORM, this would entail considering the incorporation into the requirements of the activity concentration values of 1 Bq/g for uranium and thorium series radionuclides and 10 Bq/g for ^{40}K — these values are already included in the standards, but only as guidance at present. The question has also arisen as to whether exposure to natural sources should be dealt with in the BSS as part of the overall requirements or as a separate chapter (as is currently the situation in the European Directive 96/29/Euratom). The present state of agreement on the structure of a revised BSS favours integration into the overall requirements, on the grounds that the radiation safety approach with respect to exposure to natural sources is in principle no different from that for other types of exposure. There are indications that the European Commission may also be considering adopting this integrated approach in its current work to revise the European Directive.

8.1.2. Public exposure to NORM residues

There is one important gap at the Safety Guide level that has not yet been fully addressed. There are a few situations where it may be found necessary to regulate materials at activity concentrations below the values quoted in Ref. [16] (i.e. below 1 Bq/g for uranium and thorium series radionuclides), for example the use of some building materials containing residues from minerals processing industries and possibly the contamination of some drinking water aquifers by mine residue deposits. More work needs to be done to establish quantitative guidance for these situations; this should include a consideration of the dose implications, although a dosimetric approach on its own is unlikely to lead to guidance that truly reflects an optimum use of regulatory resources. As illustrated in Section 8.1.3, the dose implications need to be established with care and circumspection, because of the considerable uncertainties associated with exposure modelling and the need to ensure that the conservatism associated with low probability scenarios is not compounded such that the overall result is unrealistic.

8.1.3. An example of problems with the modelling of doses from mine residue deposits

Modelling has been carried out to estimate, for the groundwater drinking water pathway, the dose received by a person residing within the immediate zone of influence of a mine residue deposit. Contamination of a drinking water aquifer in this manner was one of the exposure scenarios considered in Ref. [24] in the derivation of the internationally agreed activity concentration values below which regulation was to be considered unnecessary [16]. As explained in Section 4.2.2, this dosimetric approach was used only for radionuclides of artificial origin, but it is a simple process to repeat the calculation for radionuclides in the uranium decay series. Preliminary results of such an exercise, together with results from a similar exercise carried out independently using different assumptions, are summarized in Table 5 and are further discussed below:

(1) Using the modelling parameters in Ref. [24], an estimation for a mine residue deposit containing 20 million m^3 of material indicated a leach rate of about 0.0001 a^{-1} and a ^{238}U drinking water contamination level of about 2.8 Bq/L per unit activity concentration (in Bq/g) in the residue deposit. This resulted in an annual ingestion dose received by an adult of about 0.1 mSv per unit activity concentration. A child of age 1–2 years was estimated to receive a similar dose. Using, instead, a predetermined leach rate of 0.001 a^{-1} (as was assumed in the alternative modelling exercise), the corresponding dose estimates were about 1 mSv.

(2) Extensive analyses of radionuclides in groundwater around the perimeters of gold mine tailings dams in South Africa (comprising a total of 6 billion t of material at an average ^{238}U concentration of almost exactly 1 Bq/g) gave a 90th percentile ^{238}U concentration of 2.78 Bq/g and a mean value of 1.22 Bq/L [25]. The 90th percentile value is essentially the same as that predicted by the model described in Ref. [24], giving the same dose per unit activity concentration (0.1 mSv) as that reported in (1). When the mean concentration was used, the dose per unit activity concentration was 0.05 mSv.

(3) Another modelling exercise carried out for a residue pile of the same dimensions [26] was based on rather different input parameters, which were considered to be “conservative but not unrealistic”. The annual ingestion dose received by an adult was estimated to be more than 5 mSv per unit activity concentration, while the corresponding dose for a 1–2 year old child was more than 10 mSv.

TABLE 5. DOSE MODELLING PREDICTIONS FOR INGESTION OF GROUNDWATER CONTAMINATED BY A MINE RESIDUE DEPOSIT

	Activity concentration of ^{238}U in groundwater per unit activity concentration in the residue (Bq/L per Bq/g)	Committed effective dose in a year per unit activity concentration in the residue (mSv per Bq/g)	
		Adult	Child, 1–2 years
IAEA model [24]			
Based on modelled groundwater contamination, including a modelled leach rate of 0.000111 a^{-1}	2.75	0.12	0.11
Based on modelled groundwater contamination, but with a predetermined leach rate of 0.001 a^{-1} as was assumed in Ref. [26]	24.83	1.06	1.01
Based on measured groundwater contamination (90th percentile) [25]	2.78	0.12	0.11
Based on measured groundwater contamination (mean) [25]	1.22	0.05	0.05
Alternative model of groundwater contamination and ingestion dose, with an assumed leach rate of 0.001 a^{-1} [26]	Not reported	5.683	10.269

The question as to which set of assumptions is the more appropriate is a matter of debate. The main purpose of this example is simply to demonstrate that the choice of modelling assumptions can have a critical influence on the result, and that it is always preferable to make the greatest possible use of measured data. It also raises some other questions, for instance:

– Is it reasonable to characterize the ‘representative person’ as a person belonging to any particular age group (e.g. 1–2 years as in the results presented above), or is it more appropriate to consider only an adult or perhaps a combination of age groups weighted according to the number of years spent in each age group?

- Is it reasonable to assume that residents will choose (or will be permitted) to obtain their regular drinking water supply from a contaminated well next to a mine residue deposit when such water is likely to be unfit for drinking purposes due to contaminants such as dissolved salts and heavy metals?

8.2. Harmonization of standards and regulatory approaches at the national level

Despite having achieved a considerable degree of consensus in the development of international standards for NORM, the standards and regulatory approaches being adopted at the national level are still far from being harmonized. With minerals being traded worldwide on a very large scale, this is resulting in a situation that some might describe as ‘chaotic’, with severe disruptions in the movement of goods from one country to another and unnecessary interference in normal trade. In addition, scarce regulatory resources, especially in developing countries, are probably not being used in an optimum fashion, leading to the possibility that more pressing radiological issues are not receiving an appropriate level of attention. The problem is illustrated by the following anecdotal reports:

- Consignments of imported zircon and zirconia are reported to have been rejected and returned to the exporting country because their activity concentrations exceeded ‘local background’ by more than a predetermined factor ranging up to a value of ten.
- It has been reported from another country that the criterion for regulation of materials containing radionuclides of natural origin has been set at 0.1 Bq/g, ten times lower than recommended in the international standards.
- The import of certain fertilizers, phosphate ores and zirconium-containing products has reportedly been prohibited because of elevated levels of radionuclides of natural origin. It seems that the authorities applied a limit on activity concentration of 0.15 Bq/g, above which the material is rejected. This has had a discriminatory effect on some potential trading partners whose products do not meet this criterion.

Clearly, there is a need to move towards a more harmonized approach in order to minimize problems like this that appear to be occurring on an ever increasing basis.

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